Space debris research

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Space debris, introduction

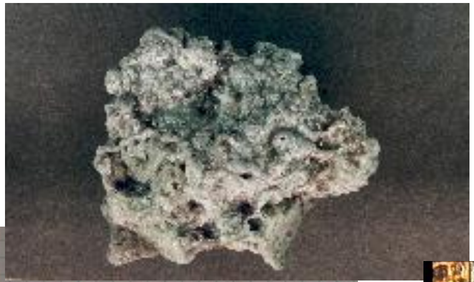
Space debris, definition

- **“All the man-made objects which are orbiting the Earth and have no further application.”**

Satellite Astra

Upper stage Agena D

Al_2O_3



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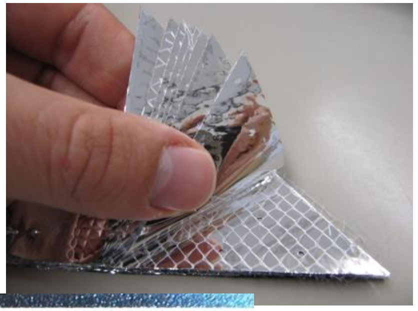
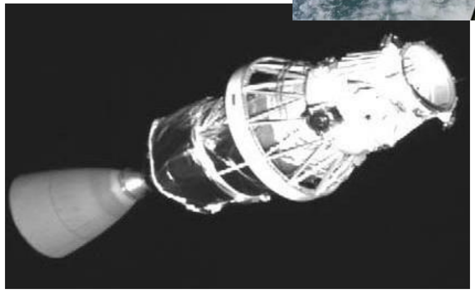
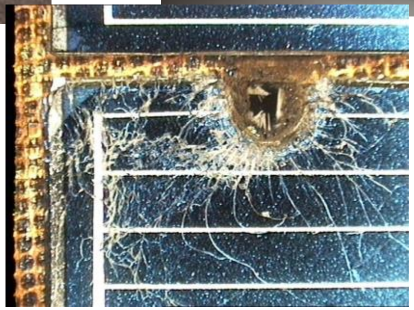


Probe Phobos Grunt



Upper stage Delta

Fragment SOCIT4 37



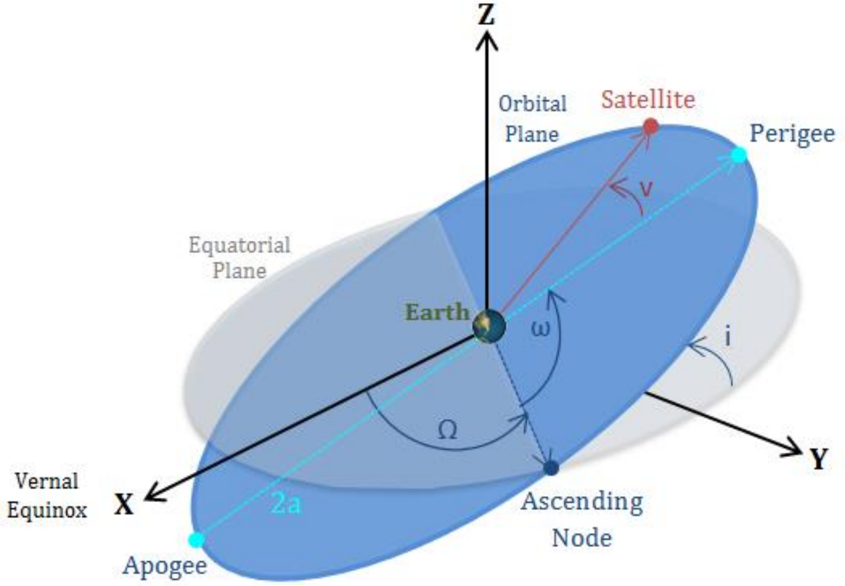
HST solar panel

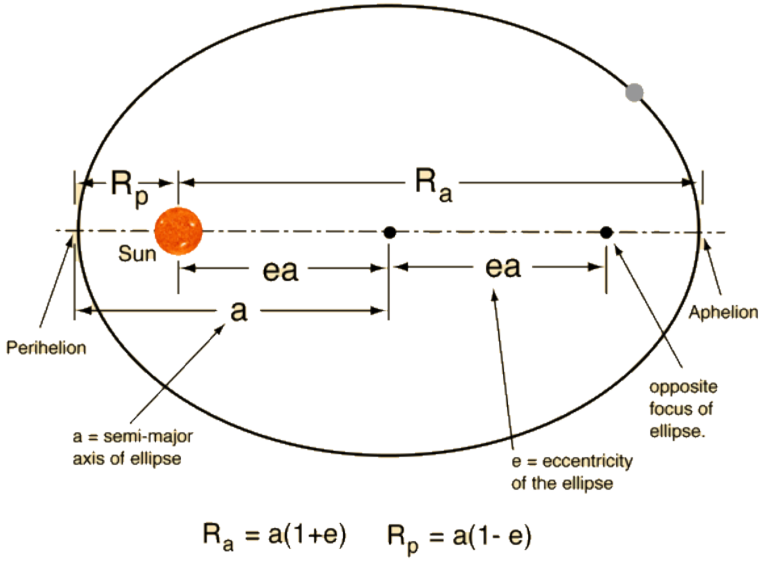
Space debris, spatial distribution

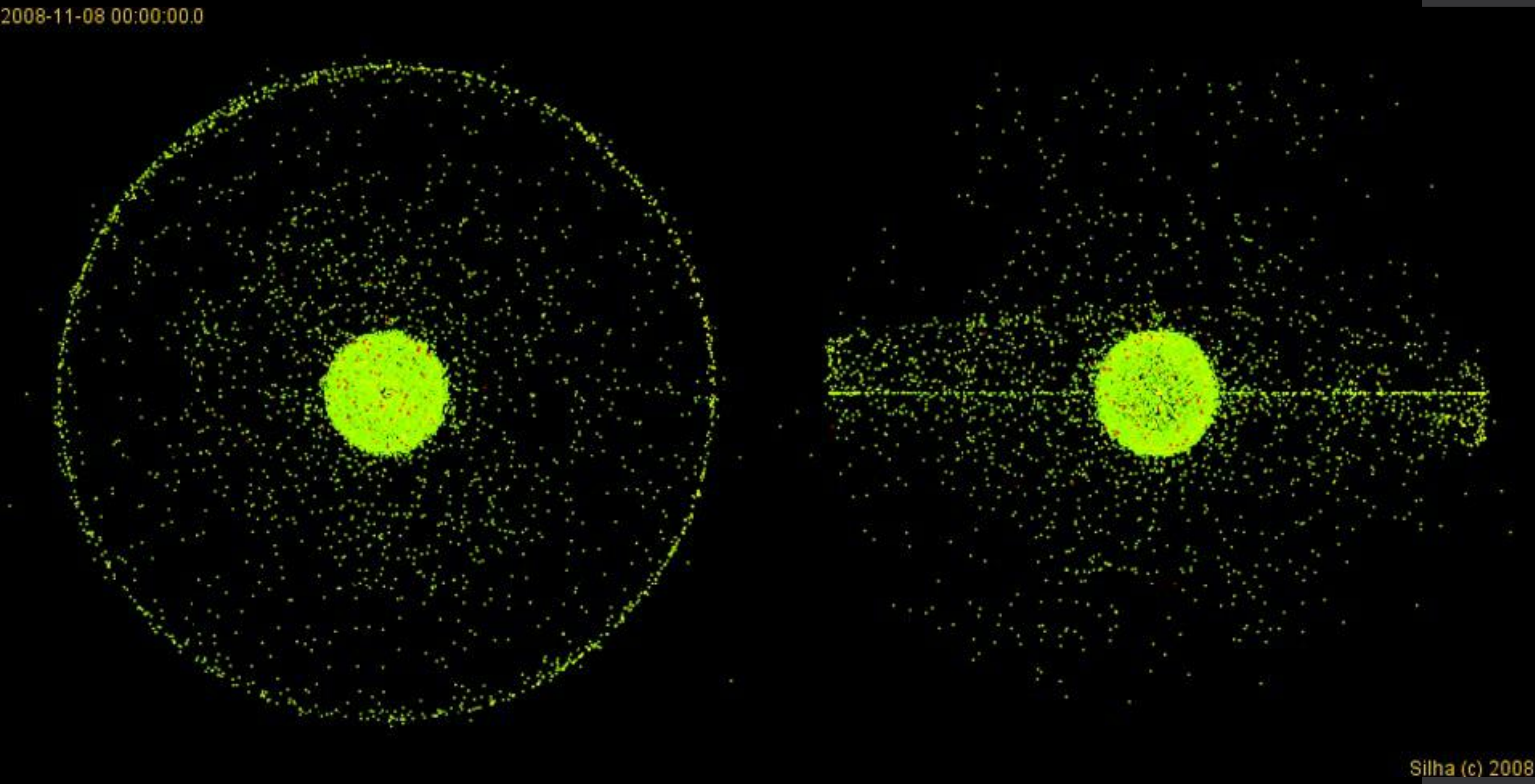
- Valid are three Kepler's laws, according to the 1st Kepler's law:

  "*<u>Within the domain of the solar system all planets describe elliptical paths with the Sun at one focus.</u>*"

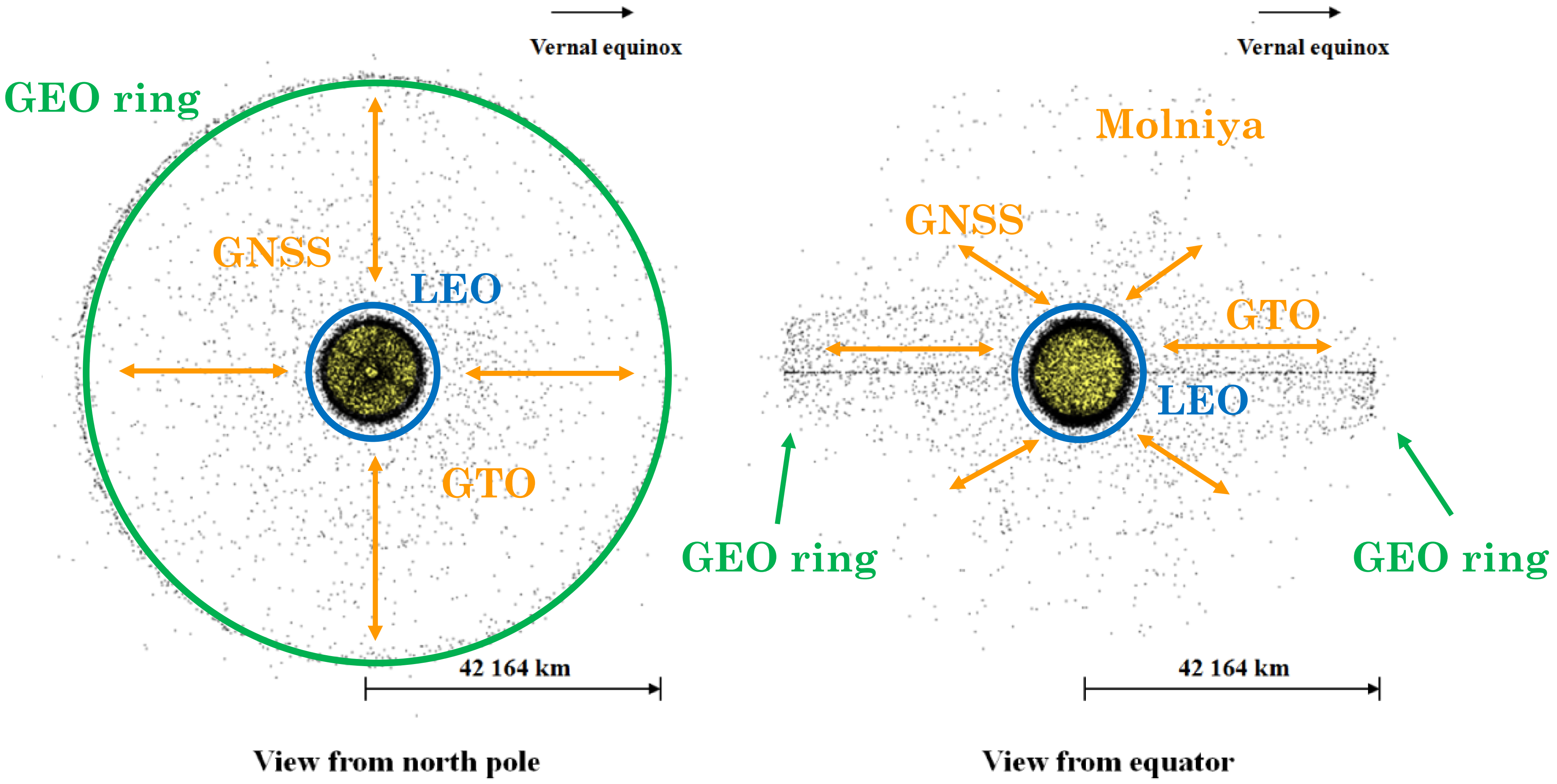
- 1st Keple's law also valid for geocentric motion, in that case any object e.g. Moon, satellite, debris describe elliptical paths with the Earth/Moon system (its barycenter) at one focus
- To describe the object current position in inertial system, two major systems are used:
  - Orbital elements – semi major axis (a), eccentricity (e), inclination (i), right ascension of the ascending mode (Ω), argument of perigee ω and true/mean anomaly (v(t)/M(t)), where t is a reference epoch
  - State vector – position and velocity vectors






2008-11-08 00:00:00.0
Silha (c) 2008

Space debris, spatial distribution



Space debris, spatial distribution

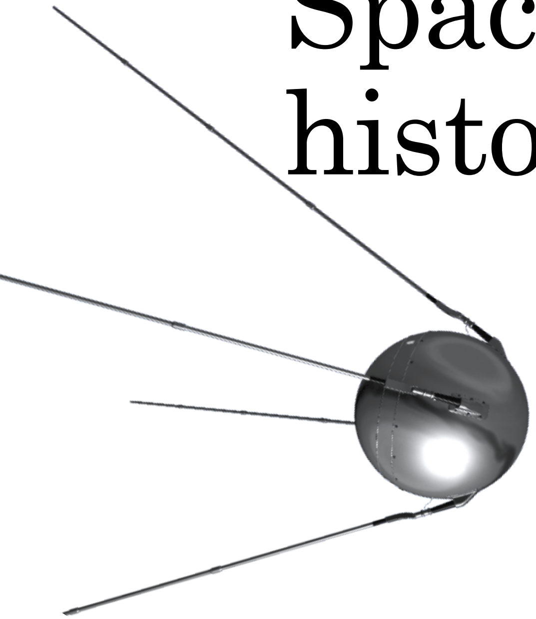
- Low Earth Orbit (**LEO**) – protected by IADC, the most dense part, man-made missions, > 10 000 catalogued objects, mostly fragments

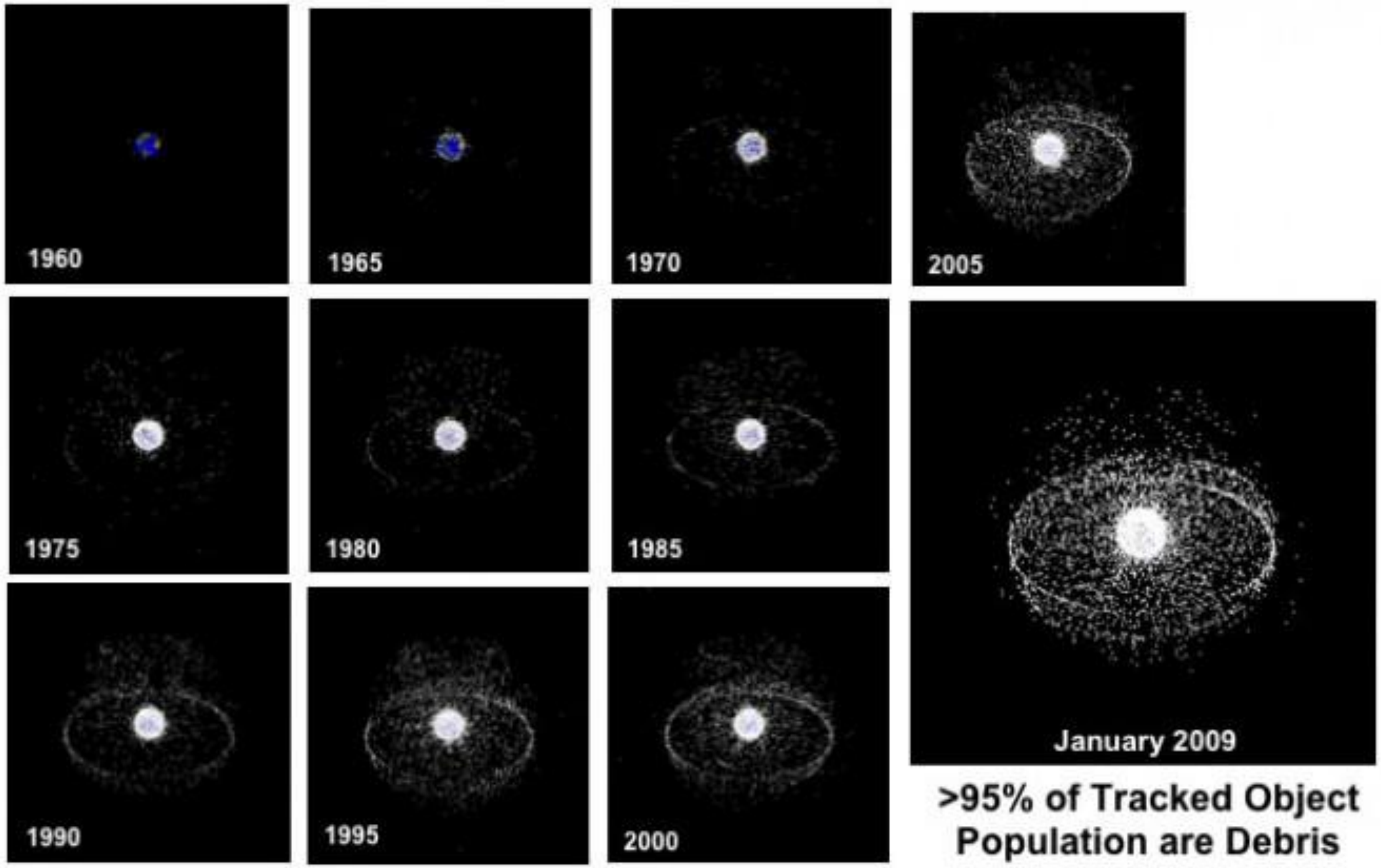
- Geosynchronous Earth Orbit (**GEO**) – almost circular orbits, with mean altitude ~ 35,786 km, mostly satellites, catalogued d > 50cm, surveys > 10cm

- **GNSS** – GPS, GLONASS, BeiDou, GALILEO, etc.

- **GTO**, **Molniya**, etc.

Space debris, history





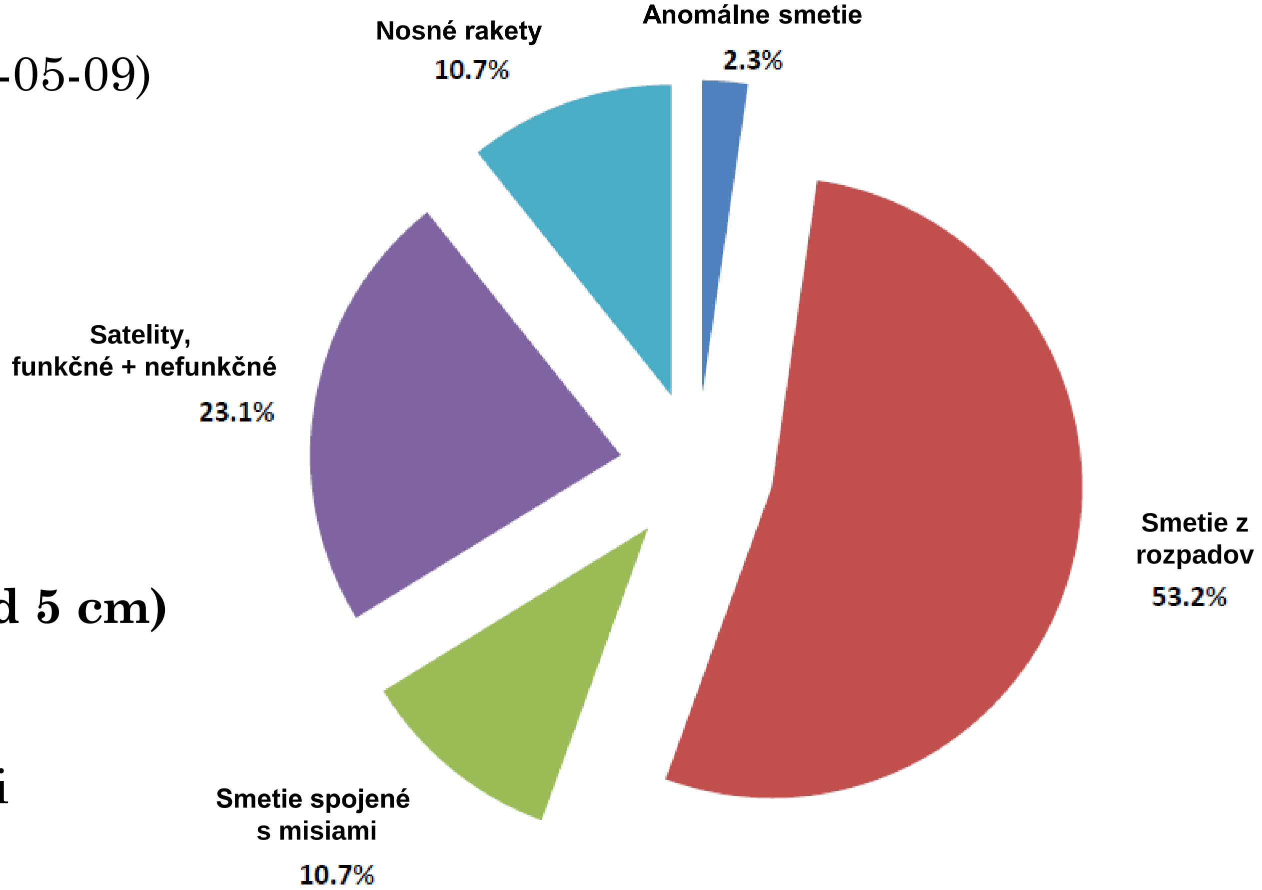
Space debris, sources

- - v súčasnosti (ku 2017-05-09)

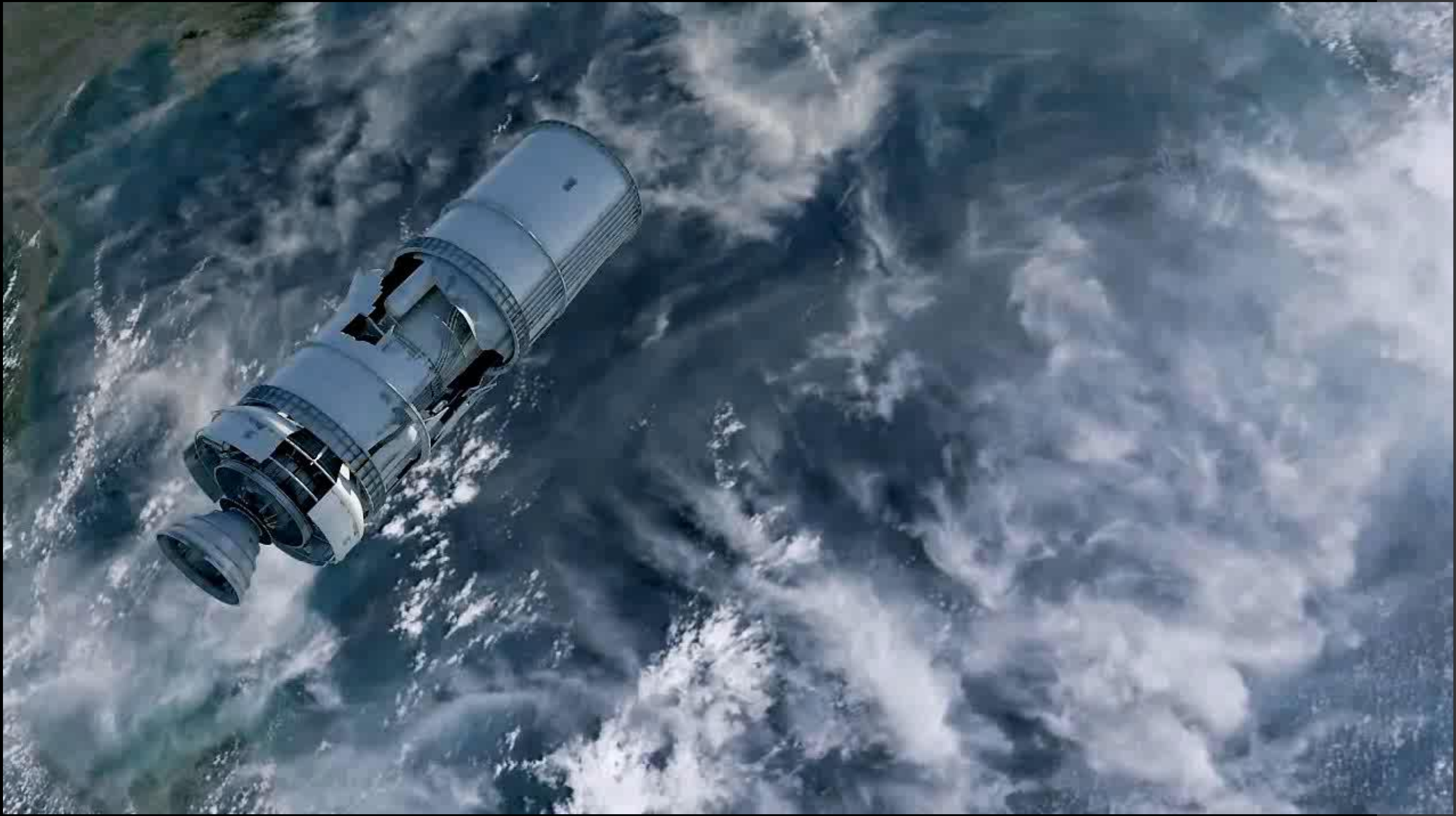
katalog. **16449** objektov

- satelity
  - funkčné (~900)
  - nefunkčné

- kozmické smetie (nad 5 cm)
  - nosné rakety
  - smetie z rozpadov
  - s vesmírnymi misiami spojené smetie
  - anomálne smetie



Prebraté z Orbital Debris Quarently News, 2017, issue 2



Research, main questions

- **Where is it?**
  - Surveys
  - Catalogues
  - Models
  - Etc.
- **How it behaves?**
  - How it rotates?
  - How it will rotate in future?
  - Etc.
- **What is it?**
  - Material composition
  - Origins
  - Other physical characteristics
  - Etc.
- **How to protect against it?**
  - Shielding
  - Orbit predictions
  - Removal
  - Etc.

Research (ESA ECSD 2017)

- Observations
- Space surveillance and cataloguing
- Orbit determination and prediction
- Attitude determination and prediction
- On-orbit fragmentation modeling
- Debris environment modeling
- Operational collision avoidance
- Re-entry analysis
- Hypervelocity impacts and shielding
- Debris mitigation, active removal

Observations techniques

- **Survey** observations used to discover new objects, to model space debris population (including small particles e.g. <1mm) spatial distribution
- **Tracking** observations used to investigate the physical and dynamical properties of space debris

- ***Optical*** (ground-, space-based)
  - Optical passive – optical telescopes (e.g. AGO 60cm and 70cm telescopes)
  - Satellite Laser Ranging (SLR) (optical active) – debris SLR systems

- ***Radar*** (ground-, space-based) – tracking and survey radar systems

- ***In-situ*** (space-based) – in-situ probe, surface

Optical observations

Optical (passive) observations

- Space debris not emitting own radiation (!)
- Interested only in the sun (visible) light reflected from the object

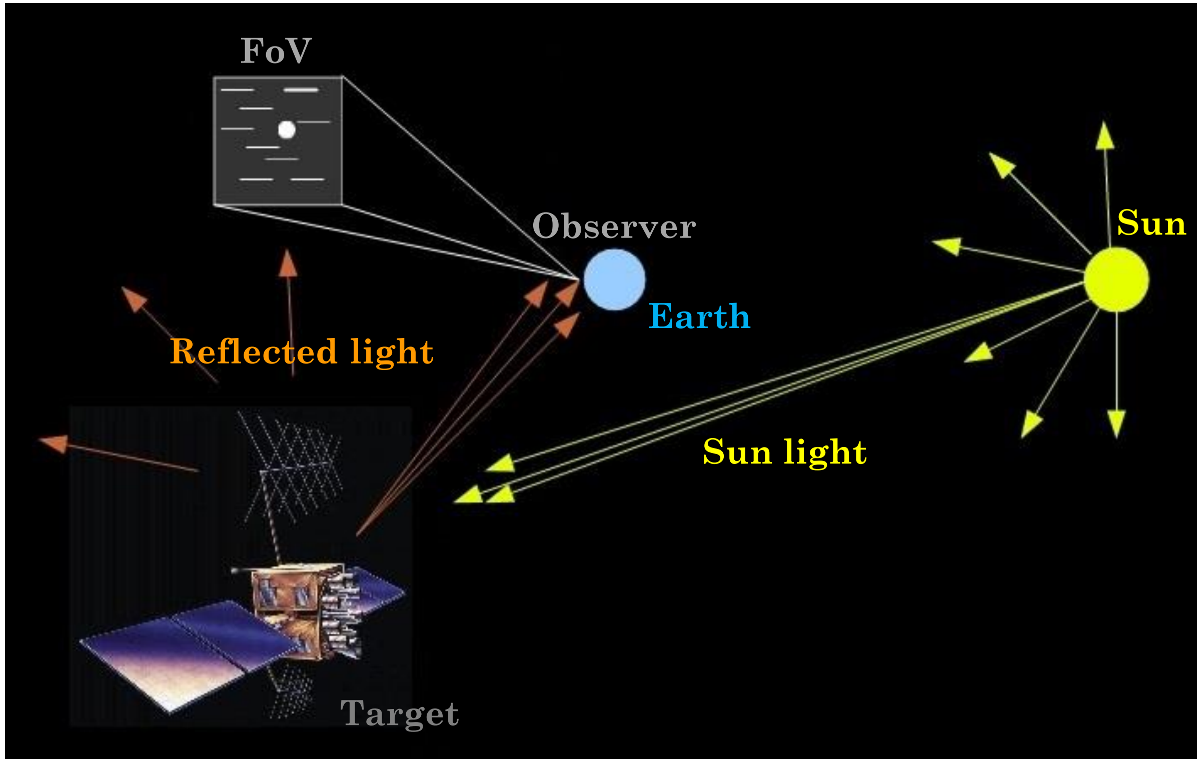


Figure – Schematic demonstrating sun light reflected from the object (satellite) toward observer.

Optical observations

- **Surveys** – to discover new objects for cataloguing and modeling

- **Astrometry** – follow-up (tracking) observations, to obtain the astrometric positions (apparent position of the object on celestial sphere) to be used for orbit determination and improvement

- **Photometry** - to get properties of the sun light reflected from the object toward observer
  - Attitude related information, light curve, rotation axis direction and rotation period size, e.g. ADR application
  - Attitude change over time monitoring, e.g., ADR application, monitoring of the near Earth environment
  - Reconstructed phase function, shape of object, e.g., object identification, type identification
  - Colors, color indices, surface properties, e.g., space-weathering, surface composition, origin identification

- **Reflectance Spectroscopy** – to get solar spectrum reflected from the object’s surface, e.g., surface composition ➔ source/origin identification

- **Spectrocsopy** – to get the spectrum of an object during reentry ➔ fragmentation modeling

Optical instruments

Space debris on FMPI and AGO

- **AGO** – FMPI CU Astronomical and geophysical observatory in Modra, Slovakia

Figure – AGO Modra main dome.

Figure – AGO Modra small upper dome.

Space debris on FMPI and AGO

- **AGO** – FMPI CU Astronomical and geophysical observatory in Modra, Slovakia
- AGO (70cm) – space debris data acquisition during tracking, astrometry and photometry, *image processing (near future)*
- AGO (60cm) – asteroids photometry, tracking, possible space debris simultaneous observations with AGO 70cm, e.g. simultaneous color photometry
- AGO (28cm) – not fixed location, space debris photometry (light curves), possible space debris simultaneous observations with AGO 70cm, e.g. simultaneous color photometry
- AMOS – all-sky meteor cameras, space debris "survey", astrometry, photometry
- AMOS-Spec – meteors spectral camera, spectroscopy

FMPI/AGO instruments, 70cm telescope

- Newton telescope with 70 cm parabolic mirror, f = 2.9 m
- Fork equatorial mount
- CCD FLI Proline PL1001 Grade 1, 1024 x 1024 pixels
- BVRI filter-changing device
- Field of view equals 29.1 x 29.1 square arcmins
- S/W development ongoing

Figure – AGO 70cm telescope.

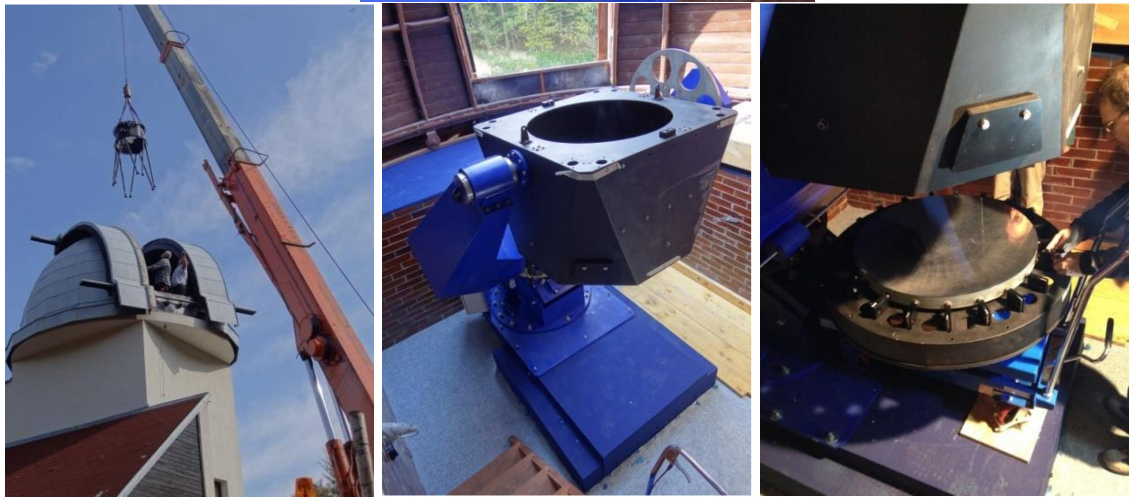


Figure – AGO 70cm telescope installation (left), mount (middle) and 70 cm primary mirror (right).

FMPI/AGO instruments, 70cm telescope

- Installed at AGO in Sep 2016
- Main objective:

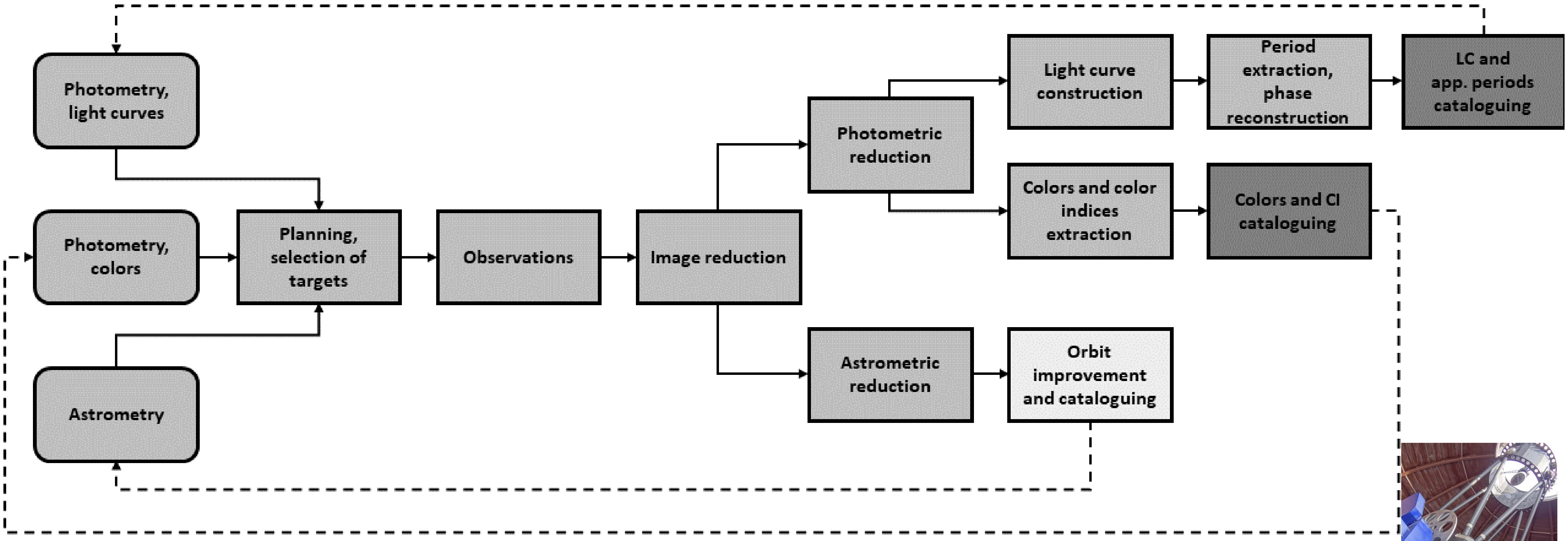
Perform tracking to space debris in order to support European space debris cataloguing, physical characteristics of debris

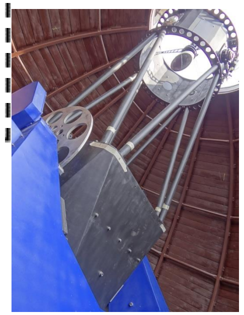
- Currently running ***ESA PECS HAMROptSen*** dedicated to the main objective, cooperation CU (SK, prime) + AIUB (CH)
- Activity covers all aspects – low-level control, planning S/W improvement, observation planning, data acquisition, data processing, image processing SW improvement, tracklet building, object identification, orbit improvement, cataloguing, data format conversion, etc.
- Once activity finished, AGO 70cm to be used for space debris research (70%) and other observations (support for 60cm, student projects, etc.) (30%)
- Currently preparation to get a follow-up study by using the Call ESA PECS Slovakia 3

FMPI/AGO instruments, 70cm telescope

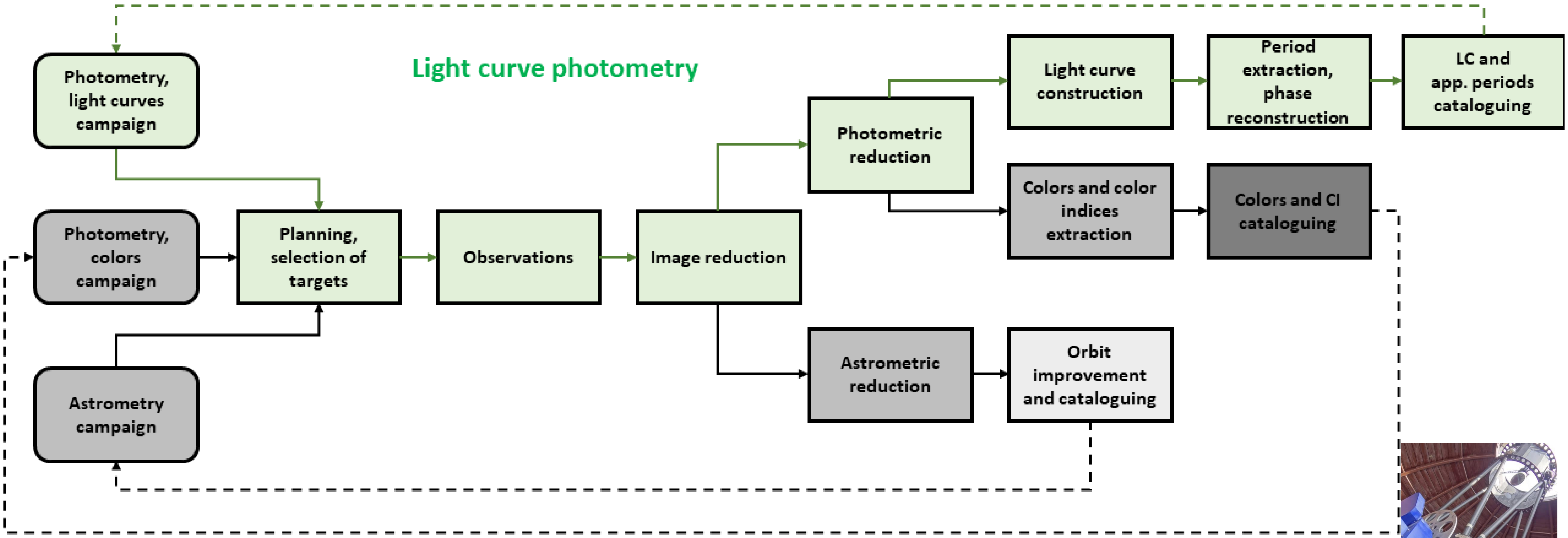
- Three major programs on AGO 70cm:
  - **Astrometry, surveys** - to maintain the objects catalogue, to discover new objects, cooperation with partners
  - **Photometry, light curves (LC)** – attitude state characterization, attitude motion determination, attitude evolution monitoring, internal LC catalogue
  - **Photometry, colors and color indices (CI)** – surface properties, space-weathering aging monitoring, internal CI catalogue

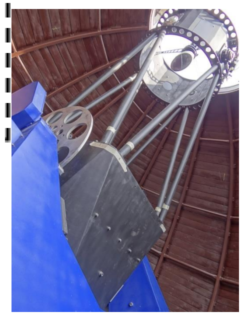
FMPI/AGO instruments, 70cm telescope



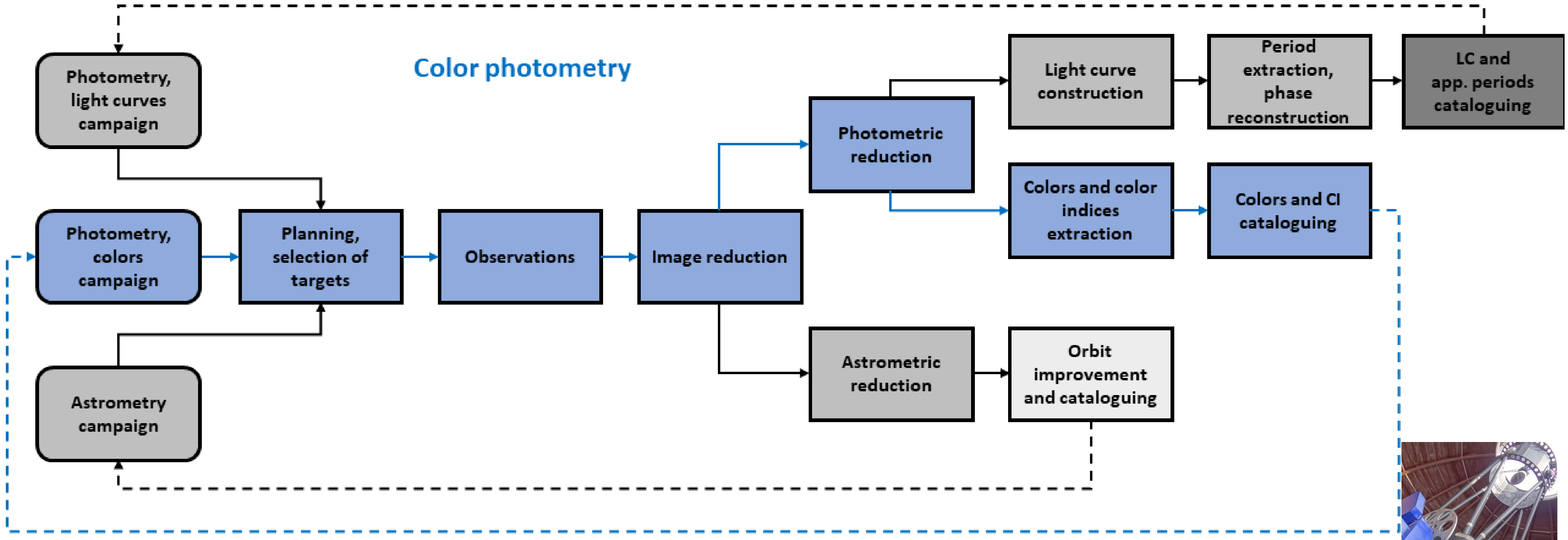


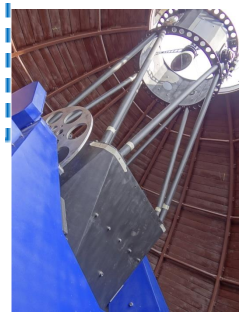
FMPI/AGO instruments, 70cm telescope



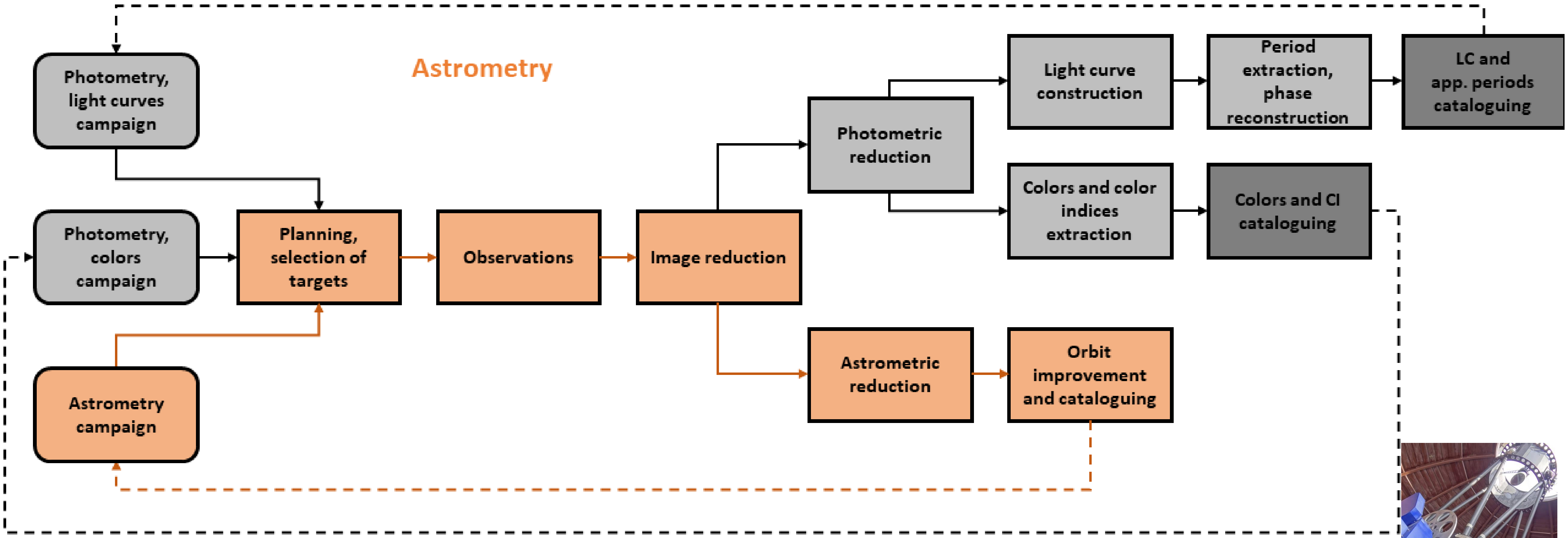


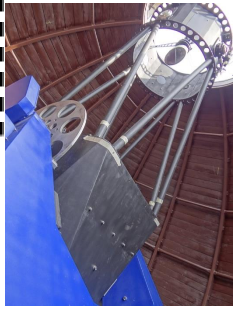
FMPI/AGO instruments, 70cm telescope





FMPI/AGO instruments, 70cm telescope





FMPI/AGO instruments, AMOS cameras

- **AMOS** (All-sky Meteor Orbit System) of Comenius University in Bratislava
- Originally developed optical system for intensified video night sky observation focused on meteors
- Network of 8 AMOS cameras in Slovakia (4), Canary Islands (2), Chile (2),

  plan to expend the network to USA (HI), Australia and Namibia
- AMOS at AGO, Tenerifa and Chile accompanied by AMOS-Spec cameras
- Currently several different national funding available for improvements
- Properties:
  - Automatic detection S/W
  - Own astrometric reduction S/W, astrometric accuracy around 4'-10', expected after improvement 1.8' (→ 0.5km for 1000 km range)
  - Limiting magnitude comparable to the naked eye, ~ 5 mag

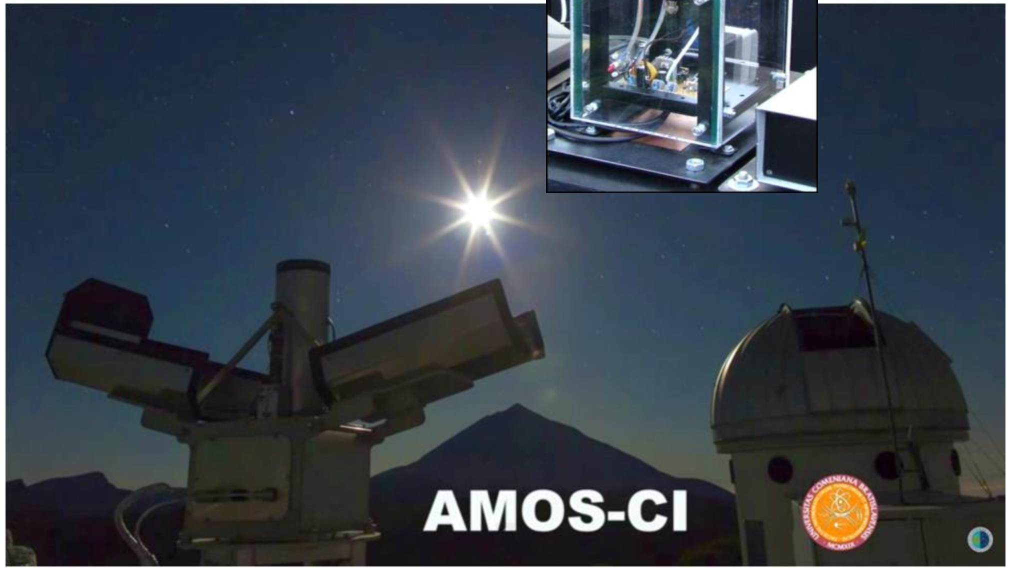


Figure – AMOS in Chile.

FMPI/AGO instruments, AMOS cameras

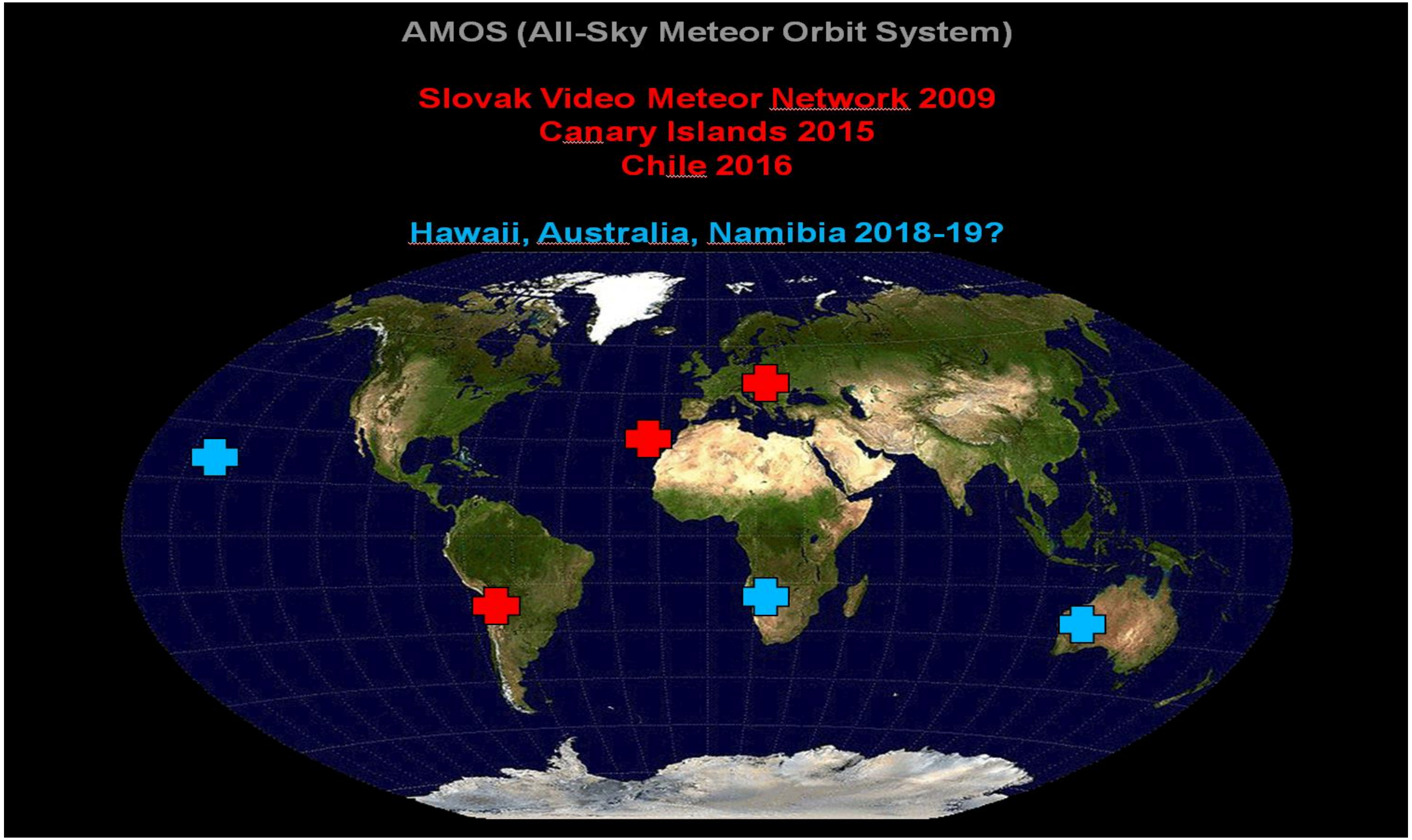
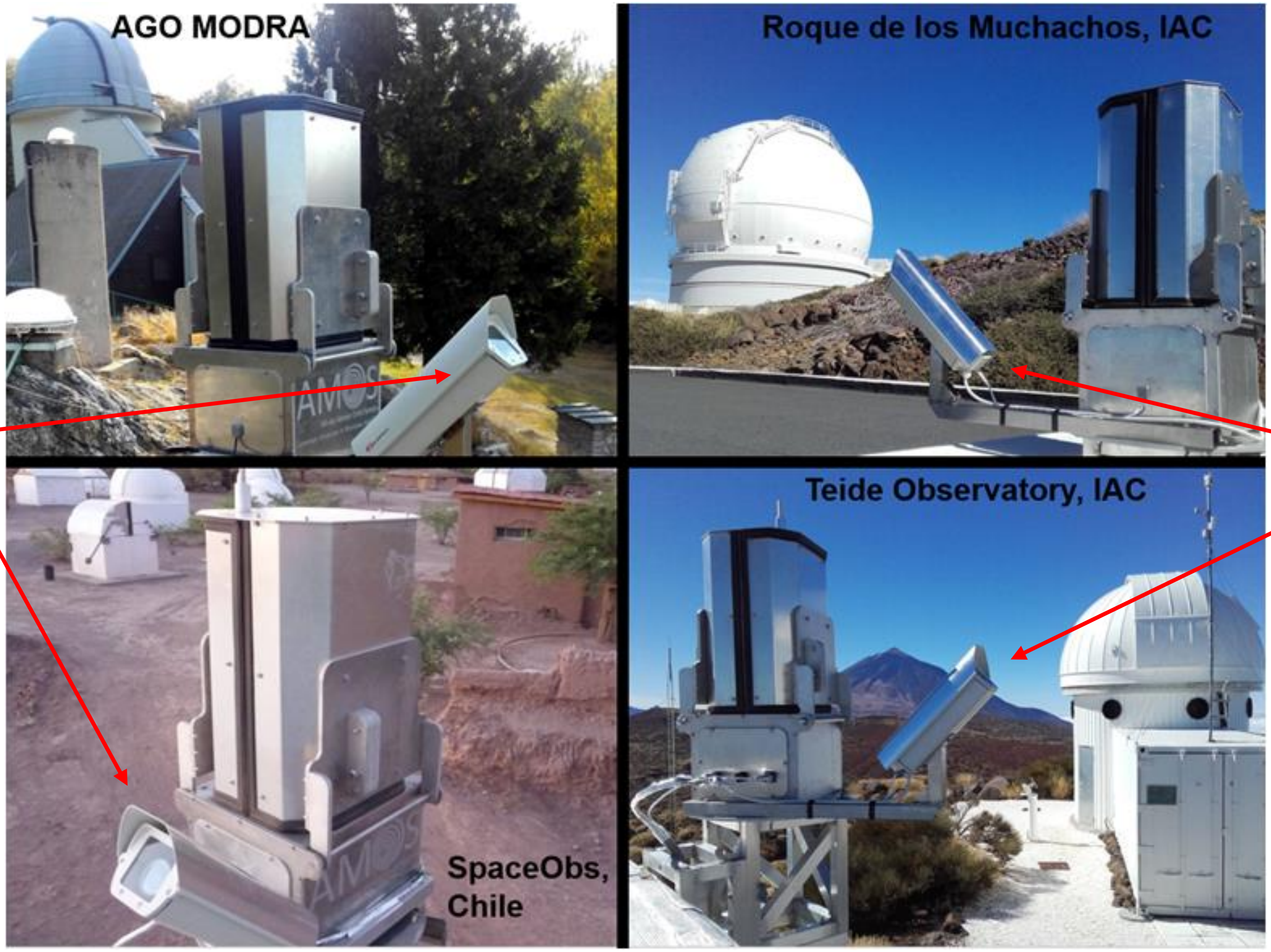


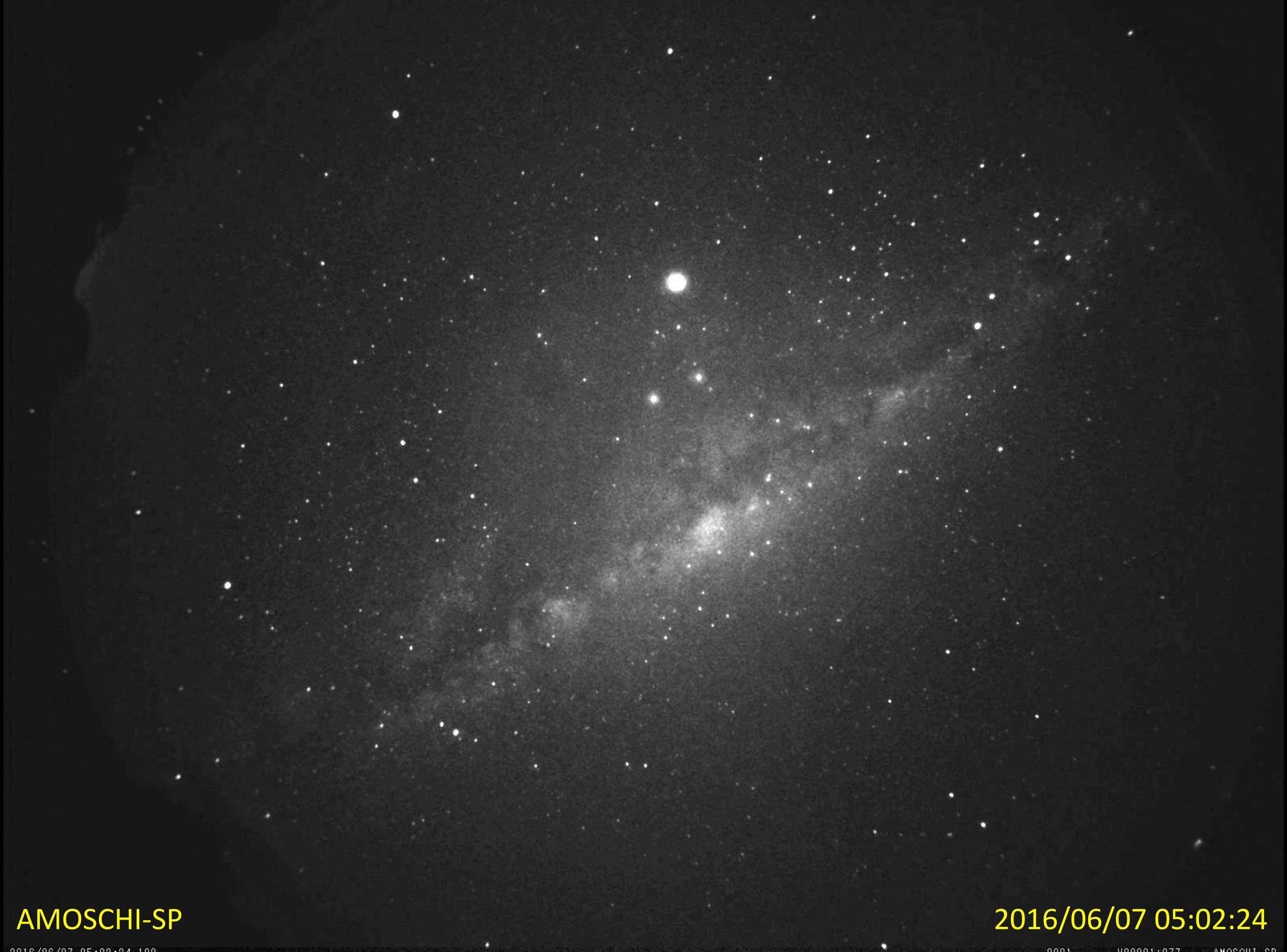
Figure – Distribution of AMOS cameras as per current status (red cross) and as planned (blue cross).

FMPI/AGO instruments, AMOS cameras



Amos-Spec

Amos-Spec


AMOSCHI-SP
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FMPI/AGO instruments, 60cm telescope

Figure –AGO main 60cm telescope.

- The main and oldest system at AGO
- The 0.6-m Zeiss mirror telescope, f = 3.26 m
- Observations in cooperation with the Ondřejov Observatory of the Astronomical Institute of the Czech Academy of Sciences.
- Telescope is equipment with a CCD camera, Apogee Ap8 with 1024 x 1024 pixels and BVRI filter-changing device
- The telescope's field of view is 24.7 x 24.7 square arc-minutes

Figure – AGO main building.

FMPI/AGO instruments, 28cm telescope

- Small “student” telescope, Celestron EdgeHD Schmidt with 28cm mirror, f = 3.29 m
- Telescope is equipment with a CCD camera, SBIG ST-7 with 765 x 510 pixels
- Used for students projects, for space debris light curve acquisition, for simultaneous color photometry
- The telescope’s field of view is 8.5 x 5.6 square arc-minutes

Figure – AGO student 28cm telescope.

Surveys

Optical observations

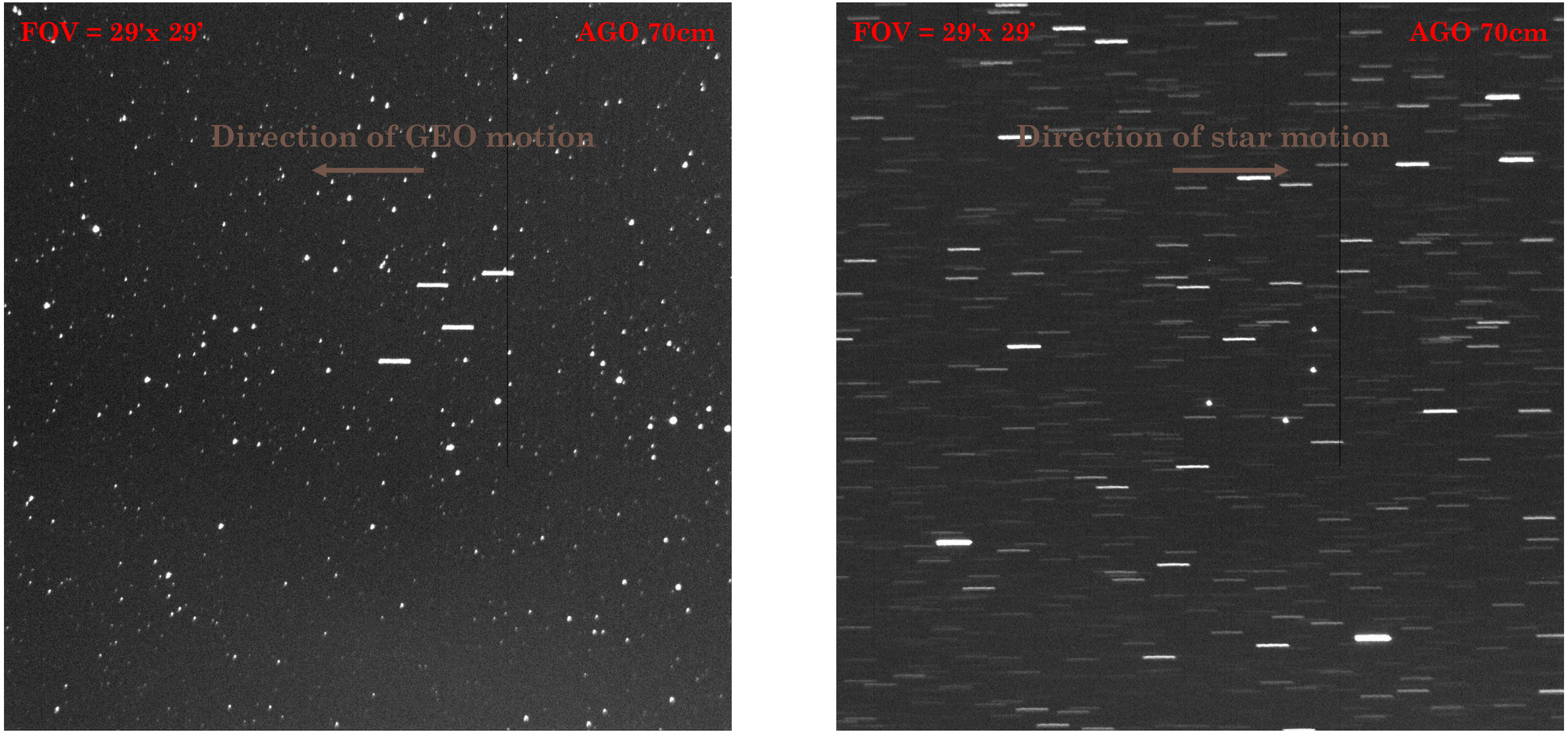
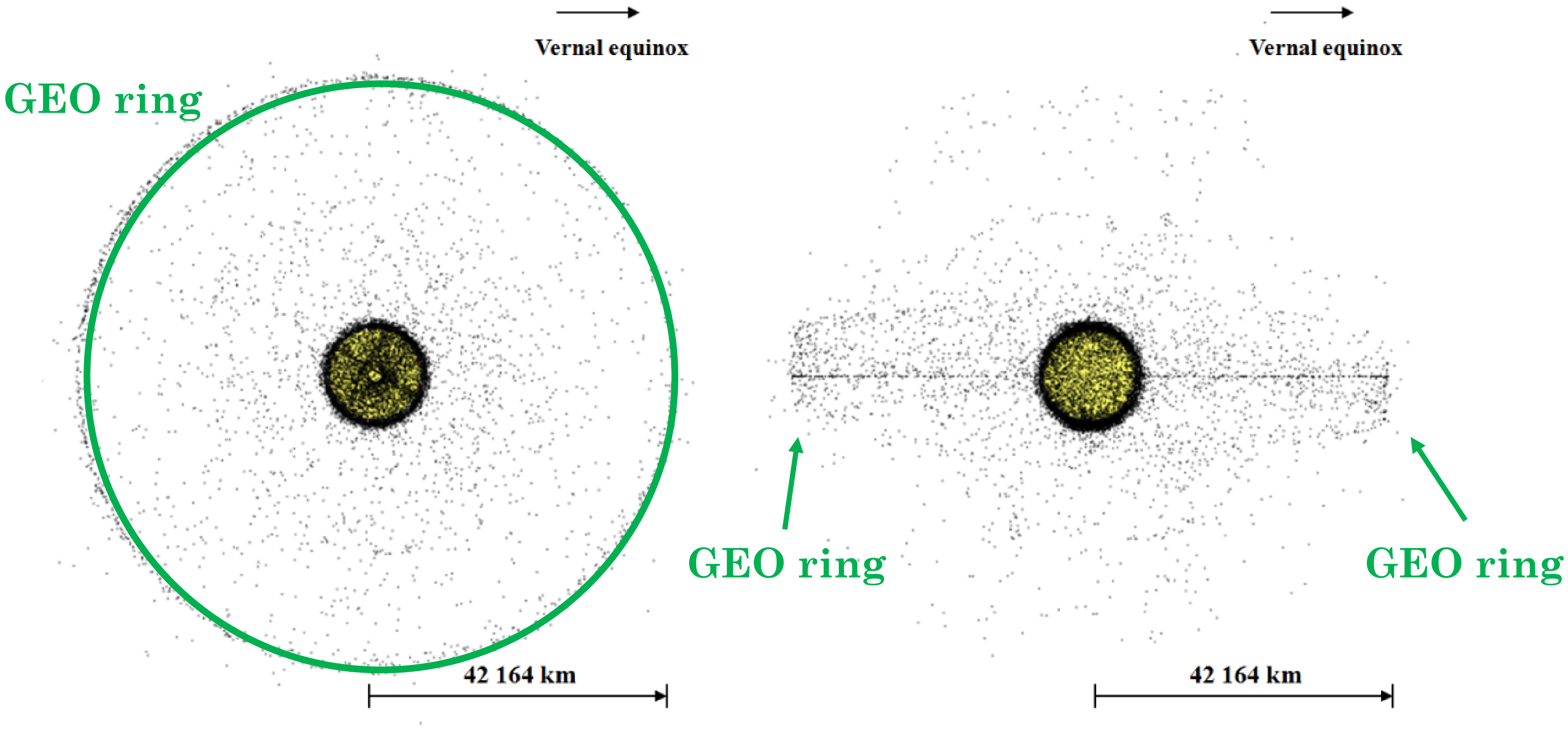


Figure – Images acquired by AGO 70-cm telescope. Astra satellites are showed on both panels. On the left, during exposure the sidereal tracking was ON and the satellites on GEO are displayed as streaks and stars as points. On the right, during exposure the sidereal tracking was OFF (for GEO equivalent to GEO tracking) so the objects appear as points and stars appear as streaks. The 5s exposure time was used in both cases. The clear (left) and I filter (right) were used.

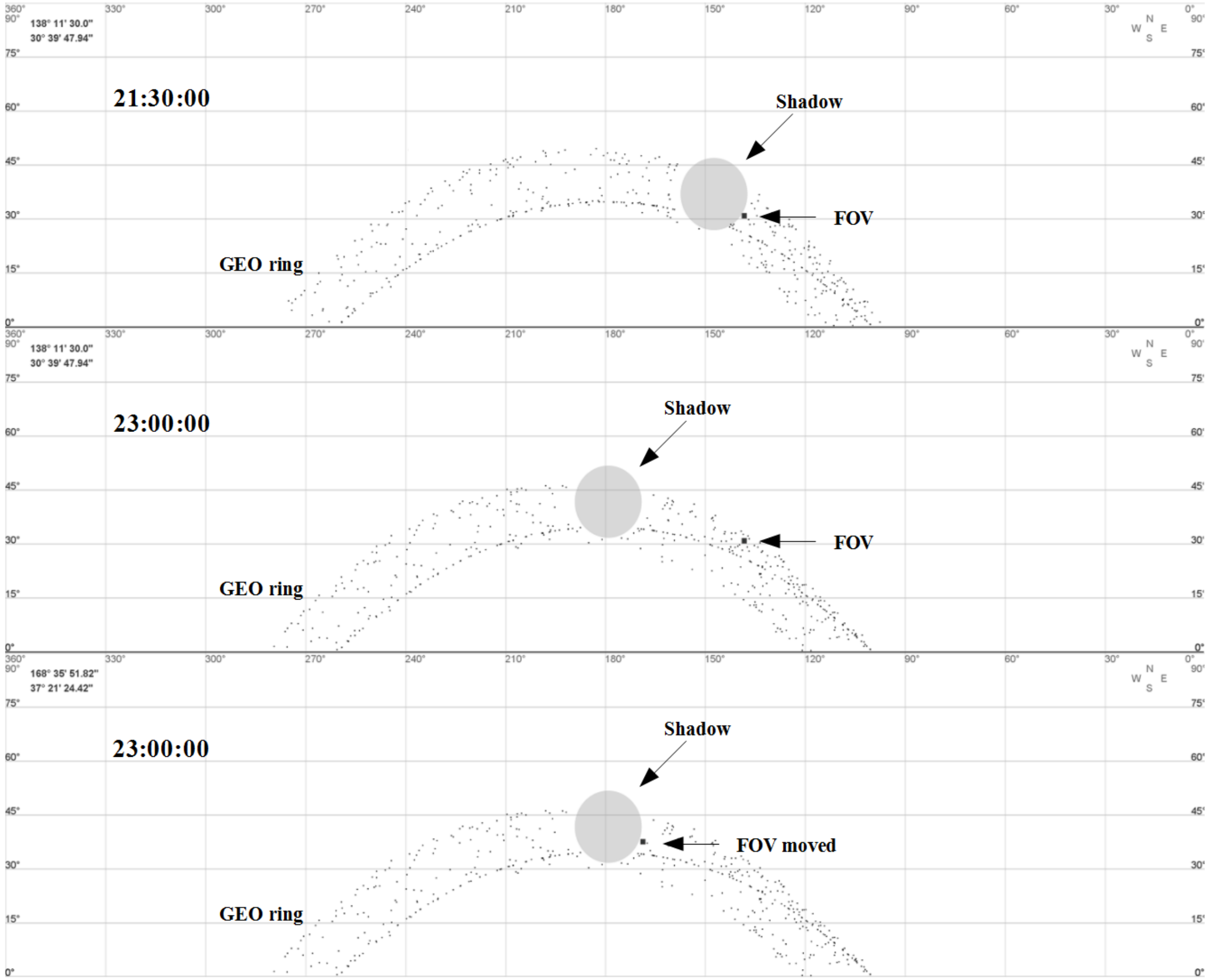
Optical observations



View from north pole

View from equator

Optical observations, survey



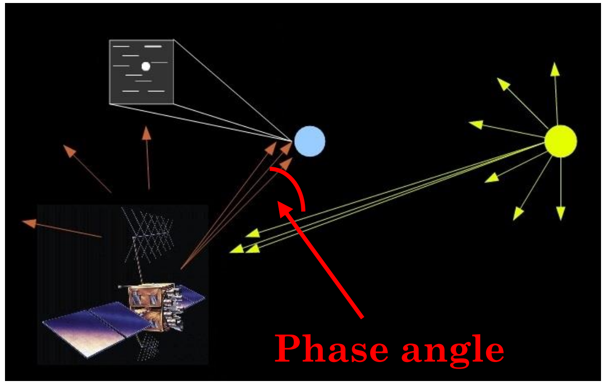


Figure – Demonstration of GEO survey strategy plotted in horizontal coordinates. At first, the field of view (FOV) (black square) is put right behind the Earth's shadow (gray circle) (upper figure). After 1.5 hours of scanning the shadow moved but the FOV didn't (middle figure). Then the telescope's FOV is moved by the observer behind the Earth's shadow to get the maximum phase angle and the scanning starts again (lower figure). Small black dots representing objects on GEO orbit.

Optical observations, survey

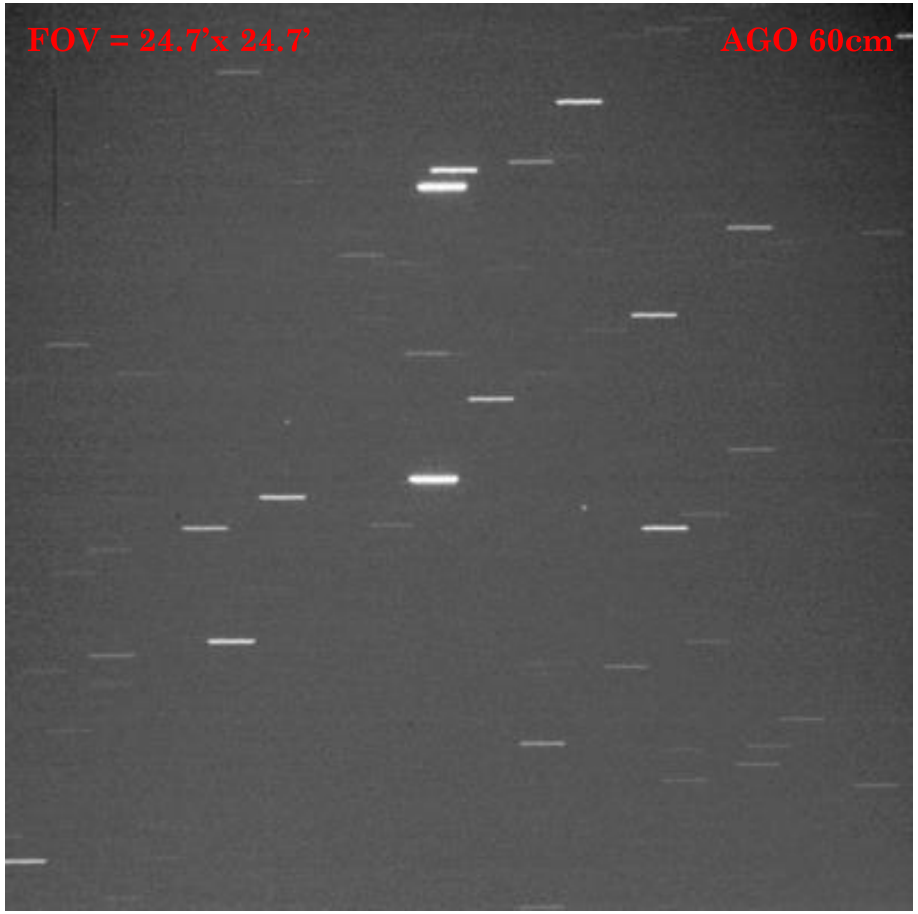


Figure – Images acquired by AGO 60-cm telescope. During exposure the sidereal tracking was OFF and the fragment of Titan 3C transtage (68081G) on GEO is displayed as point and stars as streaks. The 5s exposure time was used in both cases. No filter has been used.

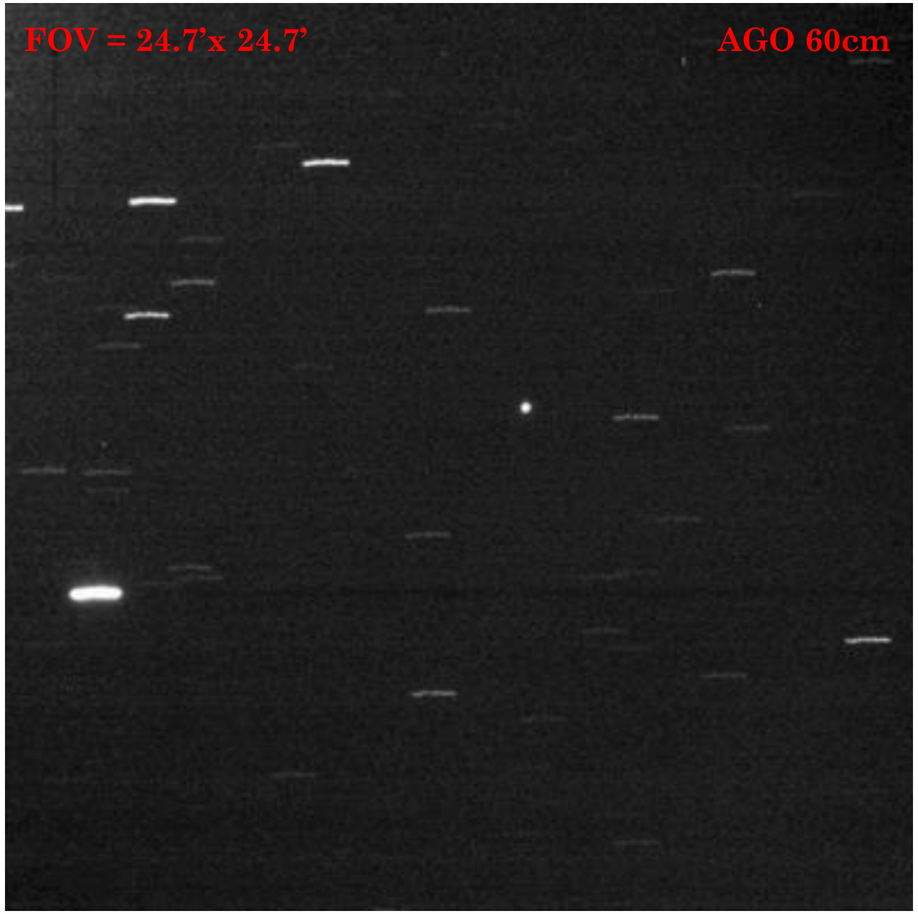


Figure – Images acquired by AGO 60-cm telescope. During exposure the sidereal tracking was OFF and the satellite Express AM-1 (04043A) on GEO is displayed as point and stars as streaks. The 5s exposure time was used in both cases. No filter has been used.

Optical observations, survey

- Example a Molniya survey from 2013 (Silha et al., 2017) showed 2x more UCTs than CTs, not included in the previous models (e.g. ESA MASTER)

Taken from Silha et al. (2017)

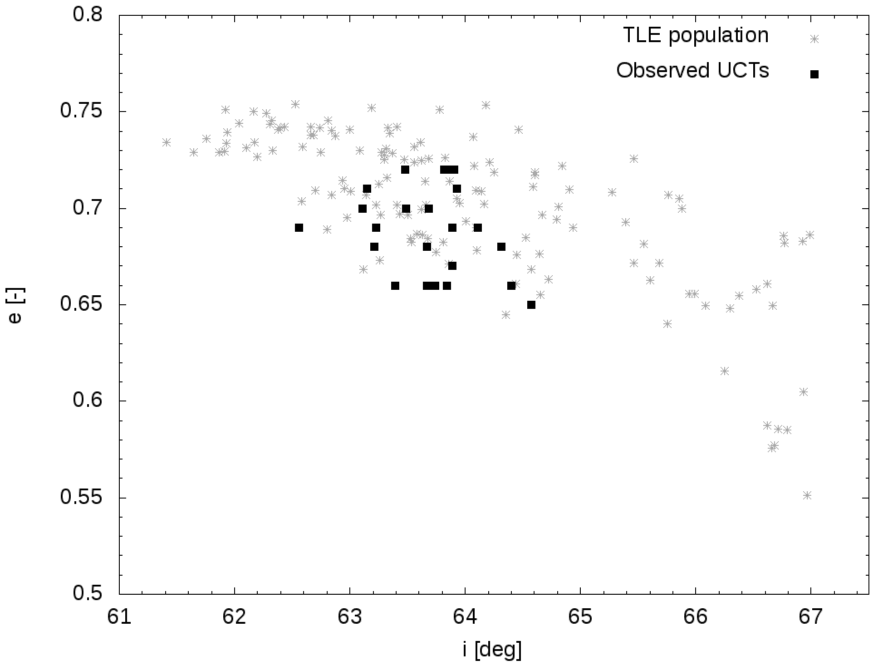


Figure – Comparison between orbital elements of TLE population (reference epoch 20131010) and 24 UCTs catalogued during the OGS Molniya surveys (reference epoch equals the date of discovery for given object). Compared are inclination vs. eccentricity.

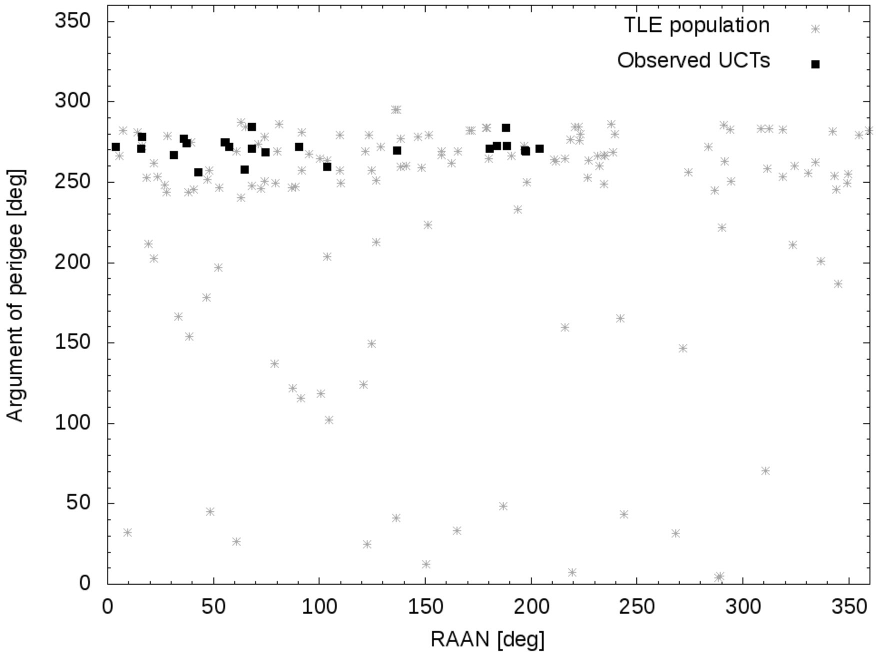
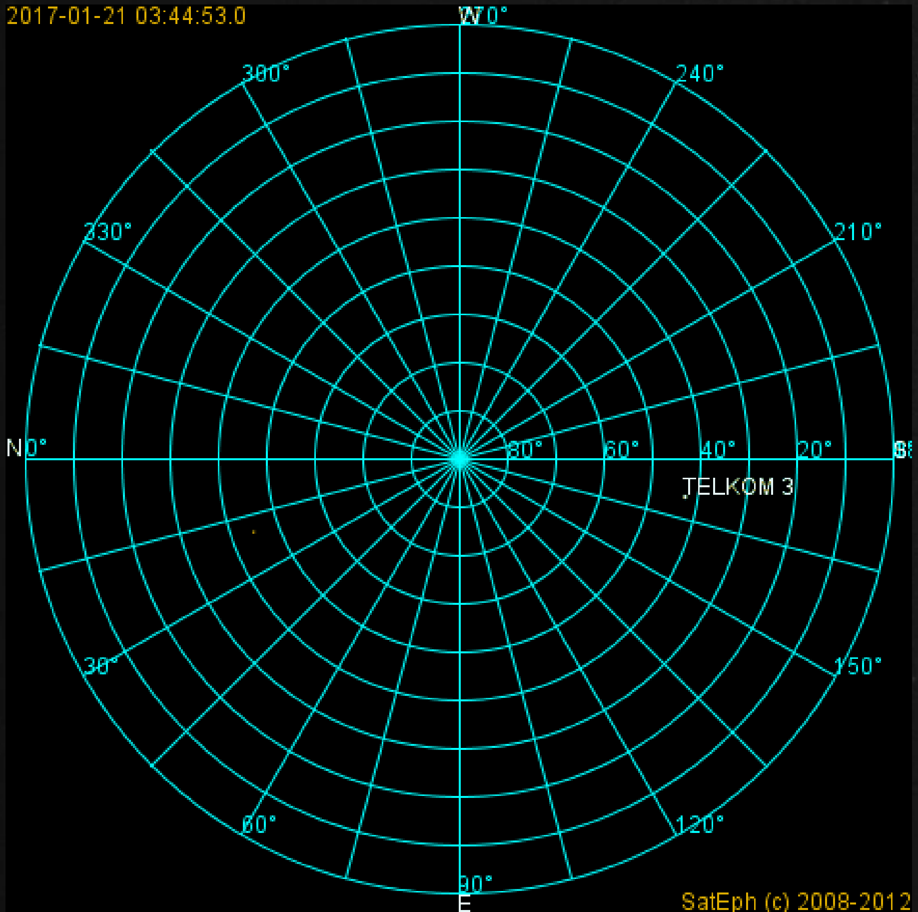


Figure – Comparison between orbital elements of TLE population (reference epoch 20131010) and 24 UCTs catalogued during the OGS Molniya surveys (reference epoch equals the date of discovery for given object). Compared are RAAN vs. AoP.

Speed 30x

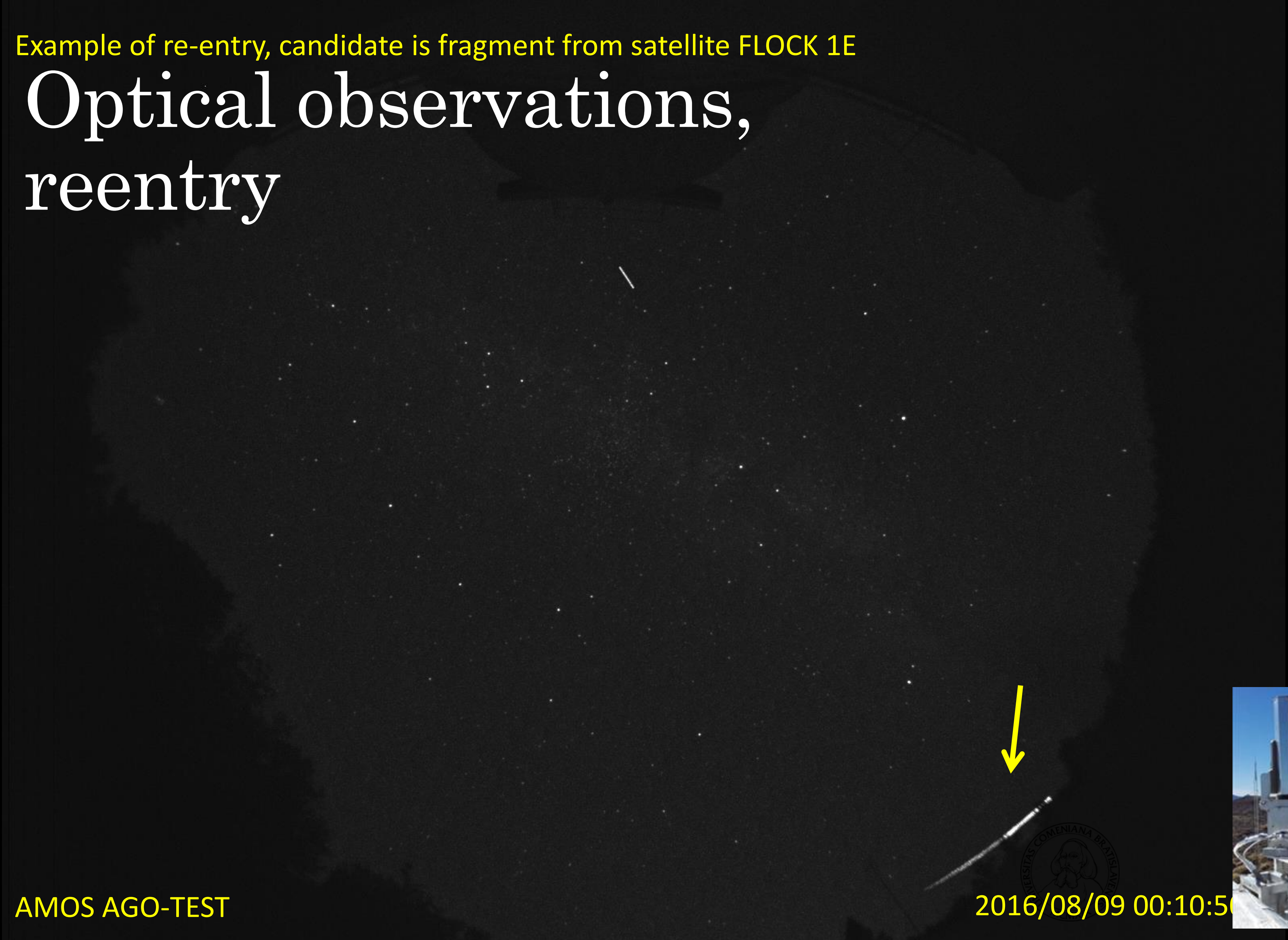
Telkom 3

Optical observations, survey



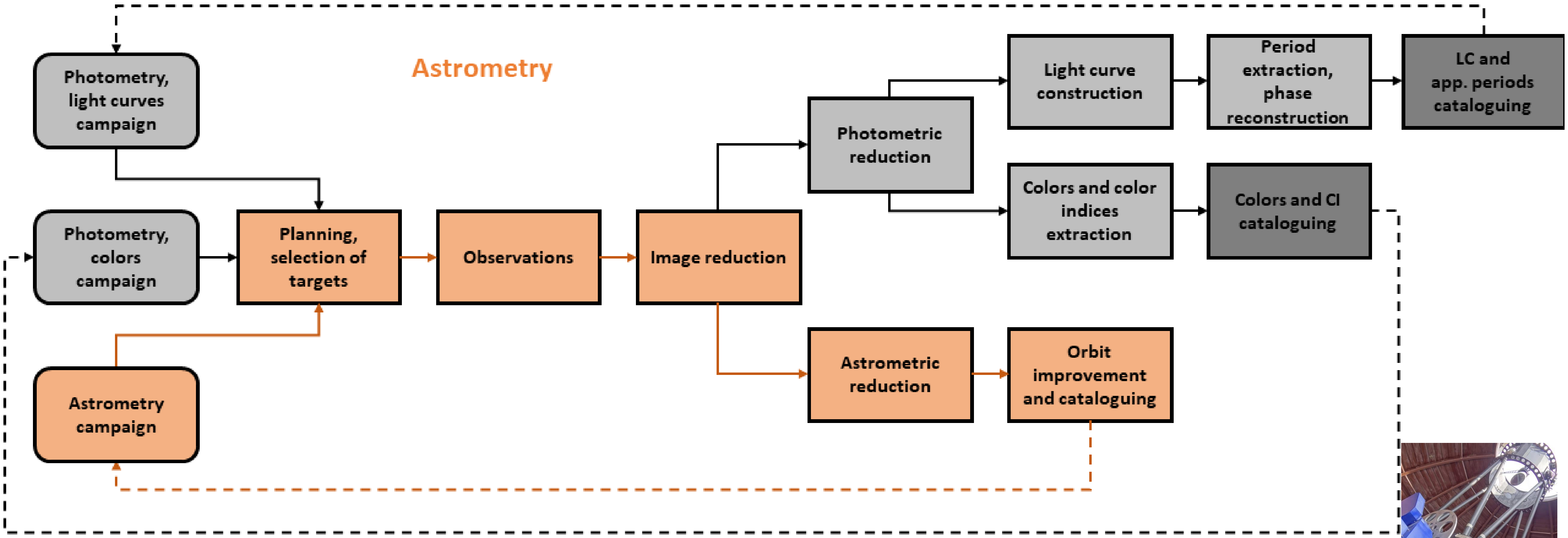
Example of re-entry, candidate is fragment from satellite FLOCK 1E

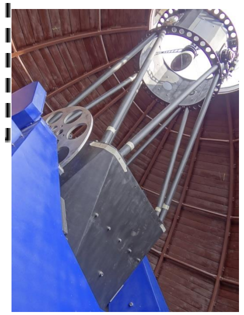
Optical observations, reentry



Astrometry

FMPI/AGO instruments, 70cm telescope



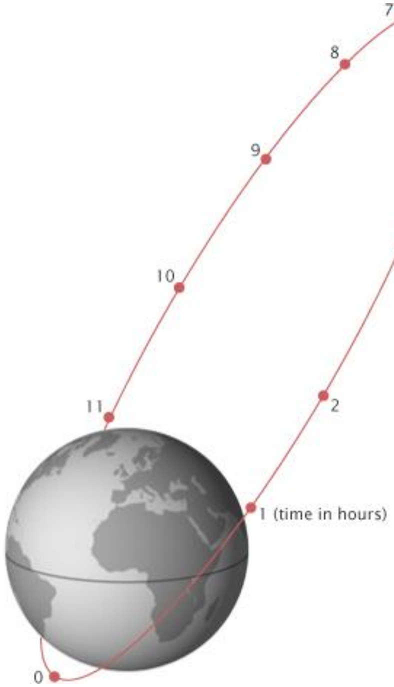


Optical observations, astrometry

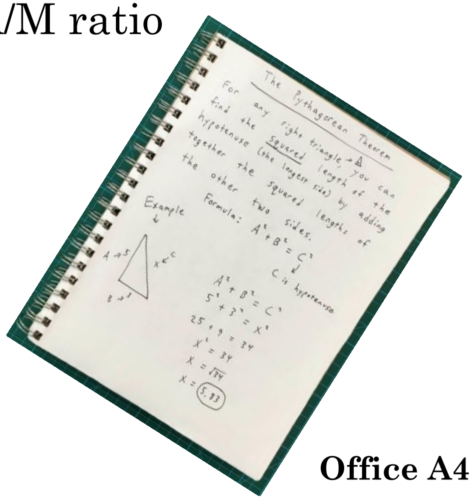
- To measure relative position of the object from the observer perspective on the celestial sphere

- Aim is to determine and improve orbit, maintain catalogues, orbit prediction

- Except dynamical parameters (a,e,i, RAAN, AoP, M(t)), also physical parameter A/M ratio



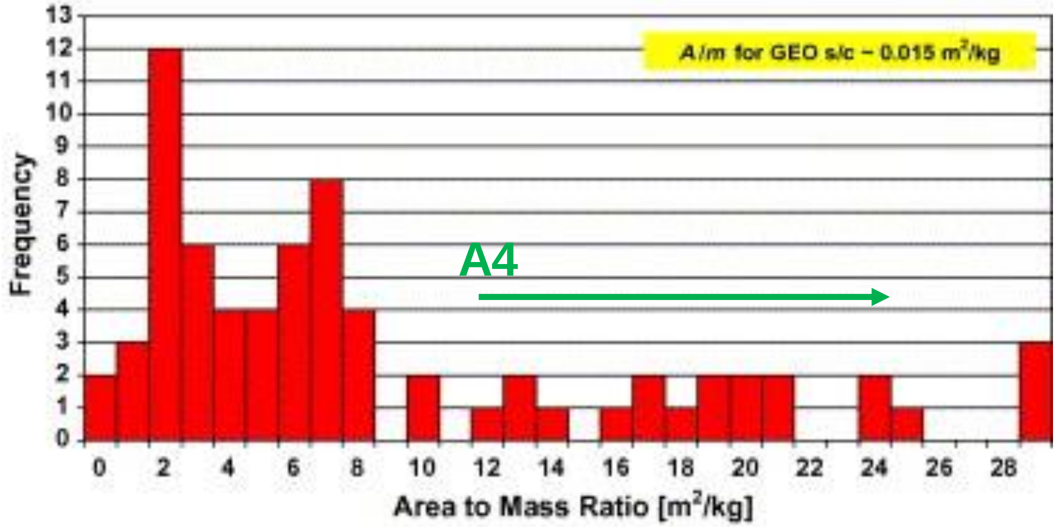
Astra satellite AMR ~ 0.02 m^2/kg



Office A4 sheet of paper AMR ~ 12 m^2/kg

Optical observations, astrometry

Taken from Schildknecht et al. (2008)



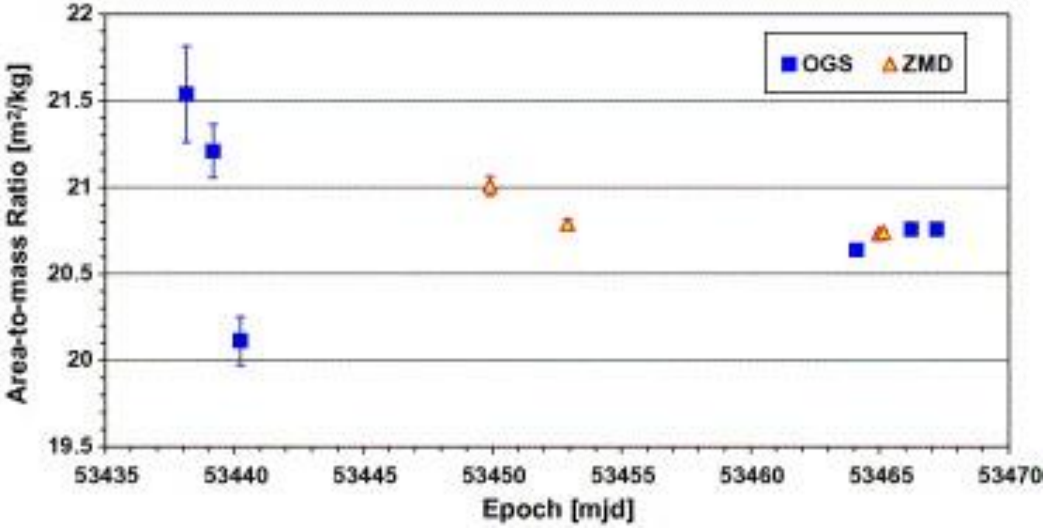
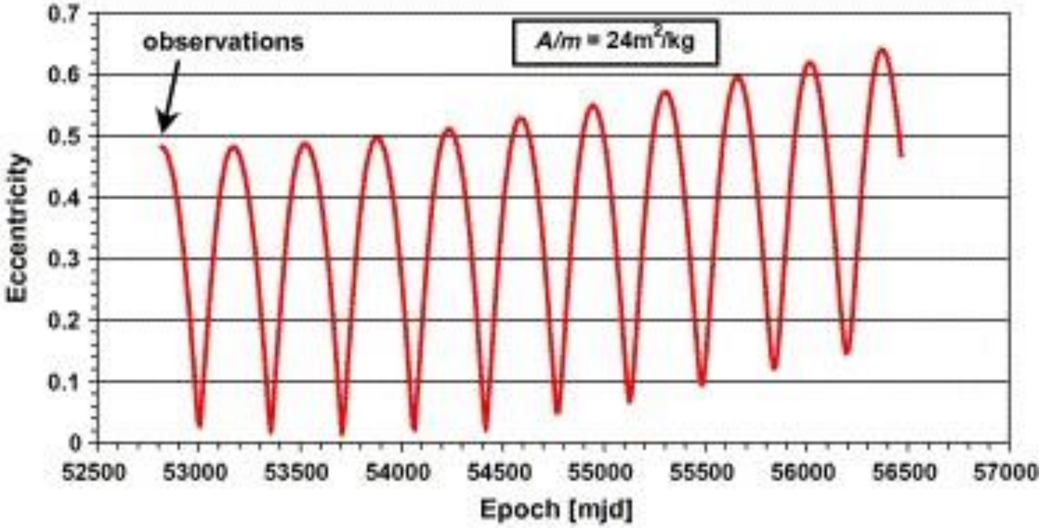


Figure – A/M values as determined for the objects discovered during OGS GEO/GTO surveys.

Figure – AMR value calculated for a one specific discovered GEO/GTO object.

Optical observations, astrometry

Taken from Schildknecht et al. (2008)



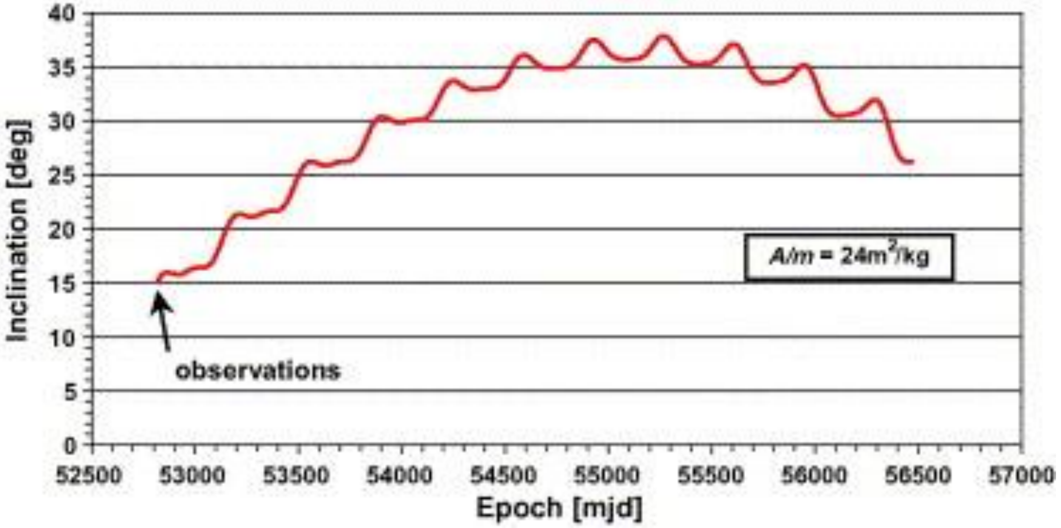
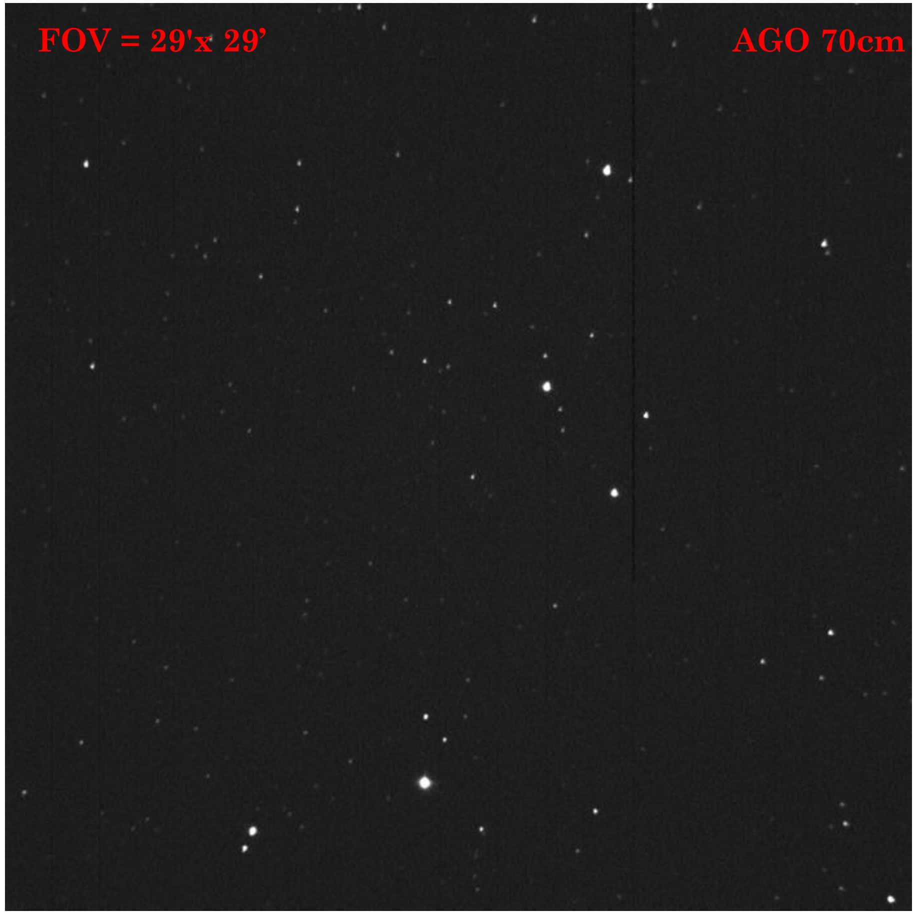


Figure – A/M values as calculated from the orbit numerical integration for an object discovered during OGS GEO survey. Object's AMR = 24m2/kg. Duration of investigated period was 12,3 years.

Figure – Inclination values as calculated from the orbit numerical integration for an object discovered during OGS GEO survey. Object's AMR = 24m2/kg. Duration of investigated period was 12,3 years.

Optical observations, astrometry



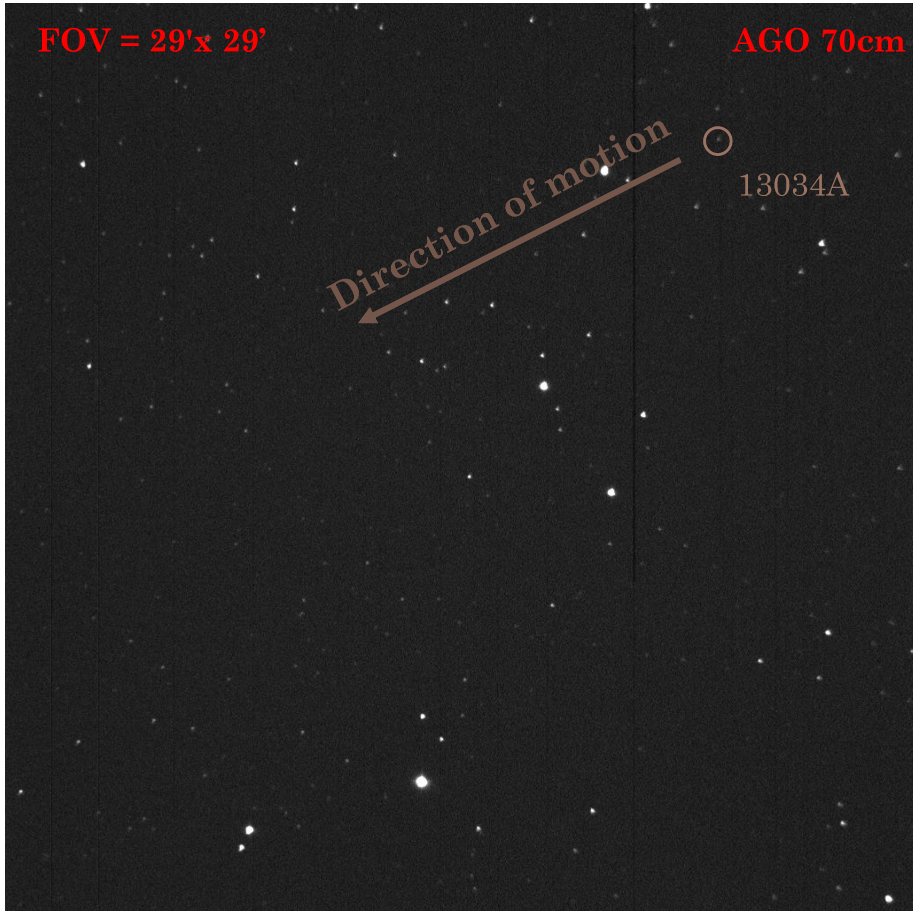


Figure – Images acquired by AGO 70-cm telescope. Astrometric observations of satellite IRNSS-1A (13034A). Other four GEO satellites crossing the FOV. Used exposure time was 0.2 s.

Optical observations, astrometry

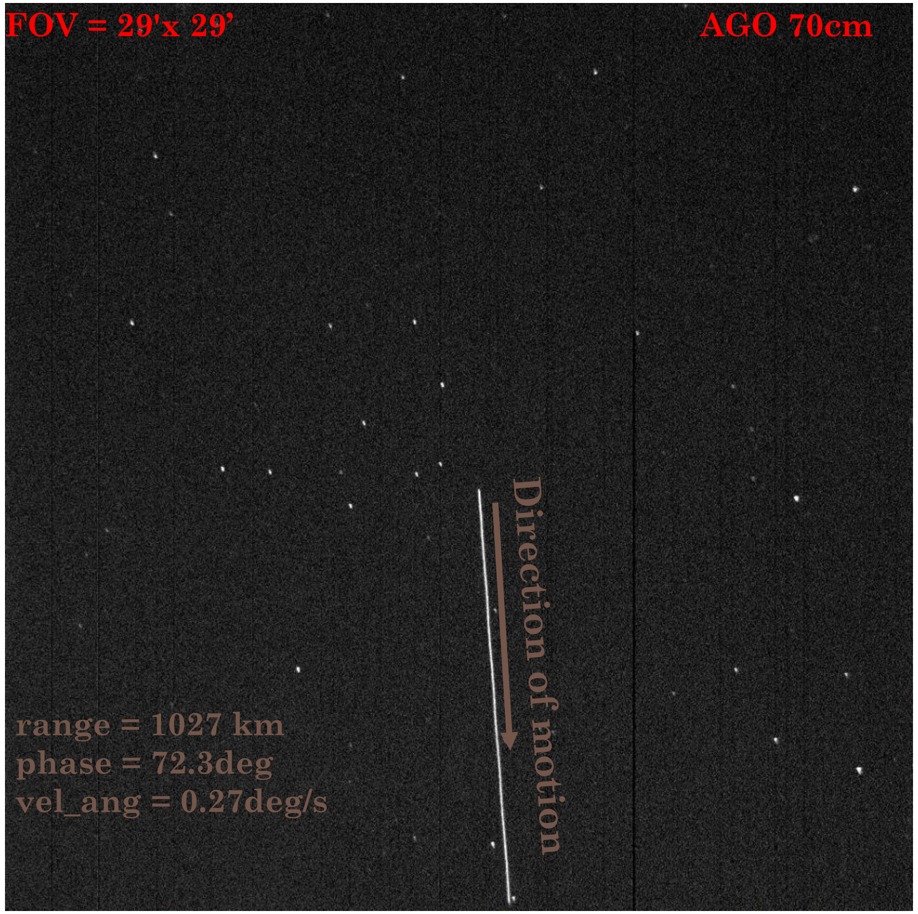


Figure – LEO defunct satellite **COSMOS 1802** (86093A) acquired by the AGO 70cm telescope. Field RA=18:20:39.57 and DEC=+48:52:33.3 observed at 2017-06-23T21:45:00.14 with 'Clear' filter, exp = 0.5s and sidereal tracking ON.

Figure – LEO cubesat SKCube (17036AA) acquired by the AGO 70cm telescope. Field RA=18:0:22.21 and DEC=+02:40:49.3 observed at 2017-08-01T19:49:00 with 'Clear' filter, exp = 0.2s and sidereal tracking ON.

Optical observations, astrometry

```
COD 118
OBS J.Silha/J. Vilagi
MEA J.Silha/J. Vilagi
TEL 0.7-m f/3.0 reflector + CCD
ACK MPCReport file updated 2017.07.25 20:01:53
AC2 ago@fmph.uniba.sk
NET Gaia DR1
     13034A   C2017 05 09.85830 15 57 11.433+21 04 28.72         17.0 R      118
     13034A   C2017 05 09.85839 15 57 19.912+21 03 57.01         17.0 R      118
     13034A   C2017 05 09.85847 15 57 28.406+21 03 25.22         17.0 R      118
     13034A   C2017 05 09.85856 15 57 36.897+21 02 53.91         17.0 R      118
     13034A   C2017 05 09.85866 15 57 45.511+21 02 21.01         17.0 R      118
     13034A   C2017 05 09.85875 15 57 53.969+21 01 49.56         17.0 R      118
     13034A   C2017 05 09.85884 15 58 02.500+21 01 17.63         17.0 R      118
     13034A   C2017 05 09.85894 15 58 10.946+21 00 45.36         17.0 R      118
     13034A   C2017 05 09.85903 15 58 19.417+21 00 13.35         17.0 R      118
     13034A   C2017 05 09.85912 15 58 27.850+20 59 42.09         17.0 R      118
     13034A   C2017 05 09.85920 15 58 36.240+20 59 10.56         17.0 R      118
----- end -----
```

Figure – Astrometric measurements of object 13034A in IAU MPC format. Measurements acquired by AGO 70cm. Astrometric reduction performed by Astrometrica.

```
AGO_70          E08219B00                        57968.016460000 21.114925000 -06.53244000 12.91   1 "
AGO_70          E08219B00                        57968.016890000 21.122551000 -06.51159000 12.91   1 "
AGO_70          E08219B00                        57968.023140000 21.210331000 -06.20441000 12.91   1 "
AGO_70          E08219B00                        57968.023390000 21.212507000 -06.19278000 12.91   1 "
AGO_70          E08219B00                        57968.023660000 21.214690000 -06.18101000 12.91   1 "
AGO_70          E08219B00                        57968.024680000 21.231154000 -06.13119000 12.91   1 "
AGO_70          E08219B00                        57968.024940000 21.233345000 -06.11539000 12.91   1 "
AGO_70          E08219B00                        57968.025120000 21.234804000 -06.11023000 12.91   1 "
AGO_70          E08219B00                        57968.025380000 21.240994000 -06.09447000 12.91   1 "
AGO_70          E08219B00                        57968.079310000 22.384178000 -01.52581000 12.91   1 "
AGO_70          E08219B00                        57968.079570000 22.390361000 -01.51454000 12.91   1 "
AGO_70          E08219B00                        57968.079650000 22.391092000 -01.51216000 12.91   1 "
```

Figure – Astrometric measurements of object E08219B in AIUB OBS format. Measurements acquired by AGO 70cm. Astrometric reduction performed by Astrometrica.

Photometry

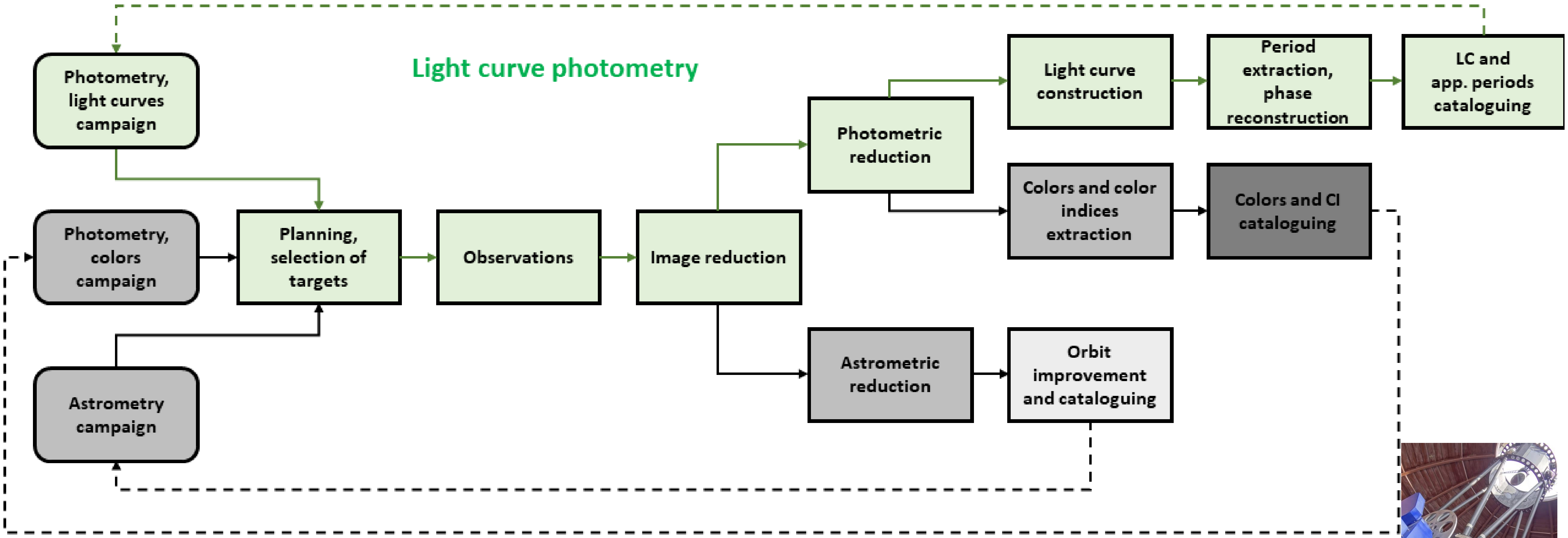
Optical observations, photometry

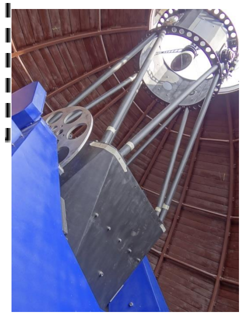
- Two types of output:
  - Light curve (relative photometry) - attitude related information
  - Colors, color indices (colors difference) (absolute photometry) - physical characteristics

- **Light curves:**
  - Present signal directly function of the object's rotation
  - Phase function shape function of the object reflectivity properties, its shape and observation geometry (phase and aspect angle)

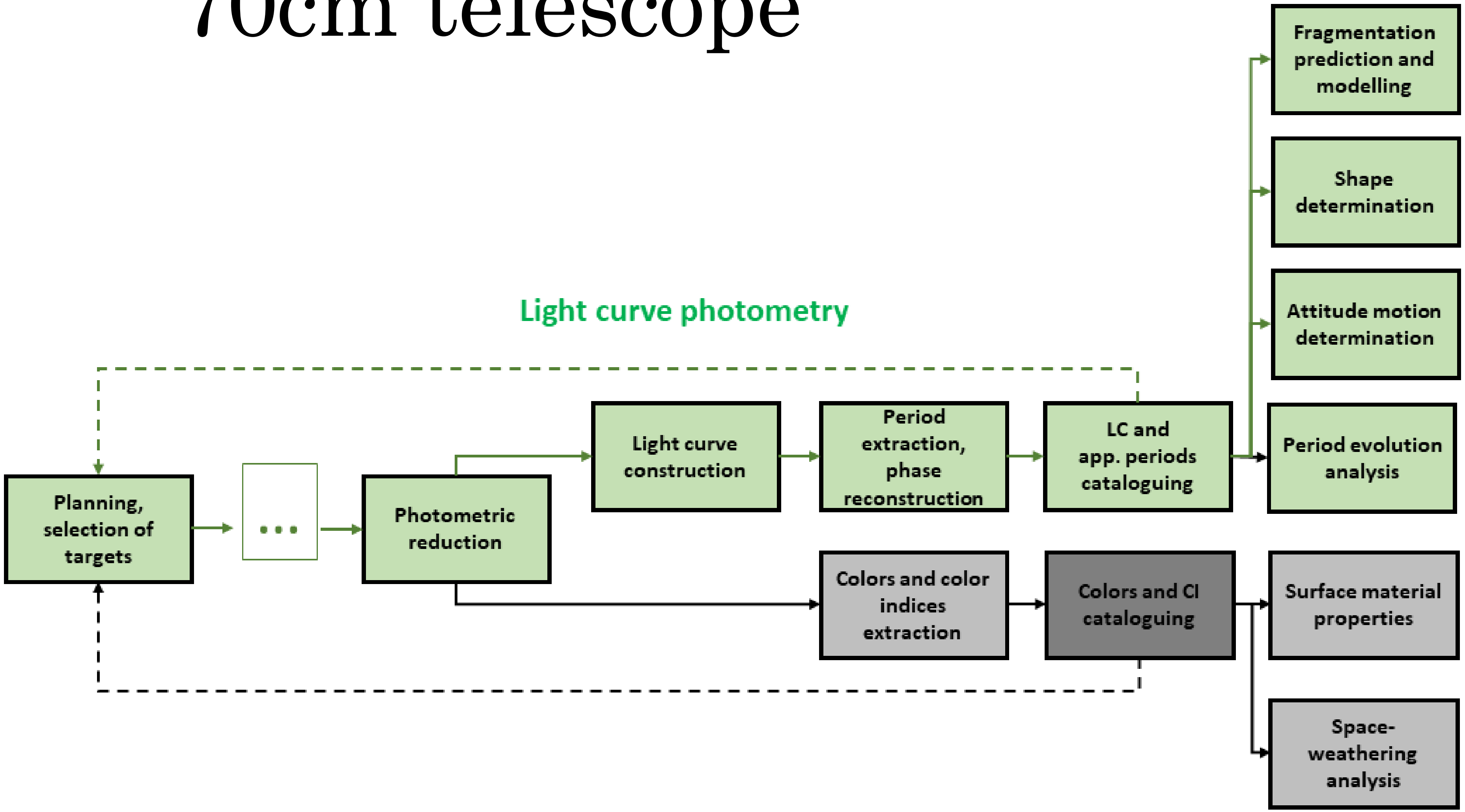
- **Colors, color indices:**
  - Directly function of the object surface properties

FMPI/AGO instruments, 70cm telescope



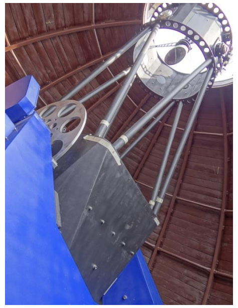


FMPI/AGO instruments, 70cm telescope



V1.1

Optical observations, light curves



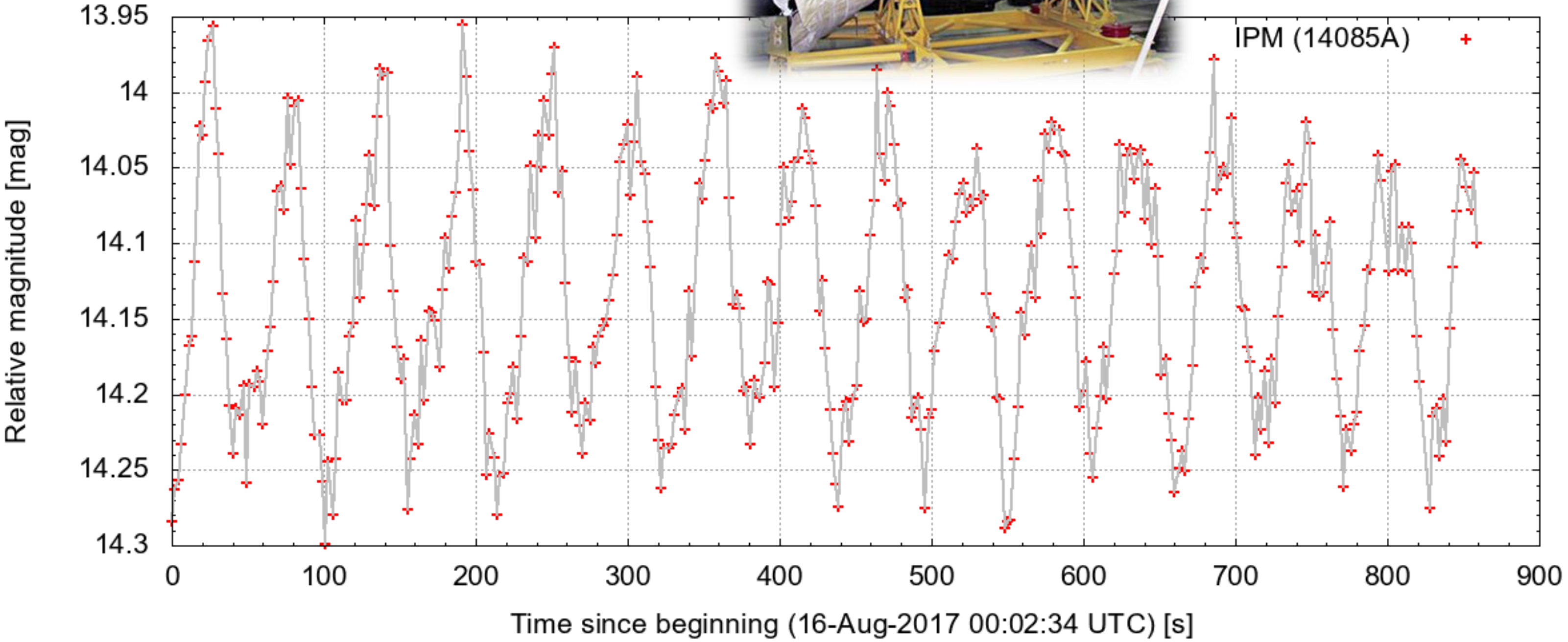
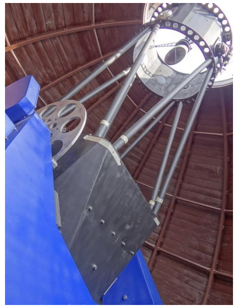
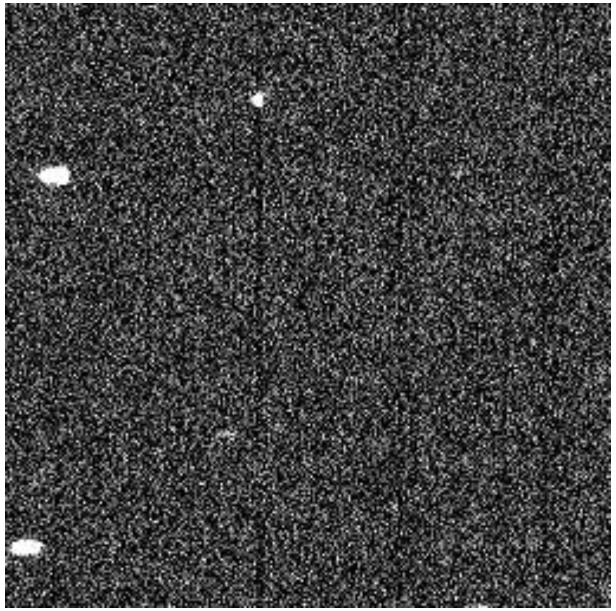


Figure – Photometric measurements acquired by AGO 70cm telescope (left) and the constructed light curve (right) for the object Dummy IPM (14085A).

Optical observations, light curves





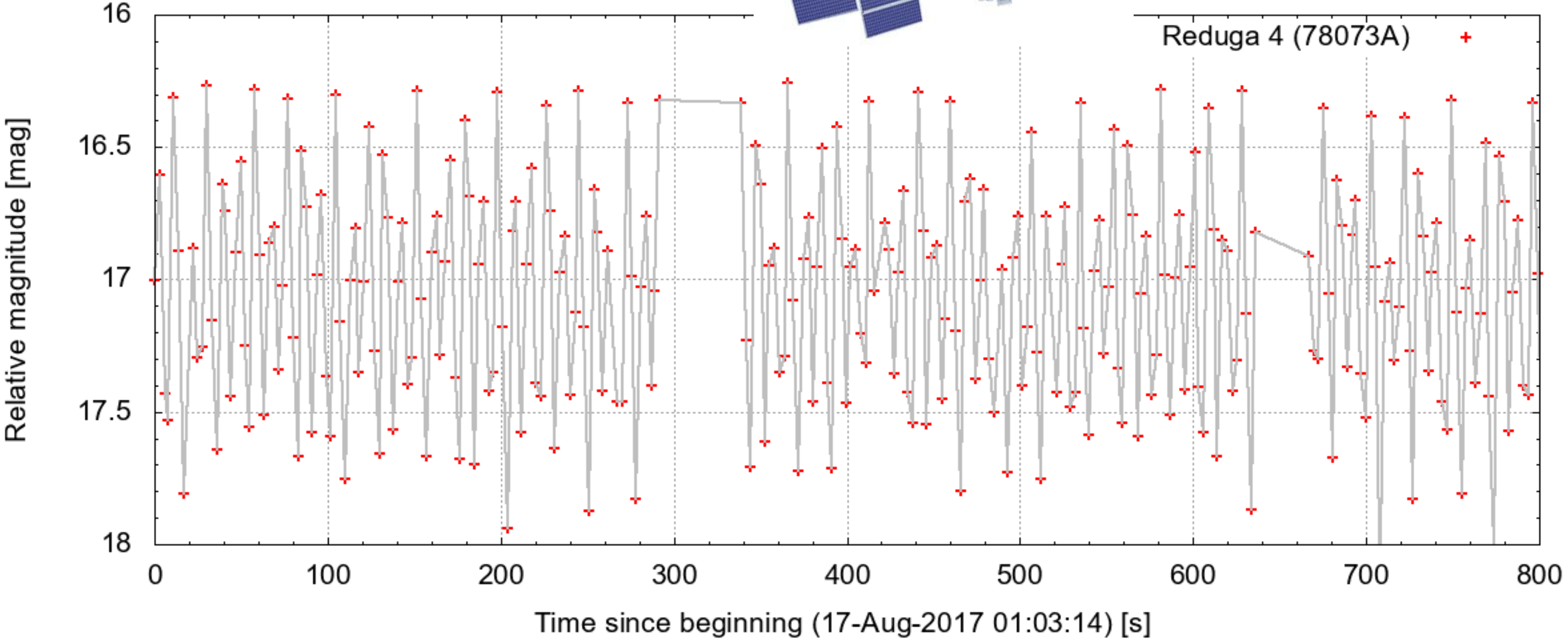
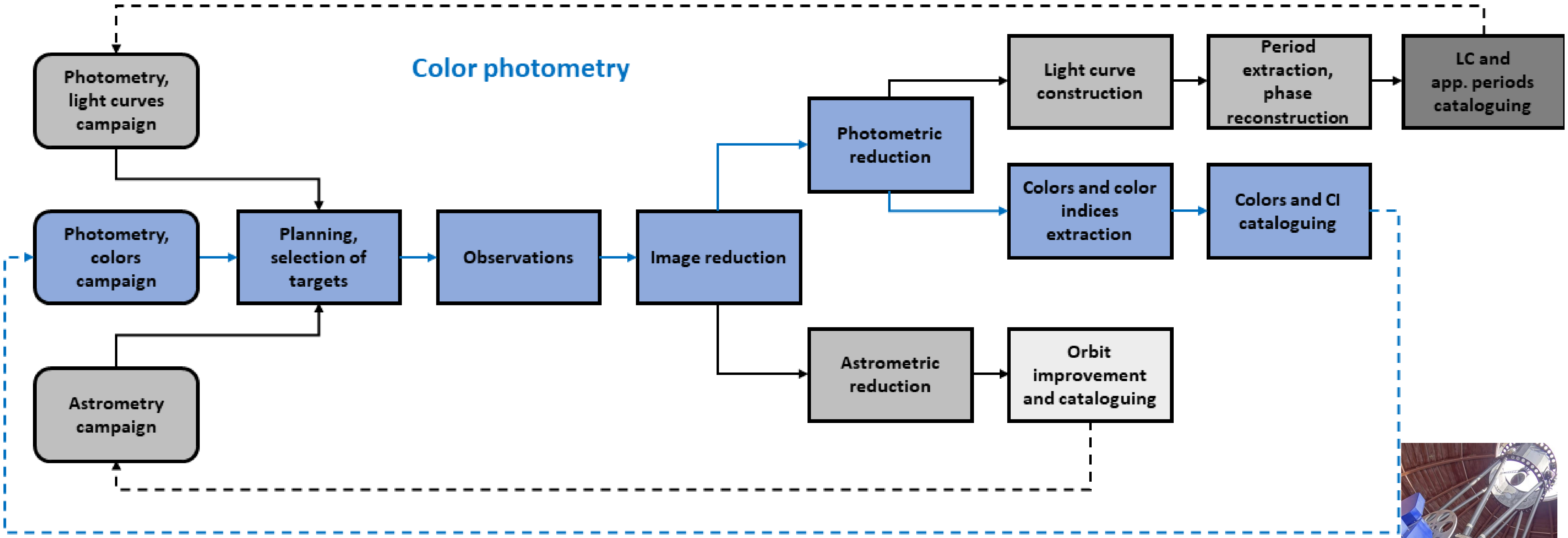
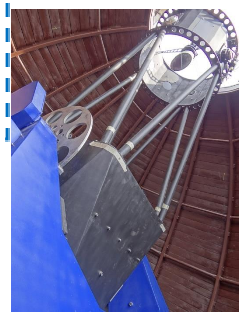


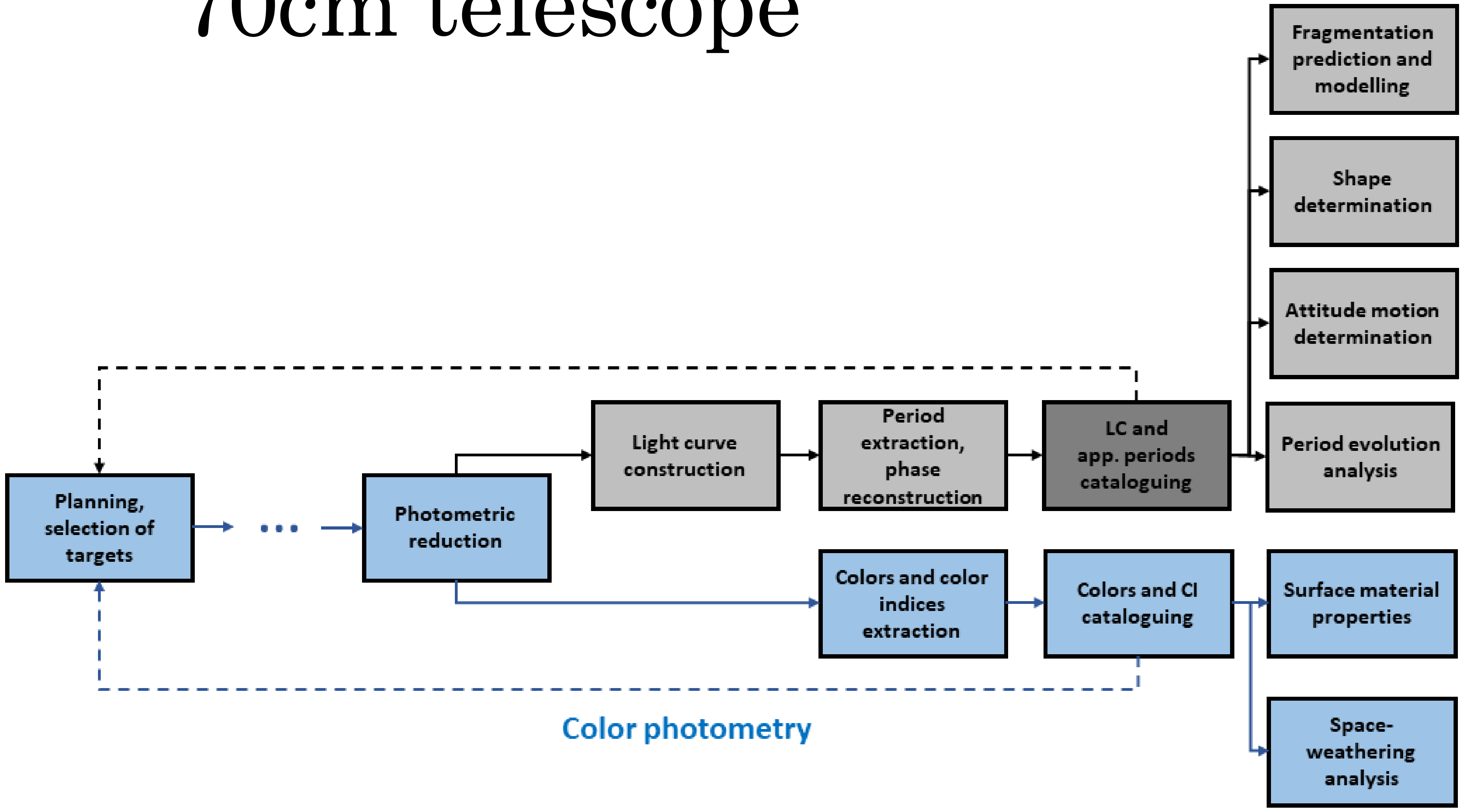
Figure – Photometric measurements acquired by AGO 70cm telescope (left) and the constructed light curve (right) for the satellite Reduga 4 (78073A).

FMPI/AGO instruments, 70cm telescope





FMPI/AGO instruments, 70cm telescope



V1.1

Optical observations, color photometry

- Only light with defined wavelengths will pass trough given filter

- Most popular Johnson-Cousins filters

  (AGO 60cm and 70cm)

- Detected light properties dependent on object's properties (absorption, emission)

- Color indices ➔ B-V, V-R, R-I, V-I, B-R

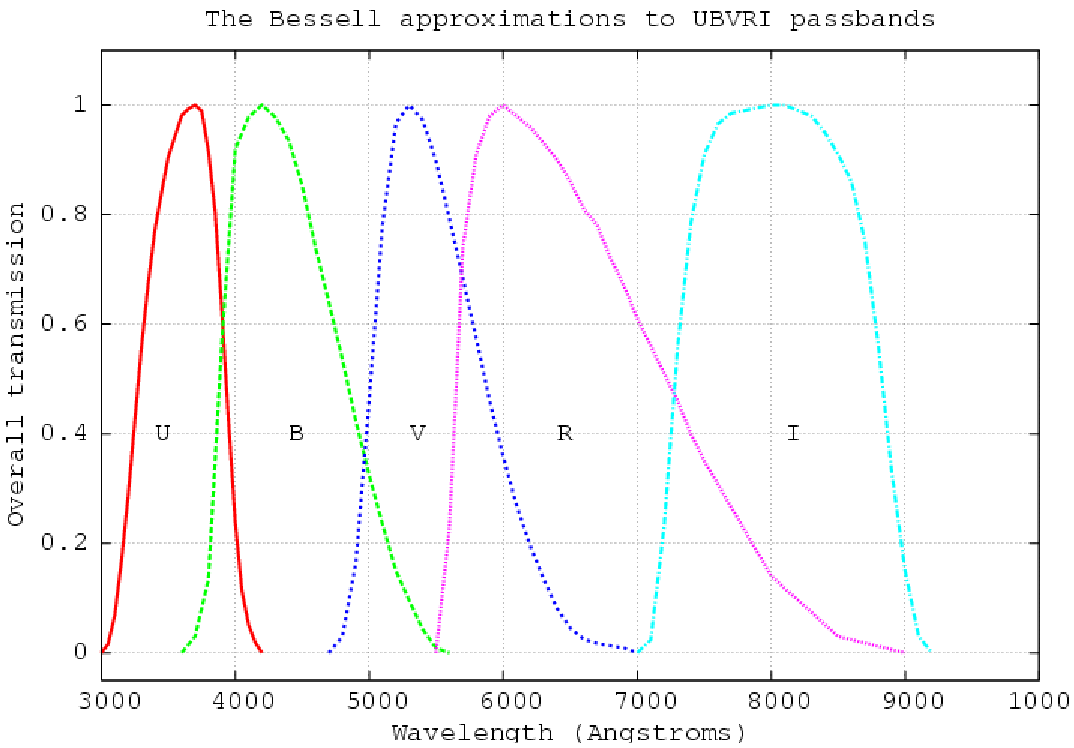


Figure – Schematic passbands of broad-band system Johnson-Cousins. Taken from Bessel (1990).

Optical observations, color photometry

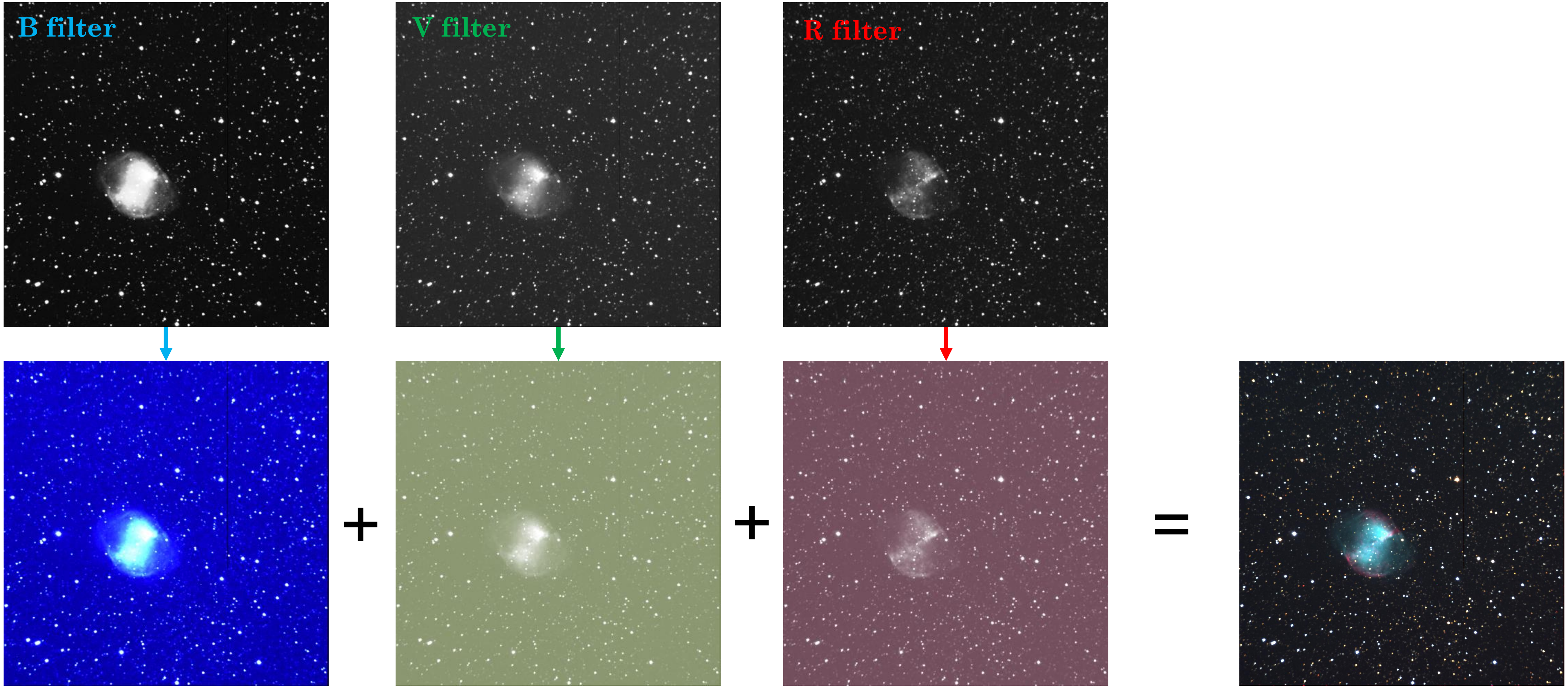


Figure – Dumbell nebula M27. Images acquired in B (left), V (middle) and R filters (right). Images acquired by AGO 70-cm telescope. Used exporuse was 60s.

Optical observations, color photometry

Figure – Dumbell nebula M27. Composition of images acquired in B, V and R filters. Images acquired by AGO 70-cm telescope. Used exporuse was 60s.

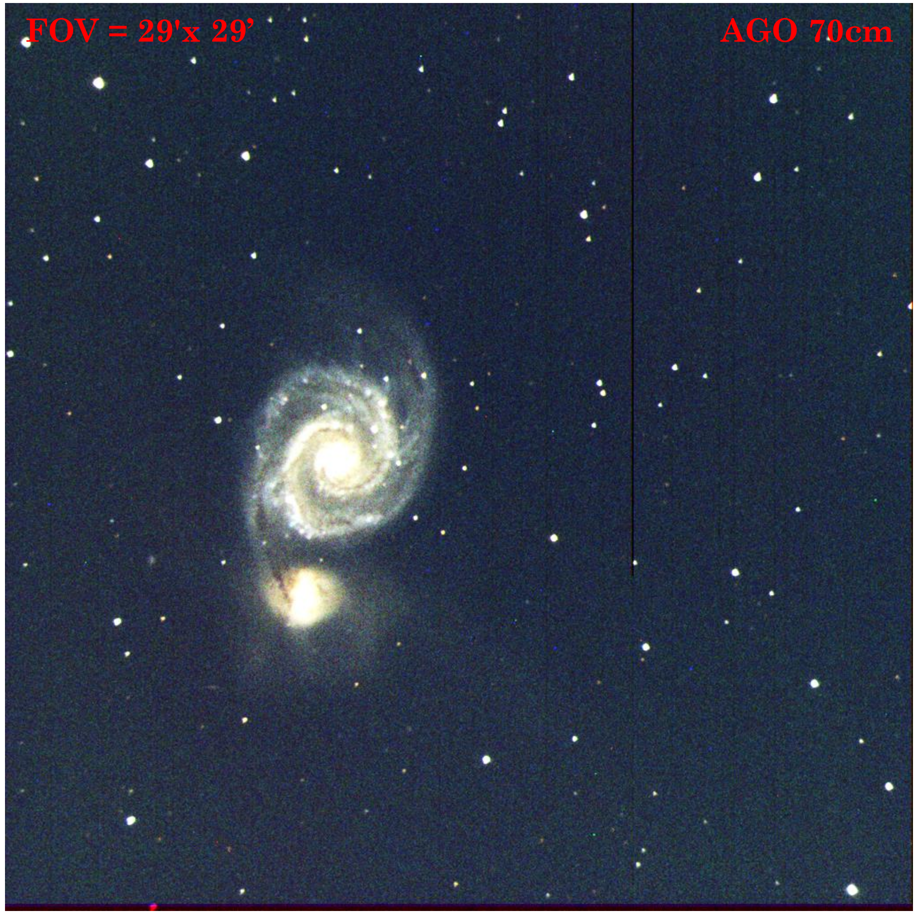


Figure – Whirpool galaxy M51. Composition of images acquired in B, V and R filters. Images acquired by AGO 70-cm telescope. Used exporuse was 60s.

Optical observations, color photometry

Taken from Silha & Hamara et al. (2013)

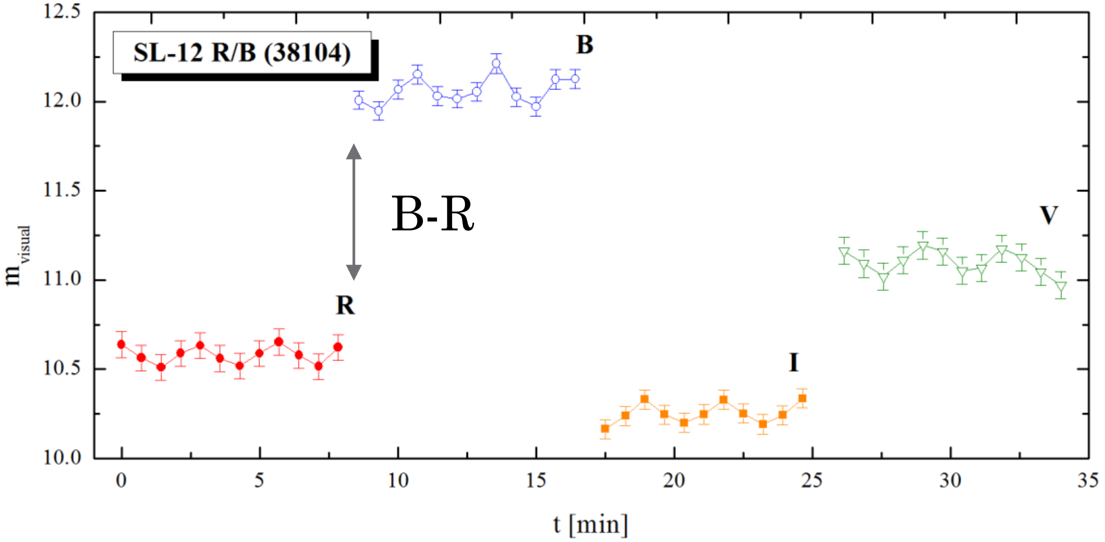


Figure – The magnitudes of the SL-12 R/B for B, V, R, I filter (y axis) as a function of time (x axis) obtained during single telescope observations.

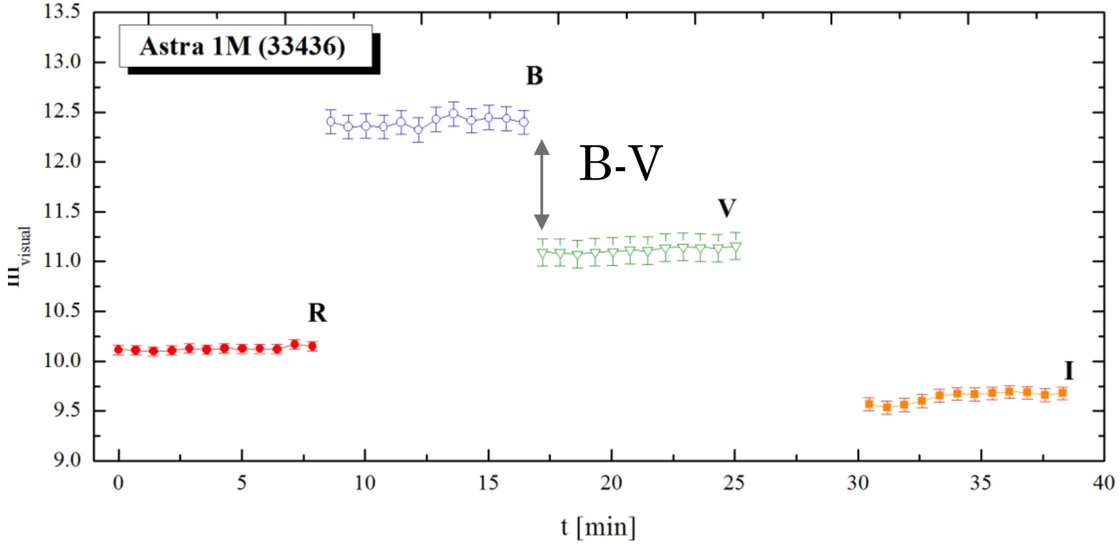


Figure – The magnitudes of the Astra 1M satellite for B, V, R, I filter (y axis) as a function of time (x axis) obtained during single telescope observations..

Optical observations, color photometry

Taken from Silha & Hamara et al. (2013)

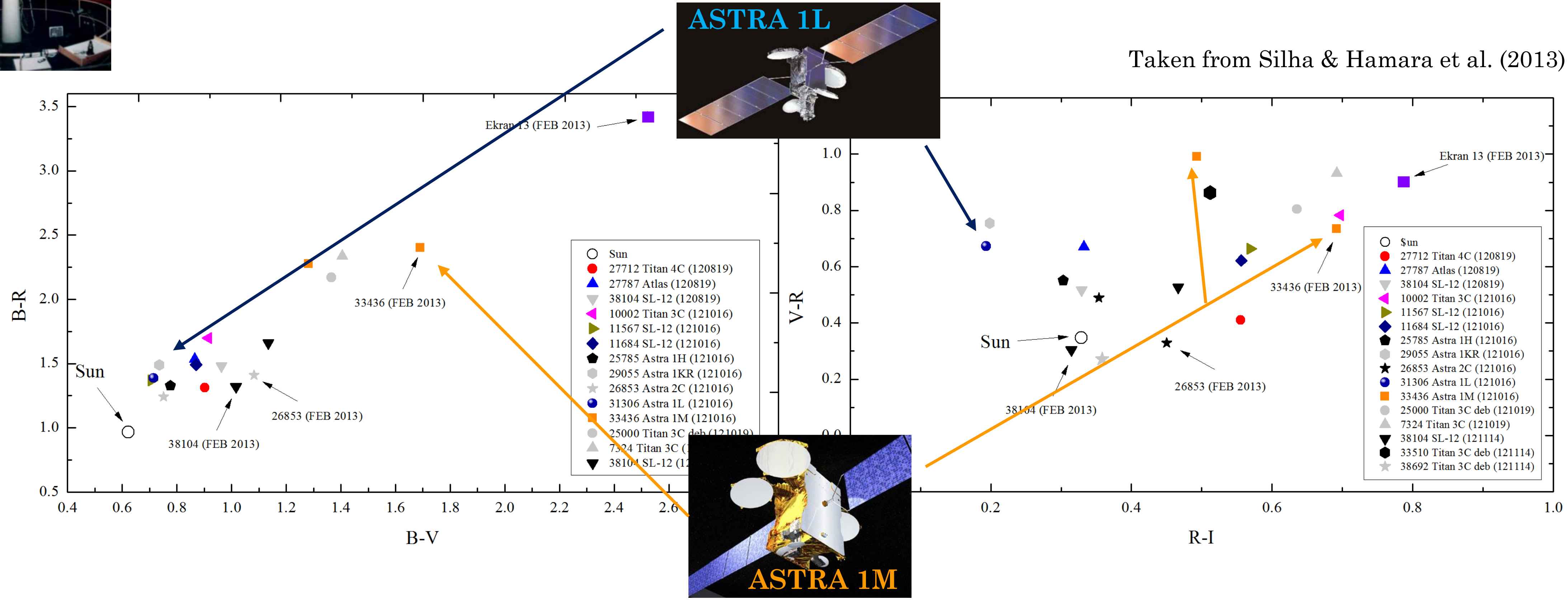


Figure – The color indices B-V versus B-R obtained during the single telescope observations (nights 2012/08/19, 2012/10/16, 2012/10/19, 2012/11/14) and during the simultaneous observations (night 2013/02/07, on plots referred as FEB 2013). For comparison the color indices for Sun are also plotted in figures.

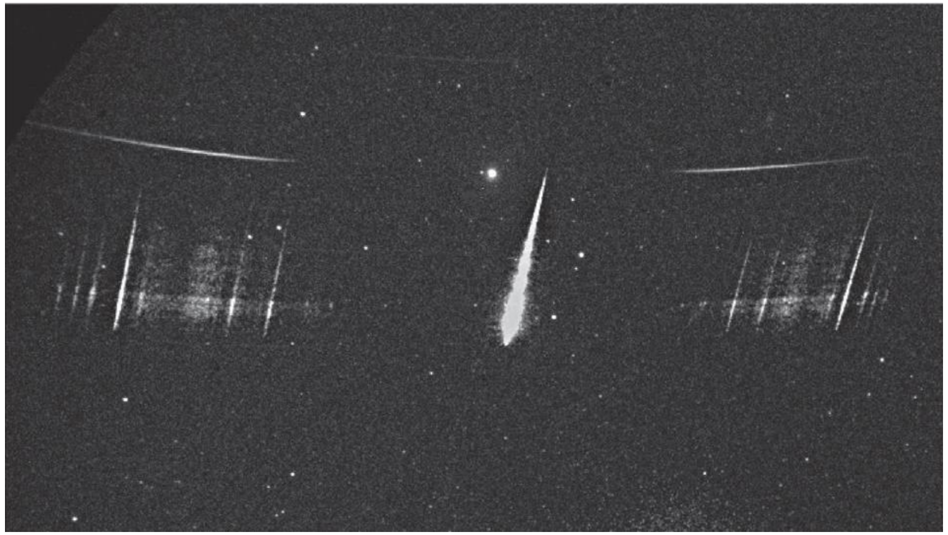
Figure – The color indices R-I versus V-R obtained during the single telescope observations (nights 2012/08/19, 2012/10/16, 2012/10/19, 2012/11/14) and and during the simultaneous observations (night 2013/02/07, on plots referred as FEB 2013). For comparison the color indices for Sun are also plotted in figures.

Spectroscopy

Optical observations, spectroscopy

- The aim is to obtain the spectra, e.g. of meteors, stars, etc.
- Spectra obtain emission and absorption lines, characteristics for given chemical elements and materials, respectively
- They allow to obtain the chemical composition of meteoroid, upper parts of the stellar atmosphere, etc.

Optical observations, spectroscopy



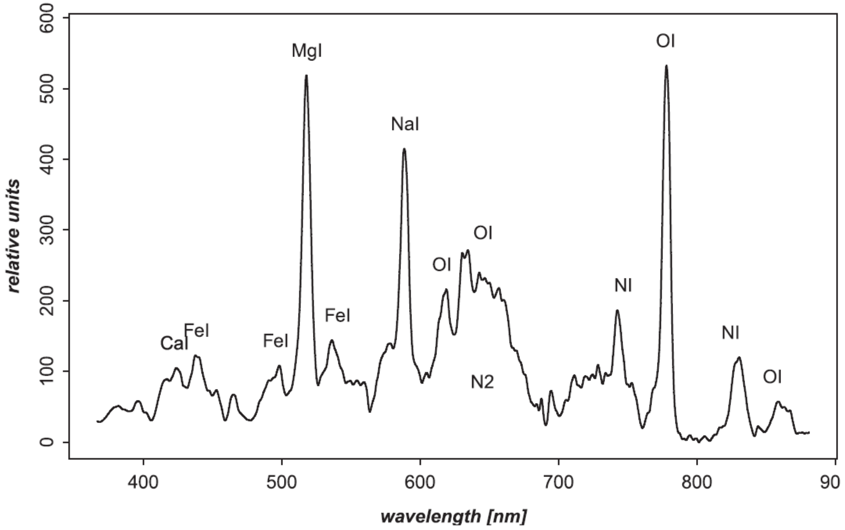


Figure – Example of meteor spectra of σ Hydrids.
Taken from Rudawska et al. (2016).

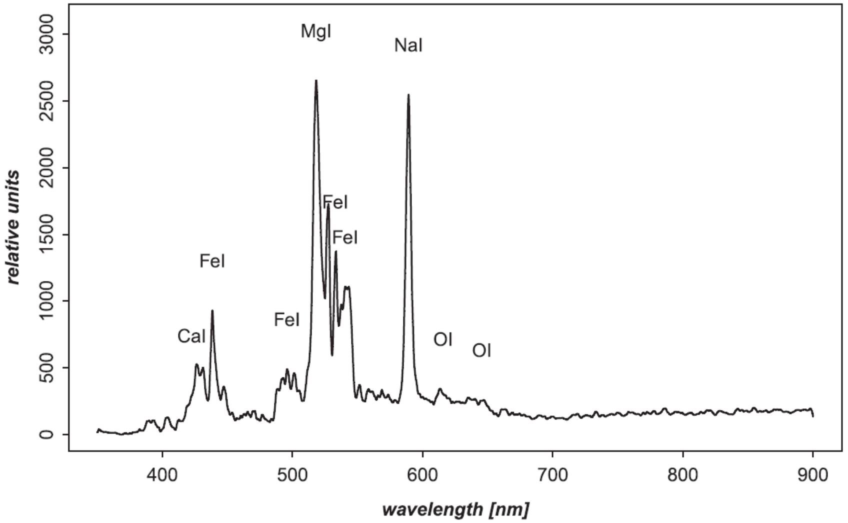
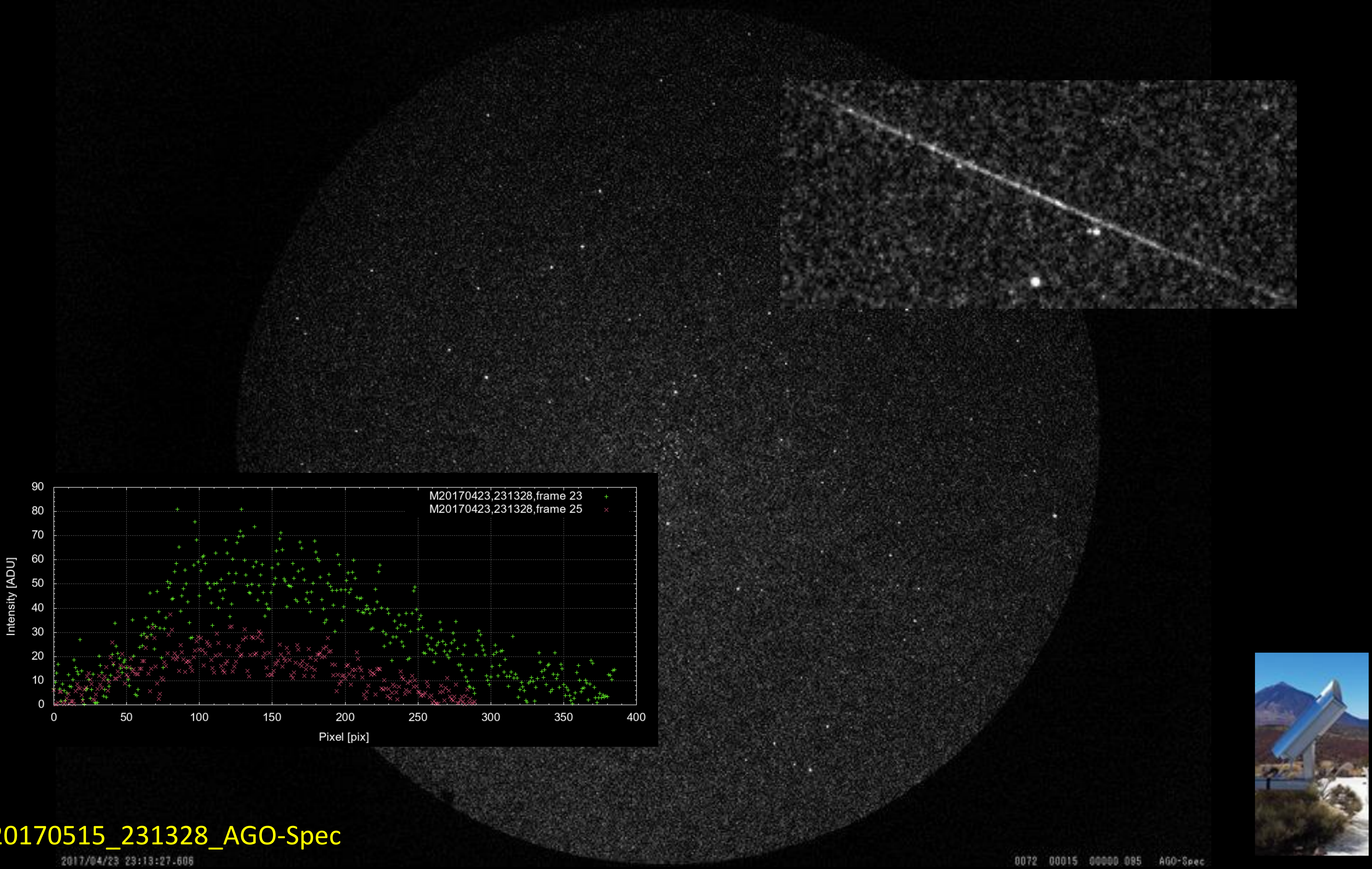


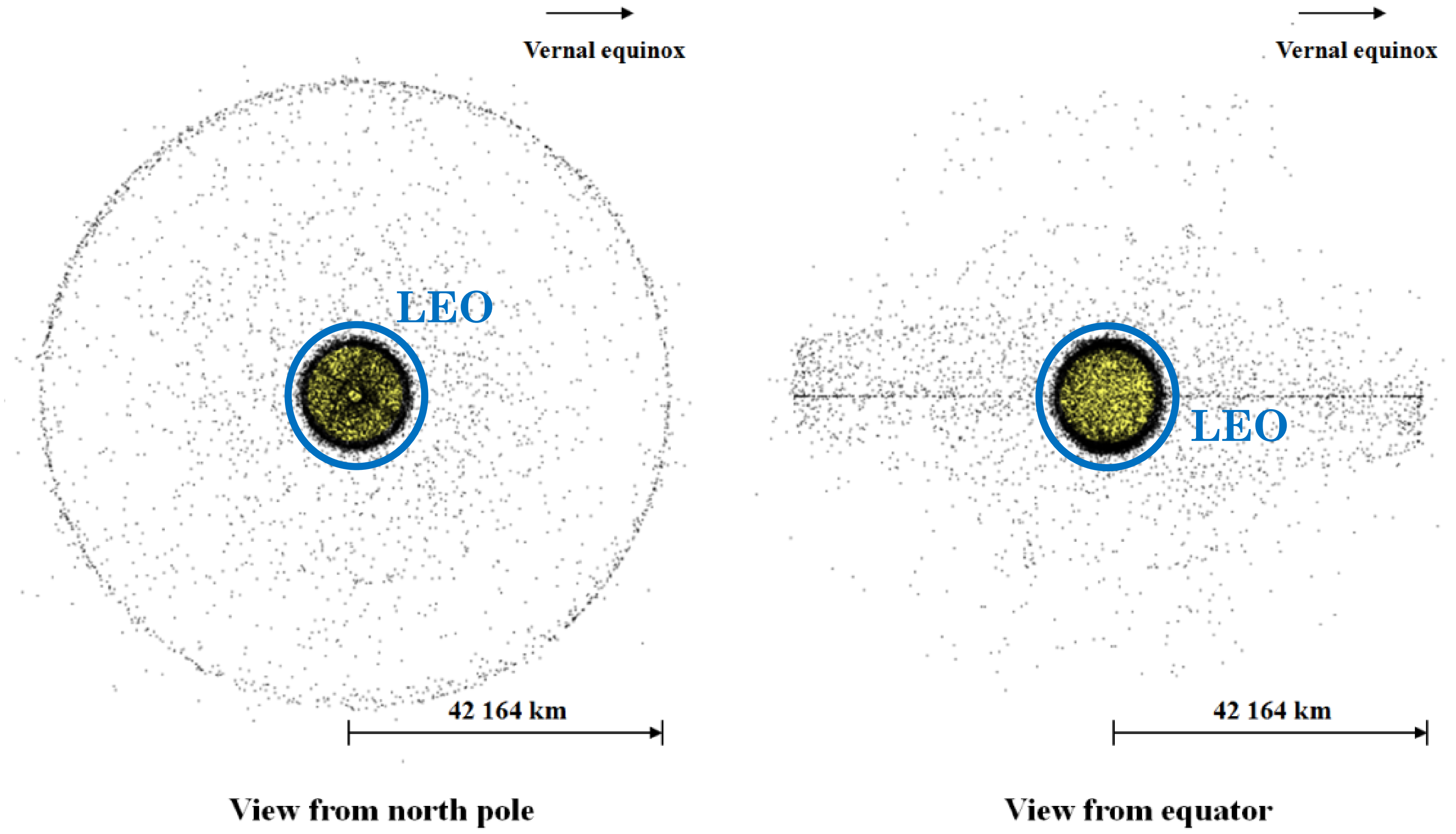
Figure – Example of meteor spectra of sporadic meteor.
Taken from Rudawska et al. (2016).

M20170515_234841_AGO-Spec



M20170515_231328_AGO-Spec

Space debris, spatial distribution



Optical observations, spectroscopy

Taken from Taken from Vananti et al. (2017)

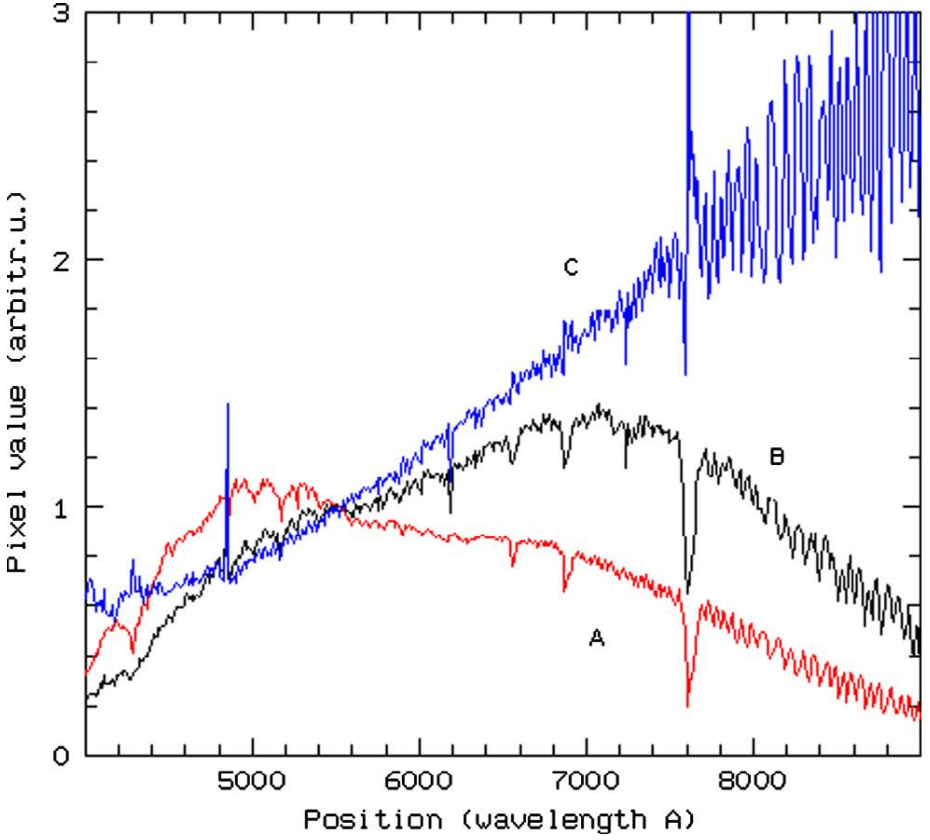


Figure – The observed spectrum of the object (A) is divided by the spectrum of the solar analog (B) to obtain the reflectance spectrum (C). Taken from Vananti et al. (2017).

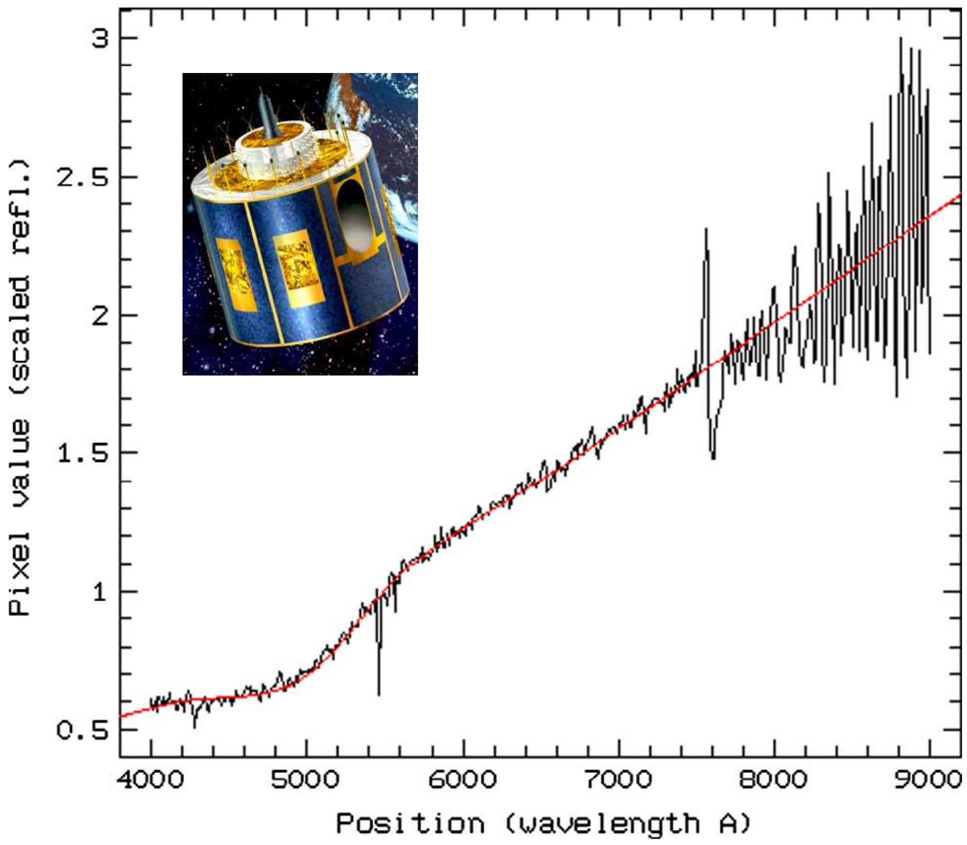


Figure – Reflectance spectrum of Meteosat satellite MSG-1 (02040B). Errors: σ450 = 0.05, σ800 = 0.11. Taken from Vananti et al. (2017).

Optical observations, spectroscopy

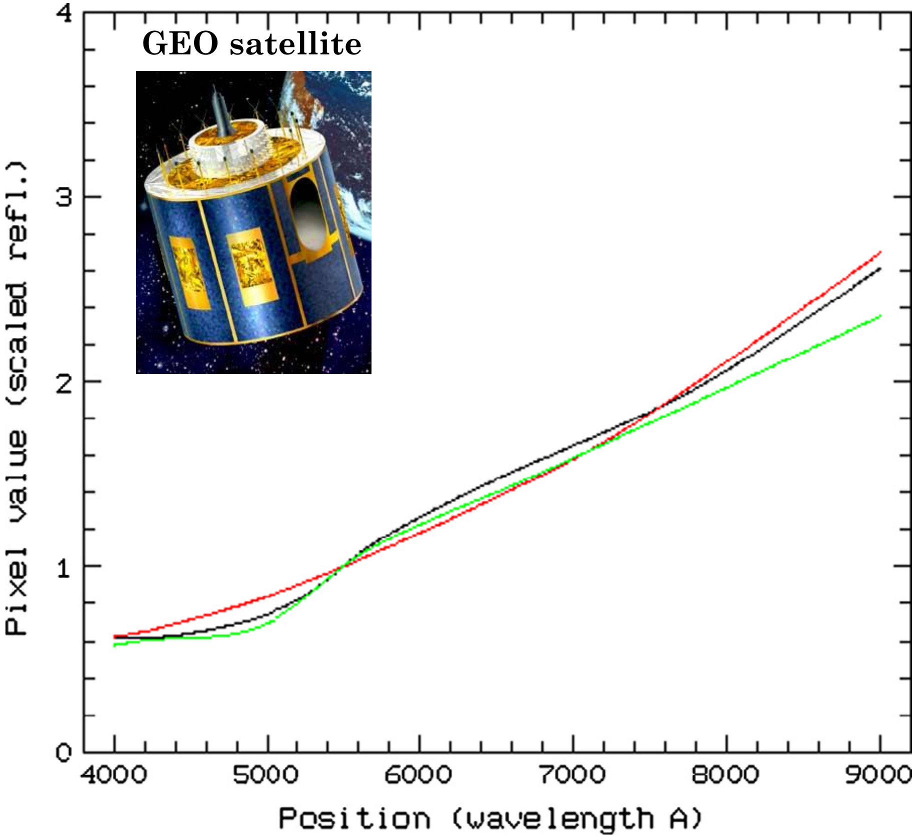


Figure – Reflectance spectra of MSG-1 measured at different phase angles: 53deg (black), 27deg (red), 60deg (green). Errors: σ450 = 0.05, σ800 = 0.1. Taken from Vananti et al. (2017).

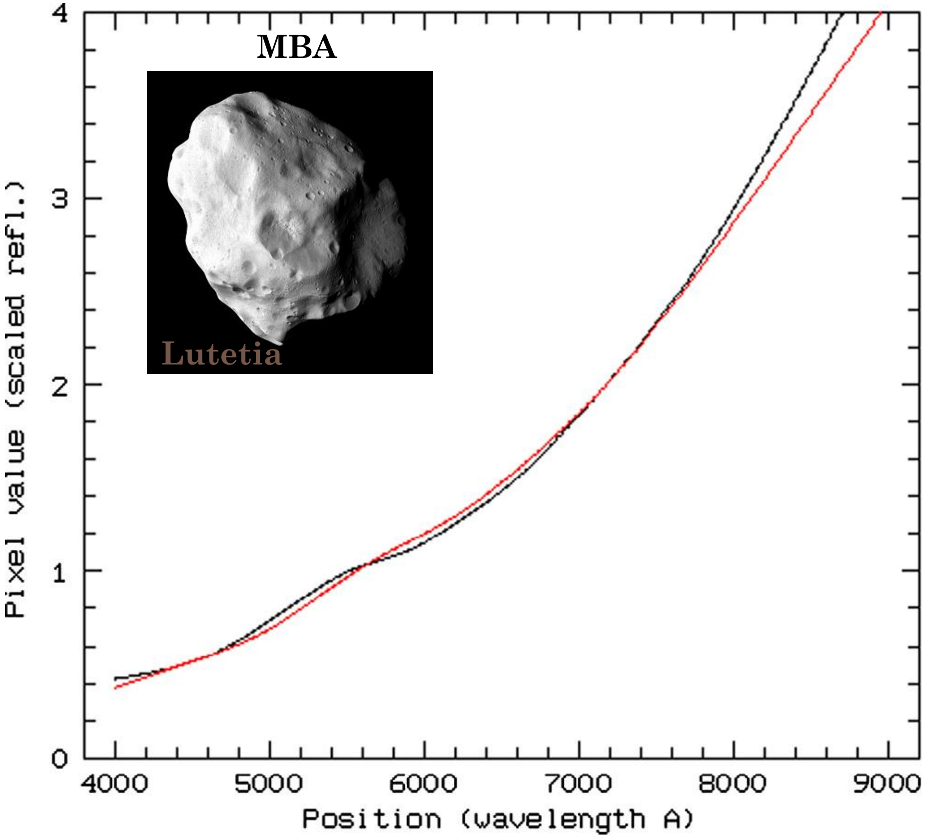


Figure – Reflectance spectra of satellite Artemis at different phase angles: 17deg (black), 52deg (red). Errors: σ450 = 0.04, σ800 = 0.16. Taken from Vananti et al. (2017).

Optical observations, spectroscopy

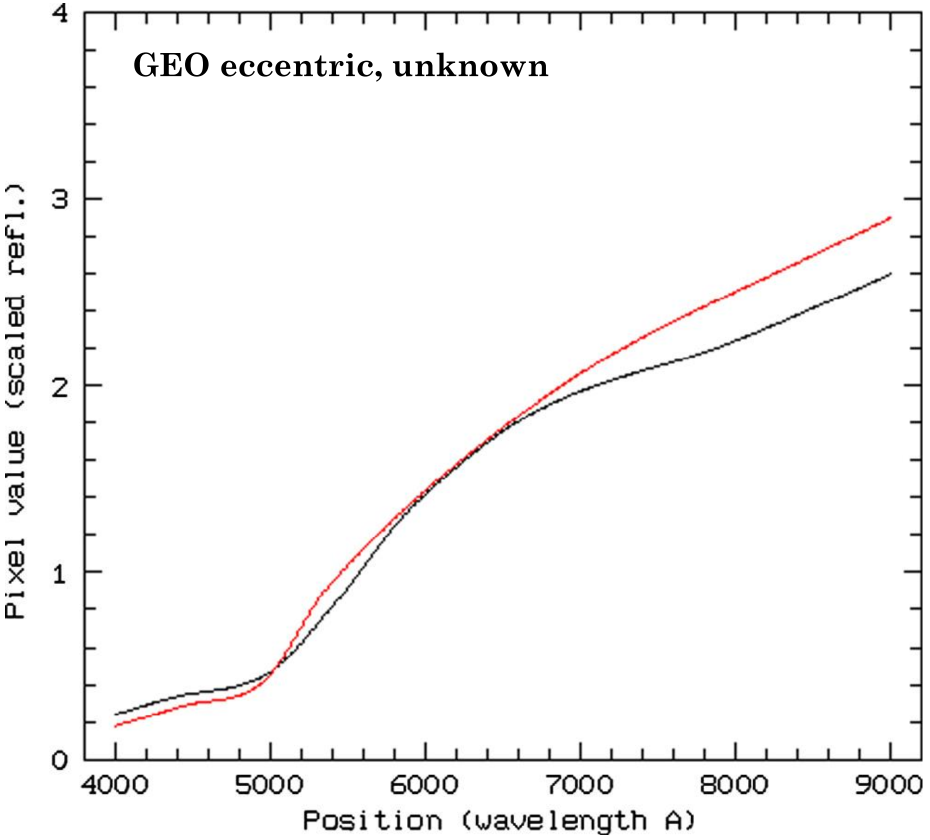


Figure – Spectra of faint 'elliptic GEO' debris object 84980 measured on different nights (mag = ~16, AMR = 3.0 m2/kg). Errors: σ450 = 0.03, σ800 = 0.12–0.14. Taken from Vananti et al. (2017).

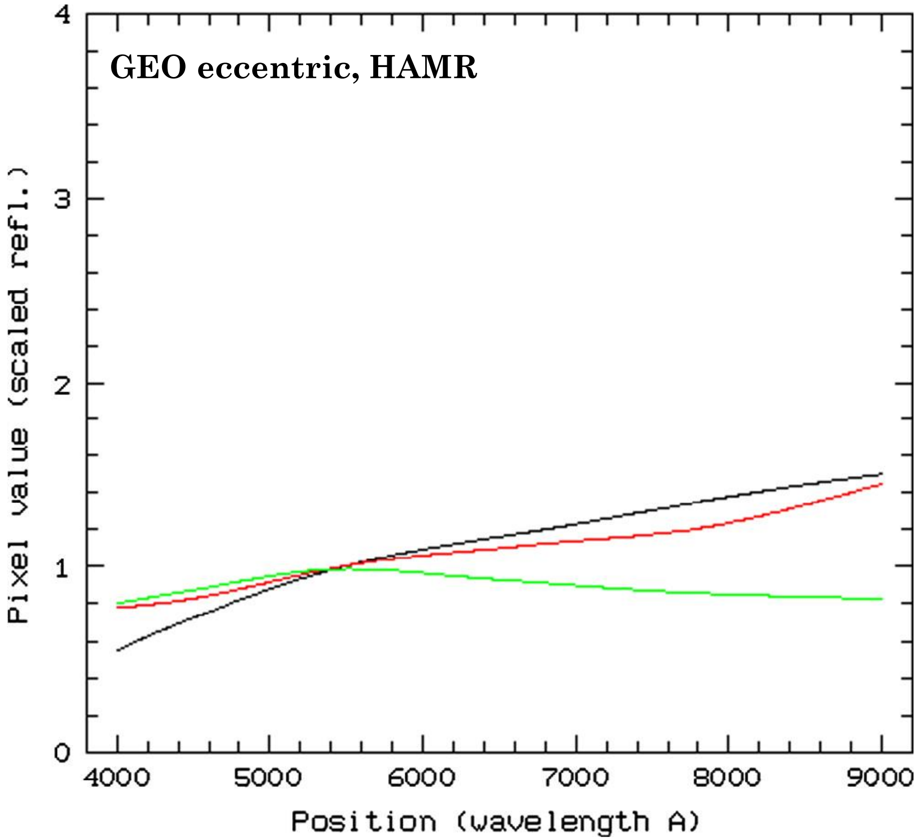
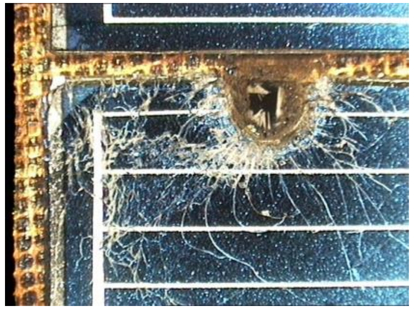


Figure – Spectra of faint 'elliptic GEO' debris object S95300 measured on different nights (mag = 16.3, AMR = 29.3 m2/kg). Errors: σ450 = 0.06, σ800 = 0.04–0.08.

Optical observations, spectroscopy

- For AMOS-Spec cameras expected mostly specular “flashes” from compact bright LEO objects (h < 1000 km)

- Specular flashes from highly reflective surfaces such as metal parts, stainless iron (Fe), aluminium alloy (Al), aluminium MLI (Al), copper MLI (Cu), solar panel (Si)



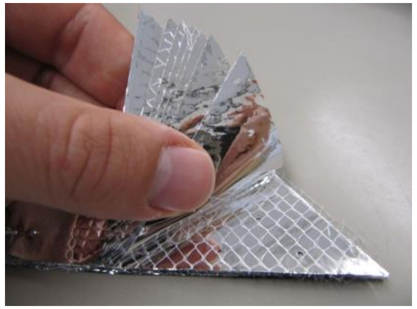
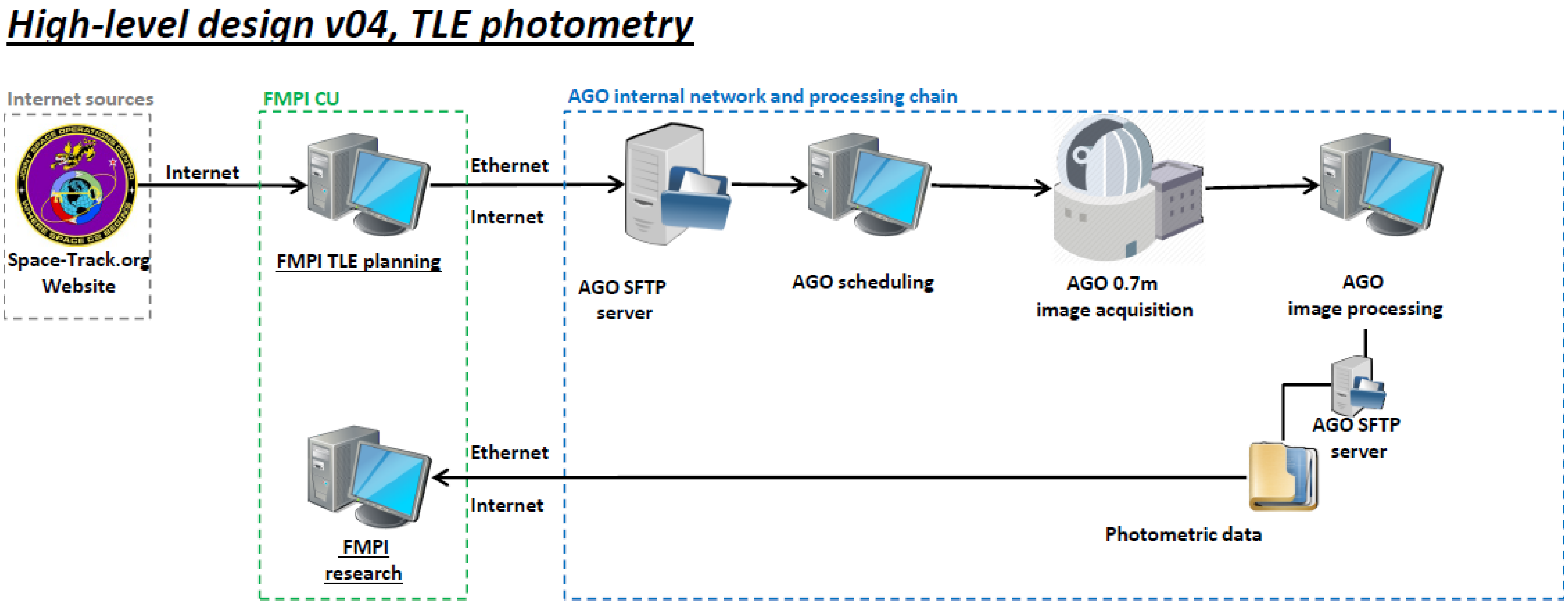


Image acquisition

Image acquisition and processing



Observation planning

- In space debris community used so-called Two-Lines Elements format for geocentric orbital elements
- TLE fully compatible with the Simplified General Perturbation (SGP) model developed by US Department of Defense in 1980s
- Originally Fortran code, now available from Vallado (2013) in JAVA, Python, C++, etc.
- FMPI has two major sources of TLEs:
  - US www.space-track.org
  - ESA/AIUB's internal catalogue
  - Alternatively Russian ISON network or US NASA

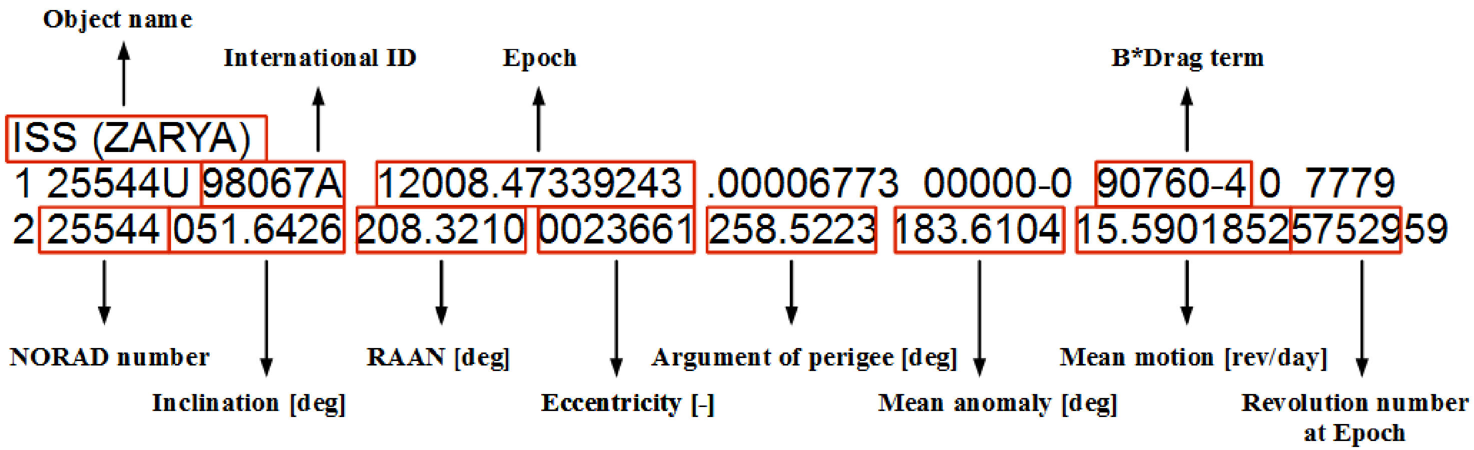


Figure – Example of TLE format for the International Space Station. Reference epoch 12008.47339243, which corresponds to date/time 2012-01-08 11:21:41.11 and MJD = 55934.47339243 days.

Observation planning

- Currently for space debris observations at AGO is used FMPI's JAVA S/W tool SatEph (Satellite Ephemeris)
- SatEph reads TLE and uses SGP to calculate the ephemeris of selected objects for given observer and observation time
- Graphic User Interface (GUI) available
- Program provides several different functionalities and outputs:
  - Topocentric coordinates of the objects, horizontal and equatorial
  - Visualization of the field
  - Output files such as ephemerides file and field emulation image

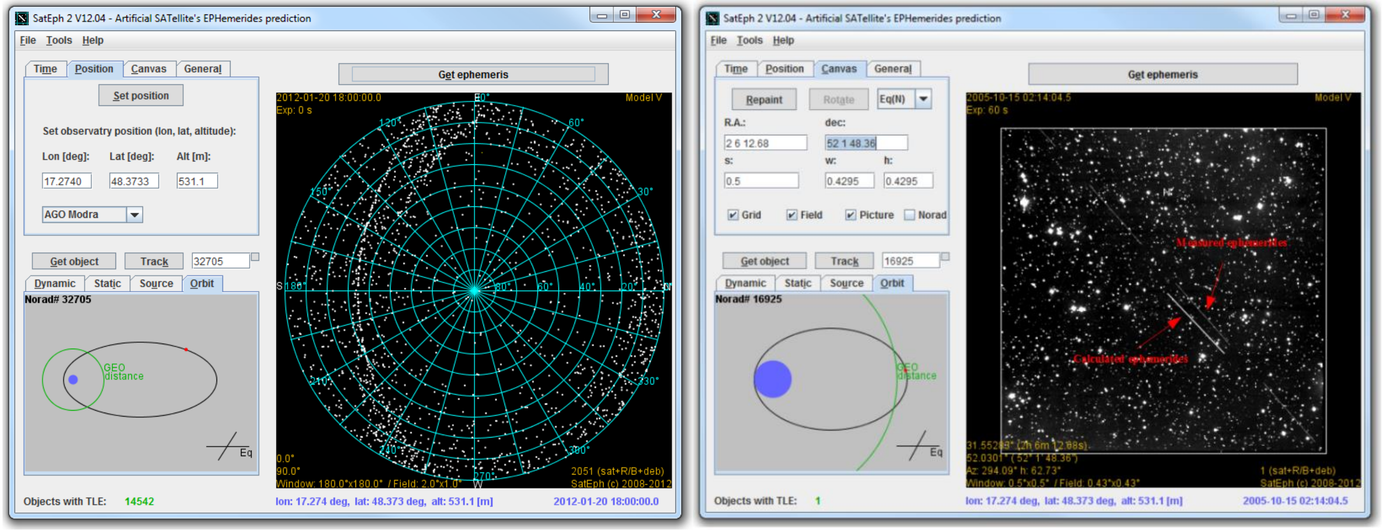


Figure – Example of SatEph's GUI main window. On left are plotted 2051 objects assuming and FOV=180deg in horizontal coordinates. On the right is plotted one object assuming FOV=0.5deg in equatorial coordinates.

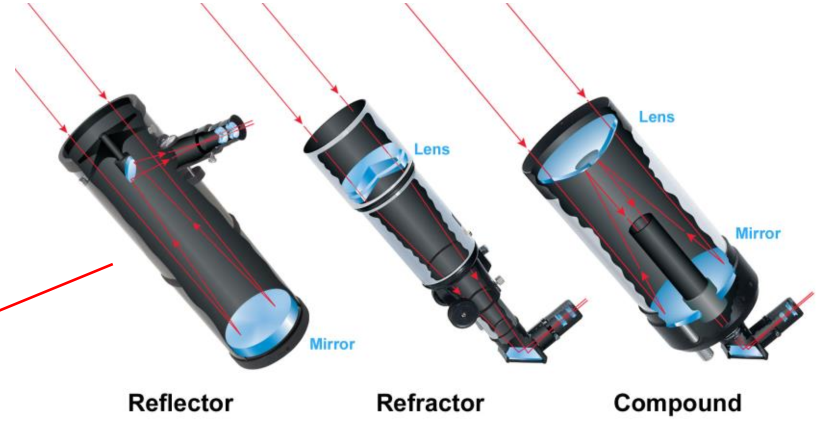
Observation planning

- *SatEph real time projection demonstration.*

Instrumentation

- The goals is to count the number of photons coming from the sources, e.g., star, asteroid, debris.
- Two basic instrument necessary to collect and count the photons, telescopes and sensors
- Telescopes help us to concentrate the light beam to a small defined area called focus
- Sensors help us to measure the number of photons (total intensity) coming from the source

Figure – Three basic configurations for telescopes.



AGO70cm

Figure – Two basic types of sensors used in astronomy.

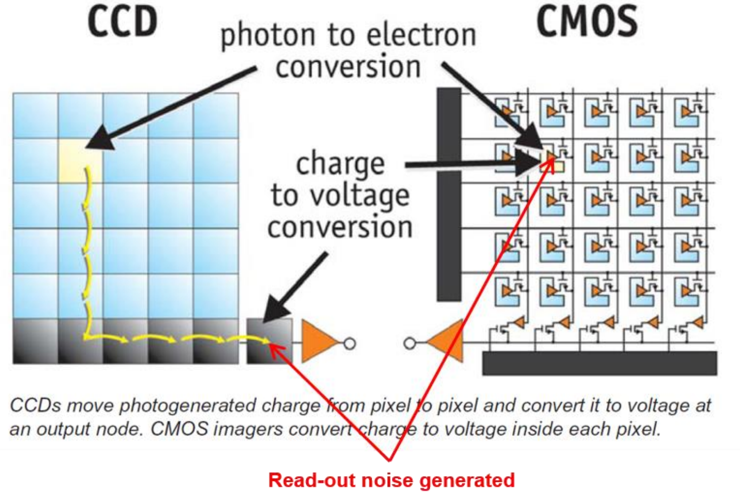


Figure – CCD camera FLI Proline PL1001 Grade 1 (left) and its chip (right).

1024 x 1024 pixels

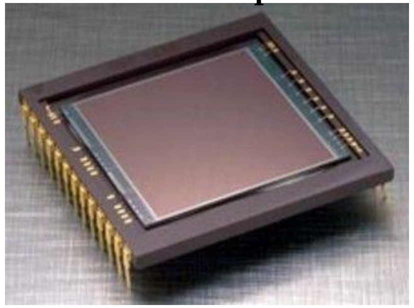


Image objects and noises

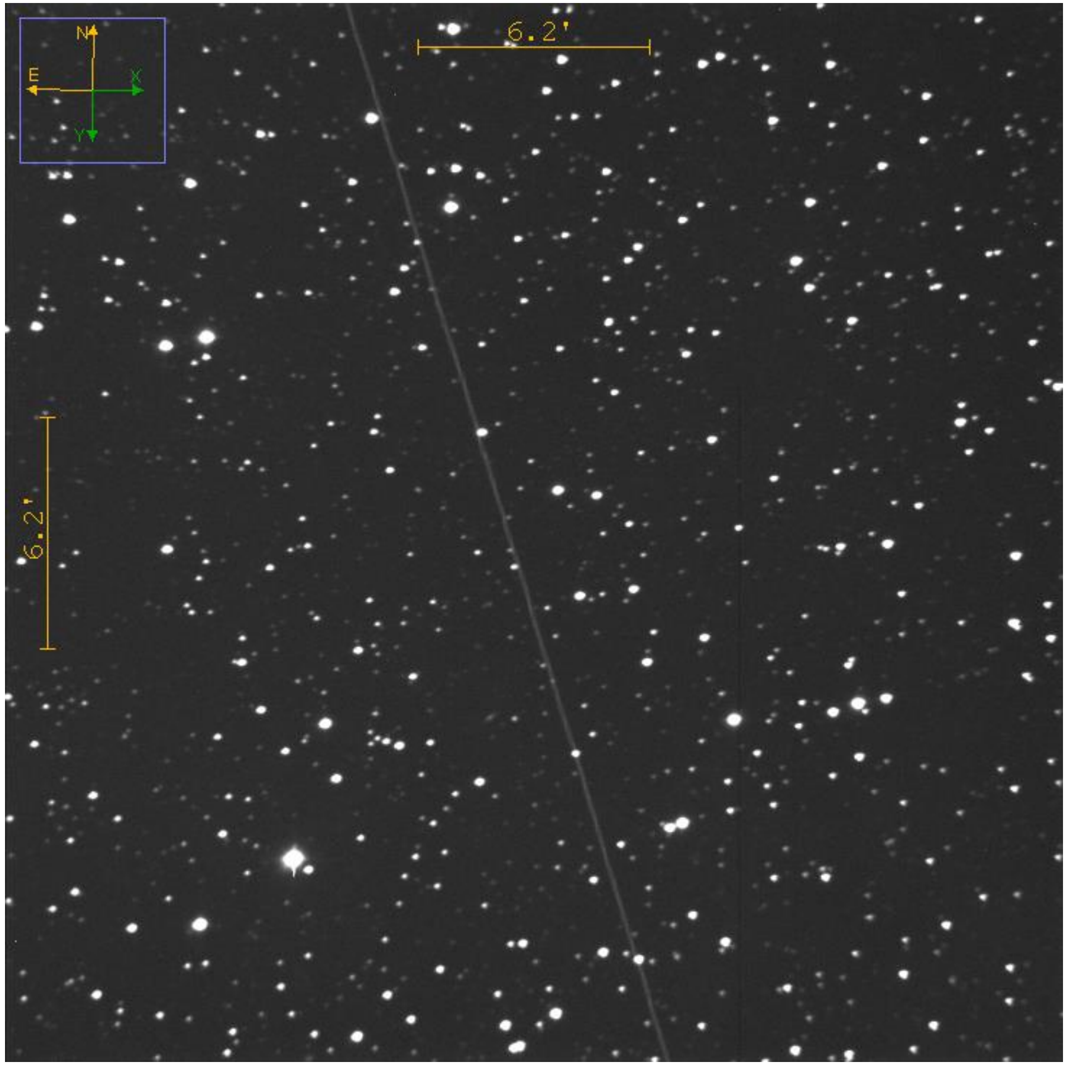


Figure – Arbitrary star field RA=21:40:38.72 and DEC=+15:49:11.0 acquired by AGO70cm at 2017-07-25 23:02:52 with no filter. Used has been exposure time of 120 s.

Image objects and noises

- If **NO diffraction and atmospheric turbulance**, the stars appear as perfect point like objects, only 1 CCD pixel absorbs all the incoming intensity

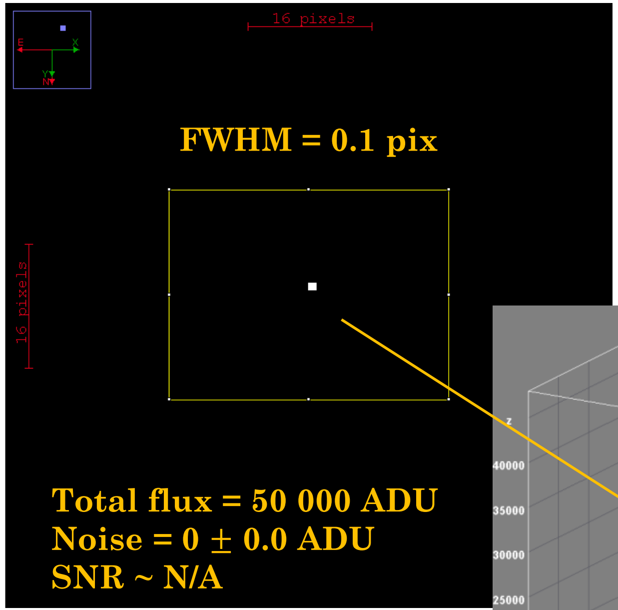


Figure – Synthetic star generated with FWHM = 0.1 pix, total flux of 50 000 ADU and no noise.

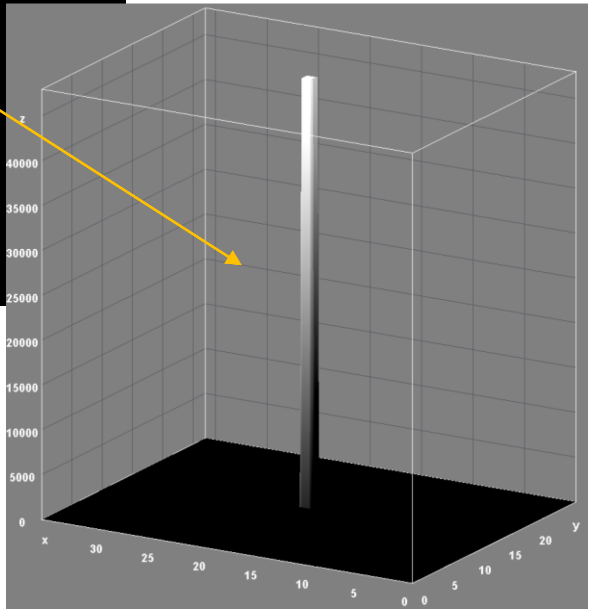


Figure – 3D profile of synthetic star.

- If **diffraction and turbulance**, the stars appear as points spread on several pixels, the distribution close to Gaussian or Cauchy

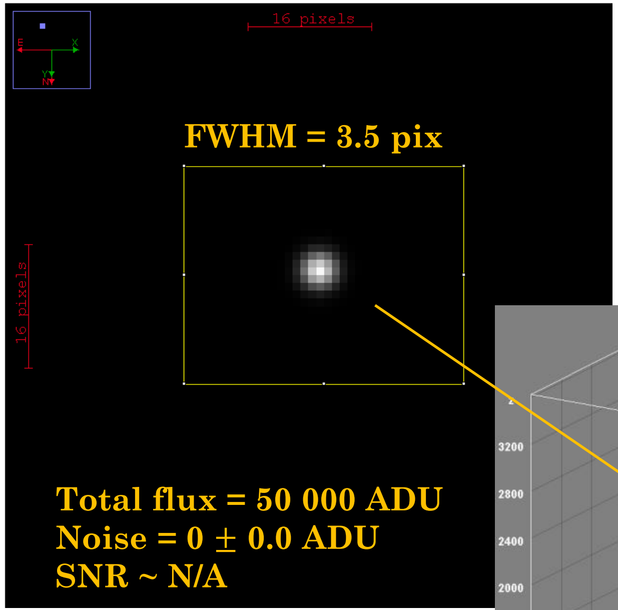


Figure – Synthetic star generated with FWHM = 3.5 pix, total flux of 50 000 ADU and no noise.

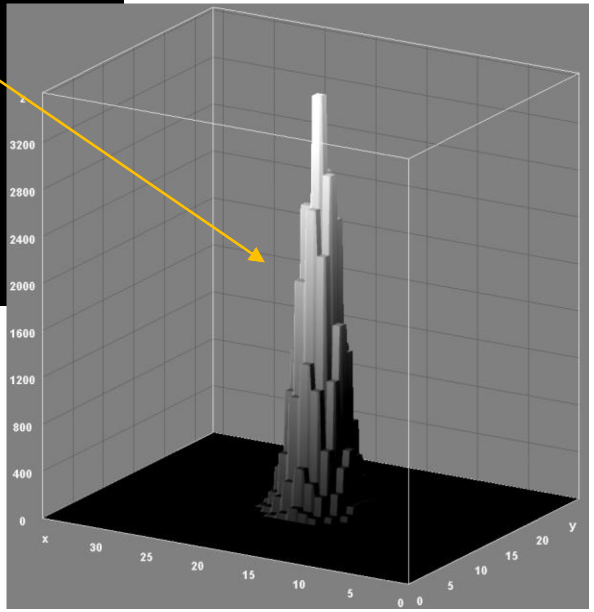


Figure – 3D profile of synthetic star.

Image objects and noises

- Noise decreases the signal of the source, hence increases the measurement error
- If noise too high, object barely detectable by eye or S/W, usually detection limit SNR~3.0, astrometry SRN >~10, photometry >~100

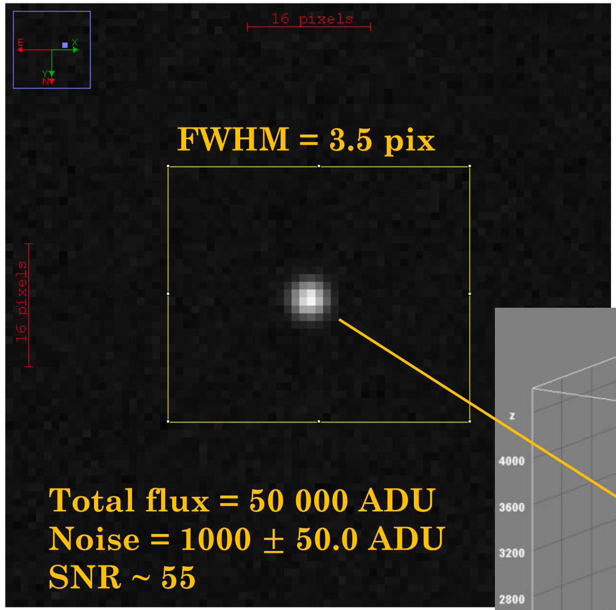


Figure – Synthetic star generated with FWHM = 0.1 pix, total flux of 50 000 ADU and background noise of 1000 ± 50.0 ADU.

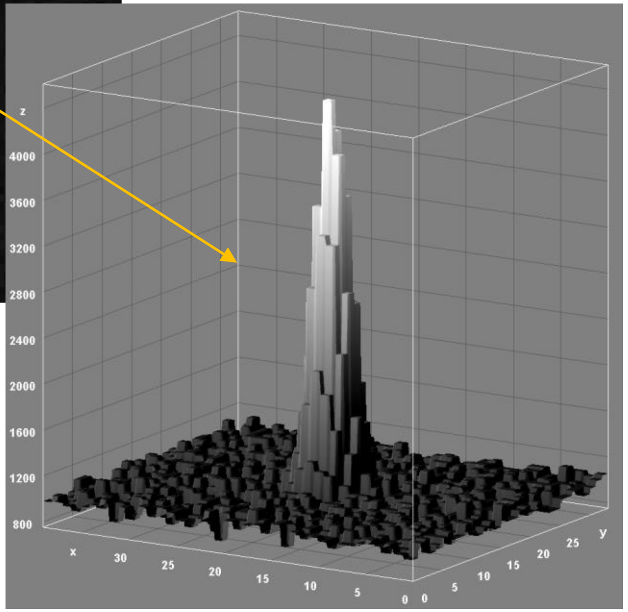


Figure – 3D profile of synthetic star.

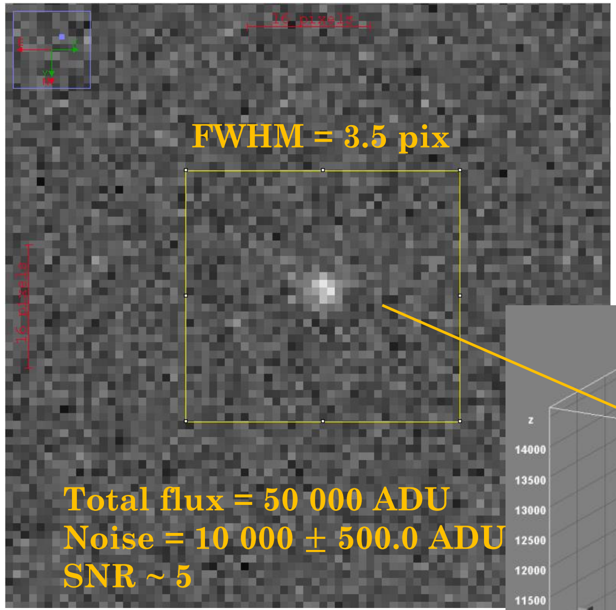


Figure – Synthetic star generated with FWHM = 0.1 pix, total flux of 50 000 ADU and background noise of 10 000 ± 500.0 ADU.

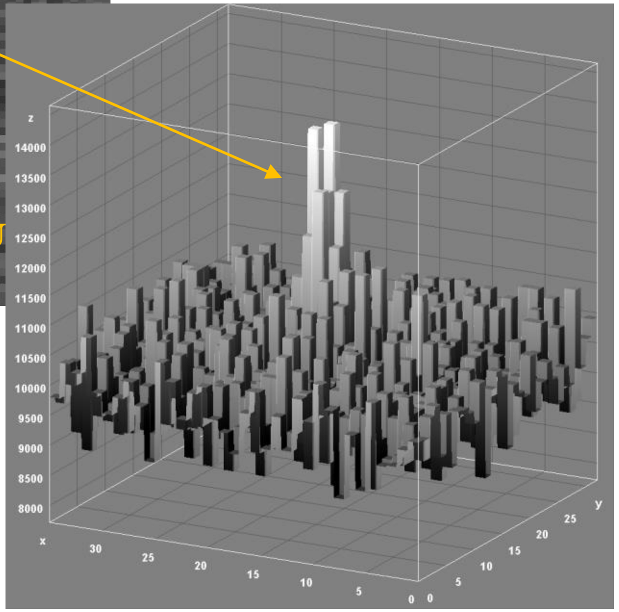


Figure – 3D profile of synthetic star.

Image objects and noises

- Worse case is for streak like objects, because the total intensity is spread over more pixels ➔ frame objects with lower SNR

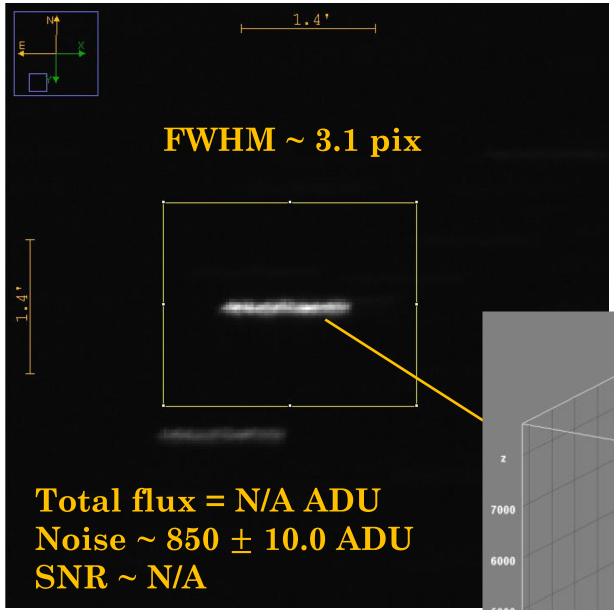


Figure – Synthetic star generated with FWHM = 0.1 pix, total flux of 50 000 ADU and background noise of 850 ± 10.0 ADU.

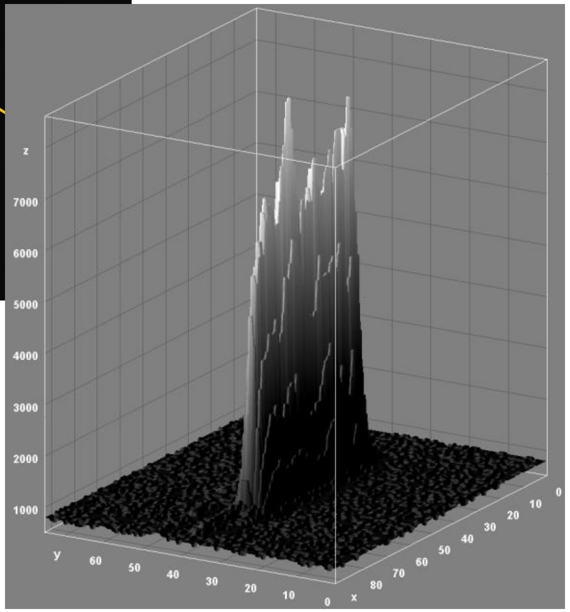


Figure – 3D profile of real star.

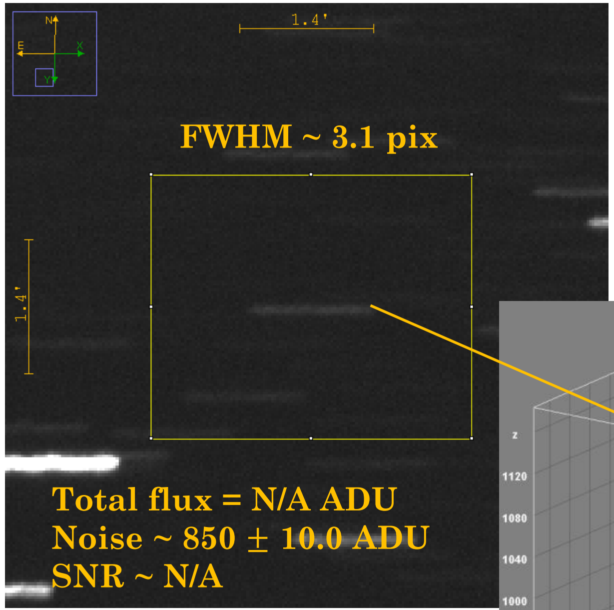


Figure – Synthetic star generated with FWHM = 0.1 pix, total flux of 50 000 ADU and background noise of 850 ± 100.0 ADU.

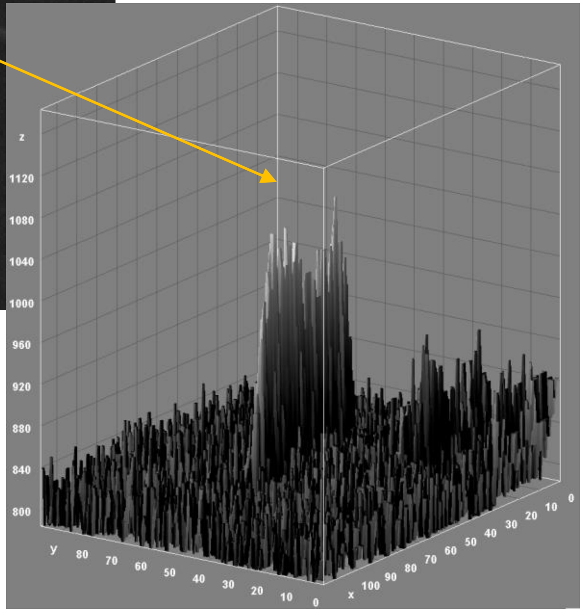


Figure – 3D profile of real star.

Noises

- Several different sources of noise, distinguished two types:

  - 1. Camera and optics
    - **Bias** – during the read out process amplifiers are used which add additional electrons to the output, typically 5 - 20 electrons per pixel, depends on the camera and used temperature
    - **Dark** – electrons in CCD are thermally excited during exposure, even during a dark exposure when shutter is closed, depends on the temperature and camera
    - **Flat field** – CCD pixels not perfectly identical, the differences can be identified by using flat field images, also dust on the optical system, e.g. on mirror(s), camera, filters, can be identified by using flat, it depends on the camera and optics properties

  - 2. External sources
    - **Sky background** – zodiacal light, faint stars, light pollution, etc.
    - **Parasitic light** - stray light, Moon light, etc.
    - **Diffused sources** - galaxy, nebula, zodiacal light, etc.

Noises, BIAS

- Series of BIAS images creates a MASTER BIAS (average, median, etc.) which is subtracted from the light image.

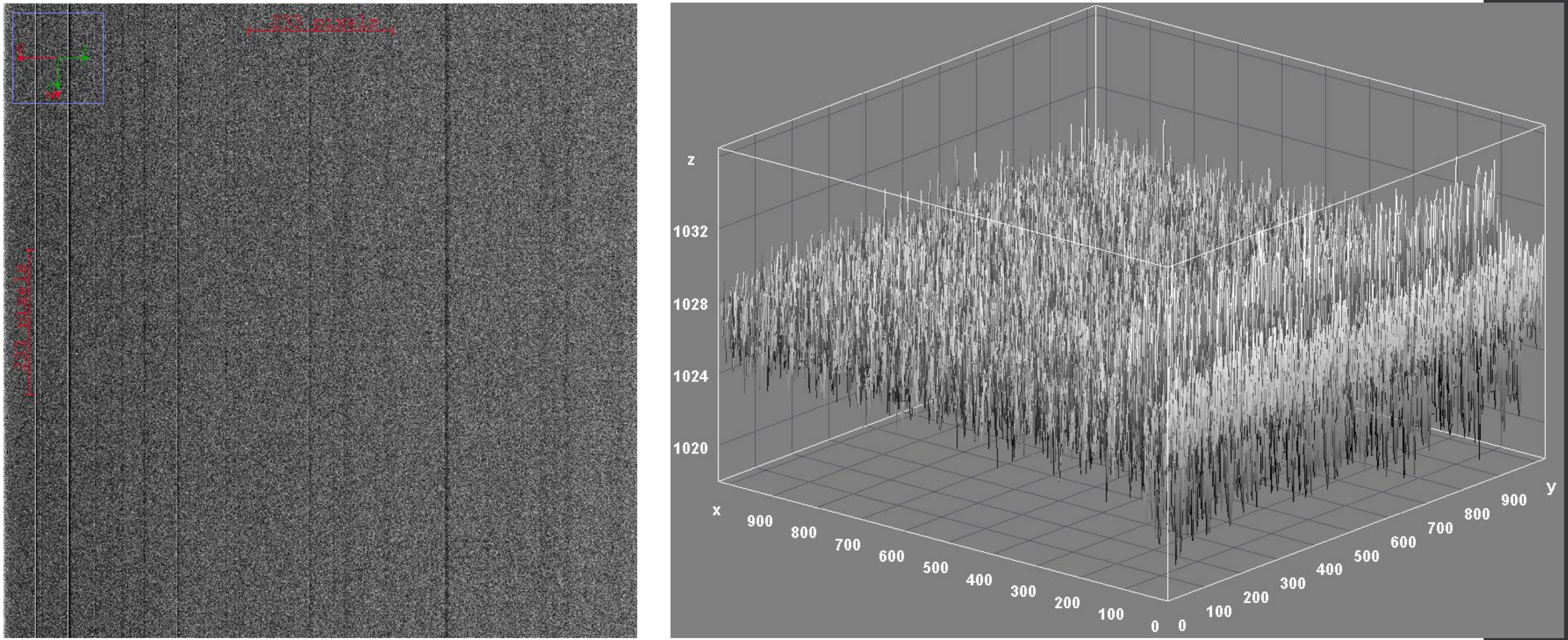
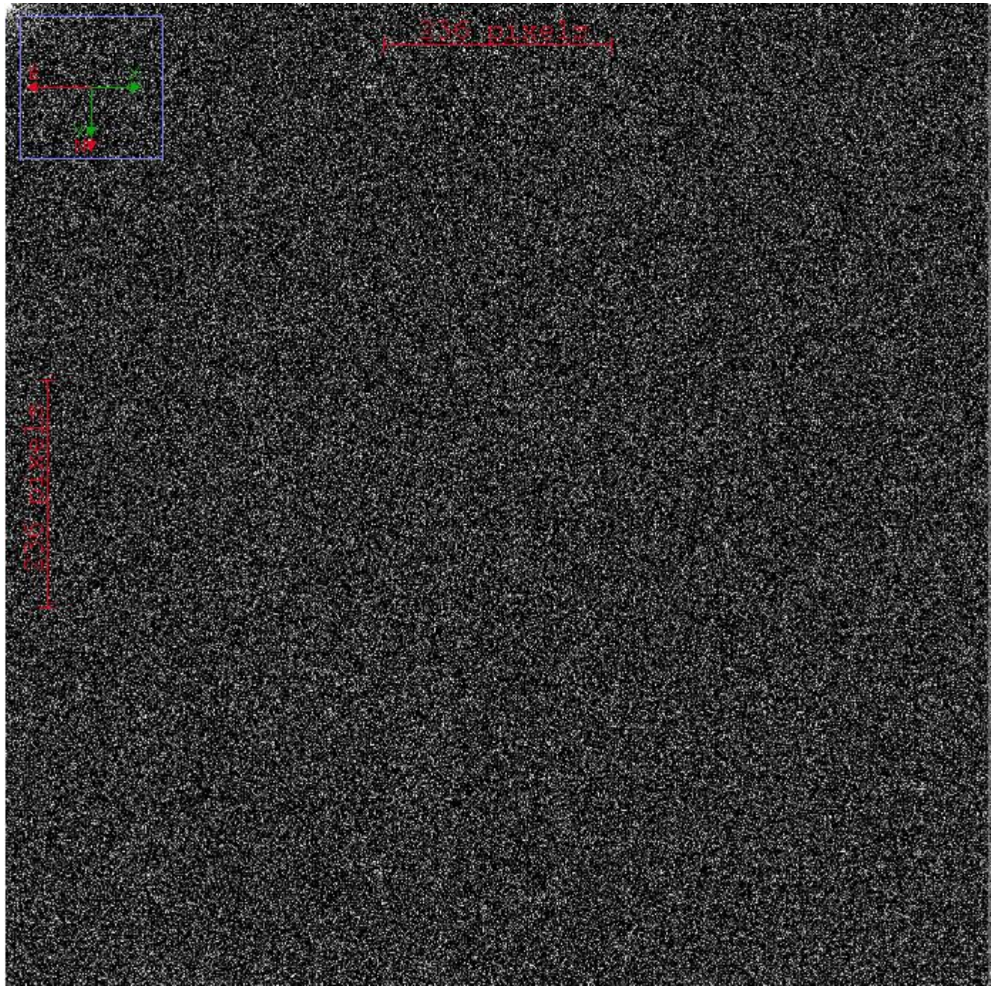


Figure – Master BIAS frame (left) and its 3D profile (right) created from 24 BIAS frames using median value.
Images acquired by AGO70cm system. CCD temperature = -35°C. Exposure time = 0 s.

Noises, DARK

- Series of DARK images creates a MASTER DARK (average, median, etc.) which is subtracted from the light image.



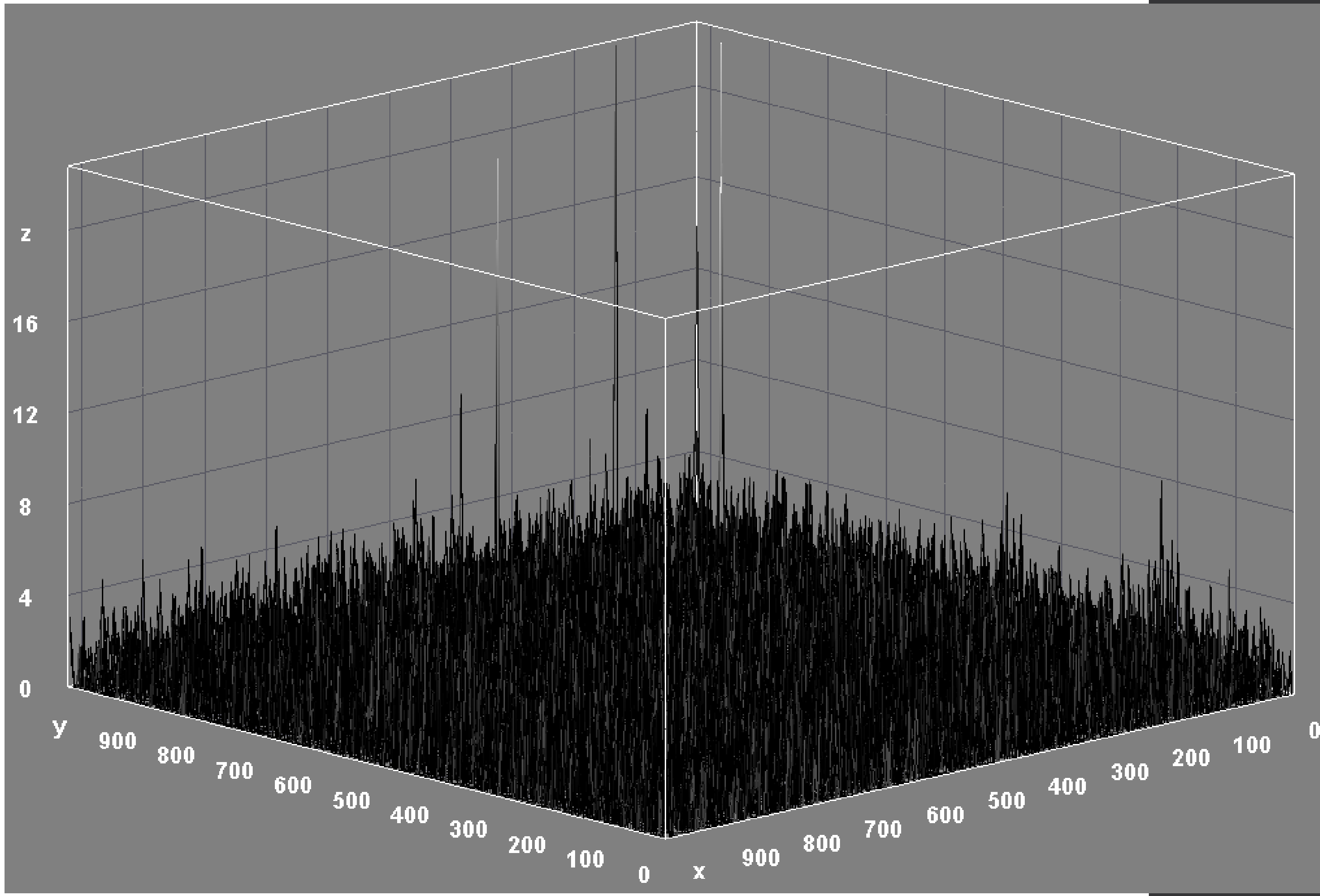


Figure – Master DARK frame (left) and its 3D profile (right) created from 24 DARK frames using median value.
Images acquired by AGO70cm system. CCD temperature = -35°C. Exposure time = 10 s.

Noises, FLAT FIELD

- Series of FLAT FIELD images creates a MASTER FLAT FIELD (average, median, etc.) which divides the light image.

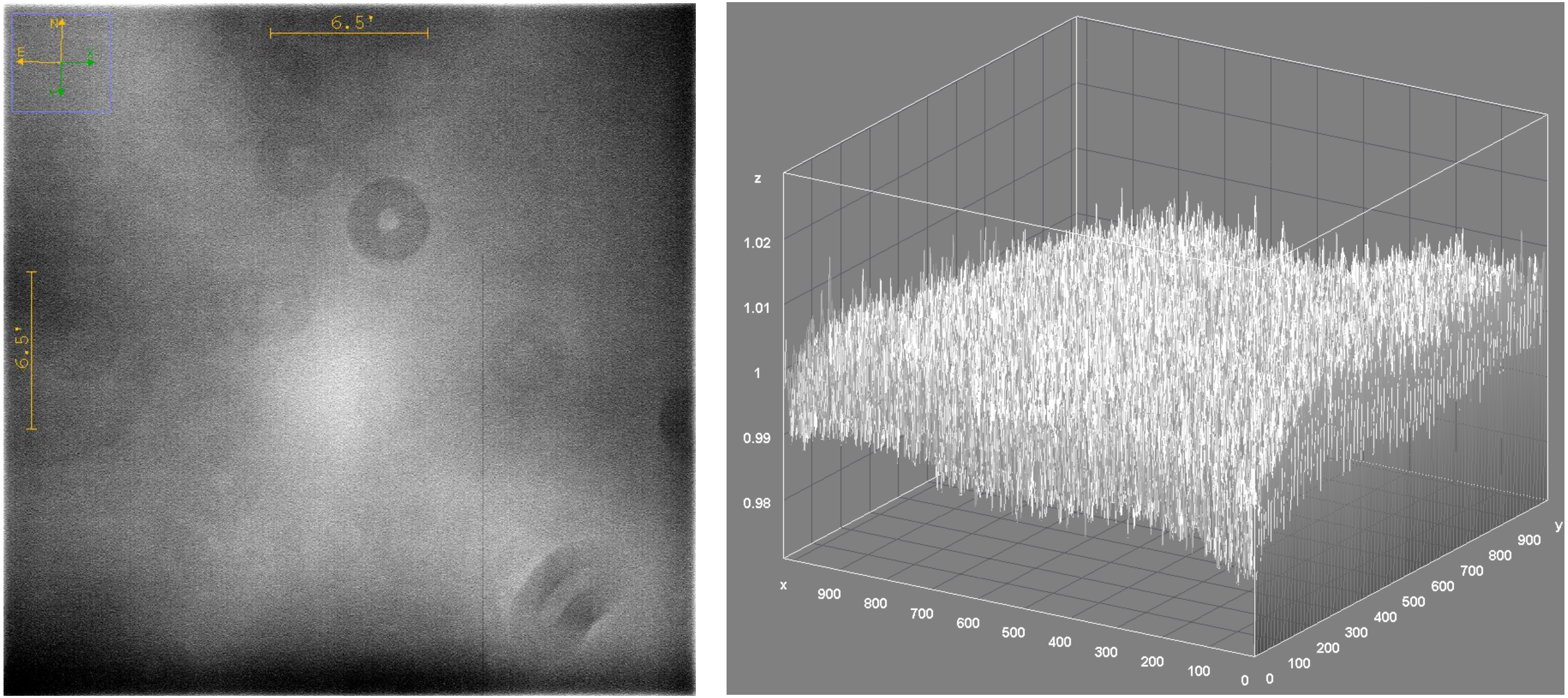


Figure – Master FLAT FIELD frame (left) and its 3D profile (right) created from 12 FLAT FIELD frames using median value.
Images acquired by AGO70cm system. CCD temperature = -35°C. Exposure time = 2 s. Used R filter.

Noises, diffused noise

- Series of light images of nebula NGC281 acquired in B, V and R filters. Nebula causes that the star background is not liear across the frame.

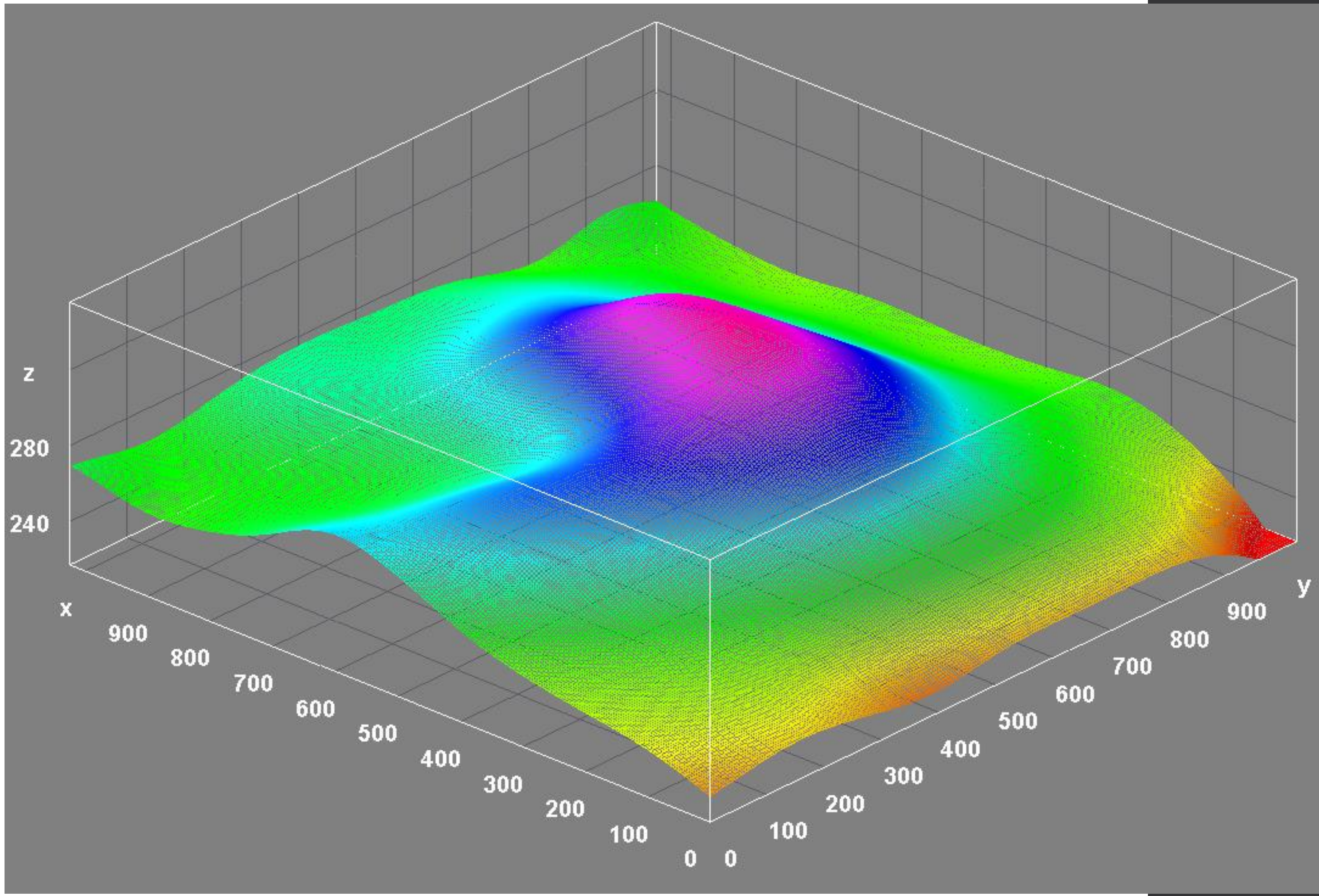


Figure – Composition of light images of nebula NGC281 (left) and its 3D profile (right). Images acquired by AGO70cm system. CCD temperature = -35°C. Exposure time = 15 s. Used B, V and R filter.

Image processing

AGO70cm processing pipeline

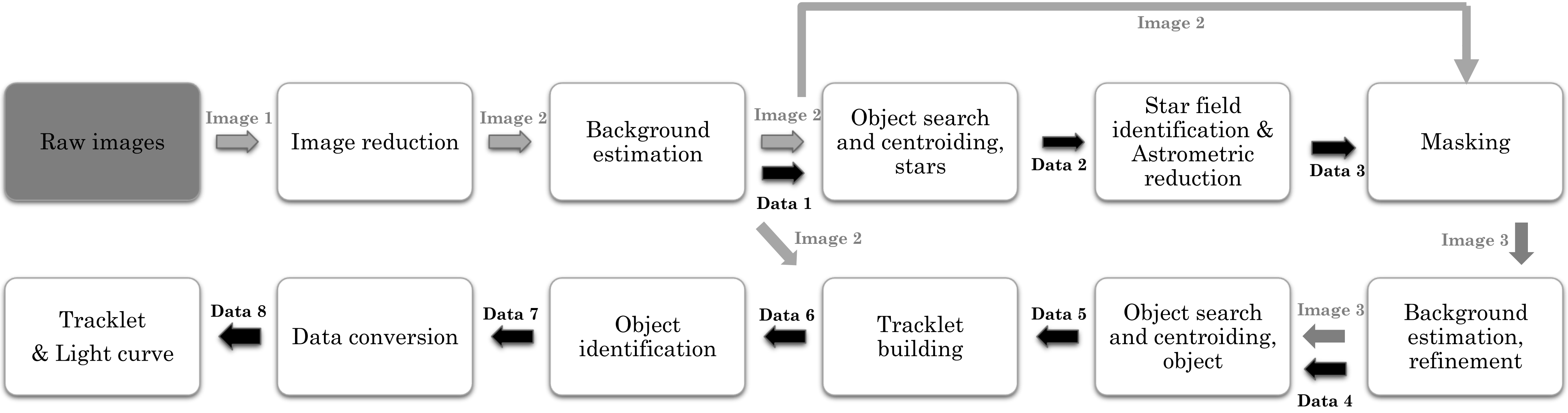


Image 1 – Raw science (light) image
Image 2 – Calibrated science image
Image 3 – Masked calibrated science image, stars removed

Data 1 – Background value, background map
Data 2 – Stars' frame objects centroid positions and total intensities
Data 3 – Astrometric reduction solution (plate constants, center coordinates, etc.)
Data 4 – Refined background value, background map
Data 5 – Non star frame object's centroids and total intensities
Data 6 – Tracklet, series of measurements for specific frame object
Data 7 - Tracklet and light curve for specific object from catalogue, internal formats
Data 8 - Tracklet and light curve, defined format

Image reduction

- Well defined procedure in astronomy, practice necessaryBasic approach is as follows, where DARK is scalable:

$$image_{science,reduced} = \frac{image_{science,raw} - image_{bias} - image_{dark,scaled}}{image_{flat,reduced,normalized}}$$

- If the same exposure used for light frame as for the DARK frames, BIAS included in DARK frames already, DARK NOT scalable:

$$image_{science,reduced} = \frac{image_{science,raw} - image_{dark,exp}}{flat_{reduced,normalized}}$$

- Each system is different, also MASTERs valid only limited period of time, DARK and BIAS usually taken each observation night, FLAT FIELDs once per few weeks, if no change to CCD or mirror alignment happen between

Background estimation

- First it is necessary to estimate the background values which can be:
  - a constant value over the whole frame - good observation conditions, not parasitic light, no diffuse sky source
  - linear function - Moon light, stray light, parasitic light, etc.

$$b_{ij} = \beta_0 + \beta_1 \times i + \beta_2 \times j$$

where i and j are the pixel indices and three parameters β are to be determined.

  - complex function to be fitted by polynomial of higher order - diffuse sky sources, complex parasitic light, etc.

$$b_{ij} = \beta_0 + \beta_1 \times i + \beta_2 \times j + \beta_{11} \times i \times i + \beta_{12} \times i \times j + \beta_{22} \times j \times j$$

where i and j are the pixel indices and six parameters β are to be determined

Background estimation

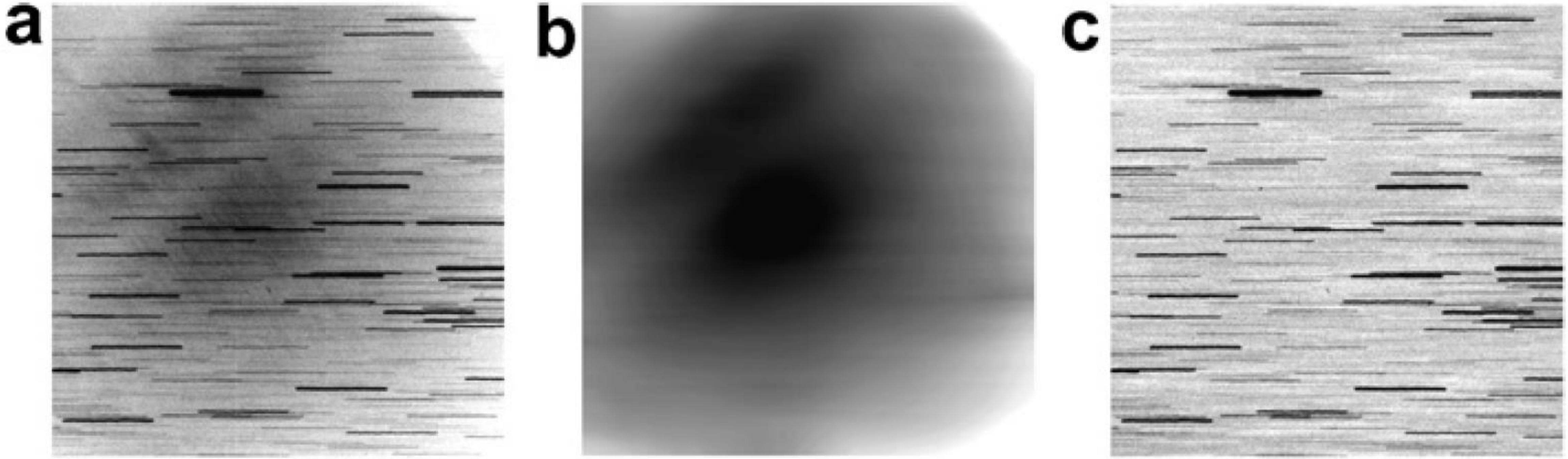


Figure – Sky background estimation: (a) original image; (b) estimated background map; (c) image after background subtraction: smoothing + sigma clipping. All images are 512 · 512 pixels. Taken from Kouprianov (2008).

Segmentation, object search and centroiding

- The goal is to identify all the *frame objects*, group of pixels belonging to specific real object such as star, asteroid, satellite, debris, etc.

- *Frame objects* detectable once SNR >~3.0, can point like, streak like, deformed features

- Different methods how to detect frame objects, e.g.:
  - using aperture measurements, where the total intensity

  in a specific region (define circle, square) needs to pass the defined threshold
  - start with the threshold peak pixel and then continuing

  searching associated pixels (left)

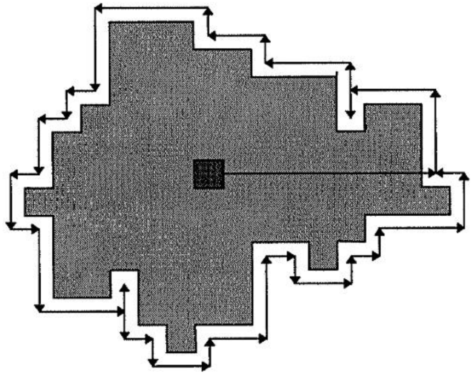


Figure – Illustration of the border-and-fill algorithm. Black pixel is the peak pixel which passed the defined threshold. Taken from Schildknecht et al. (1995).

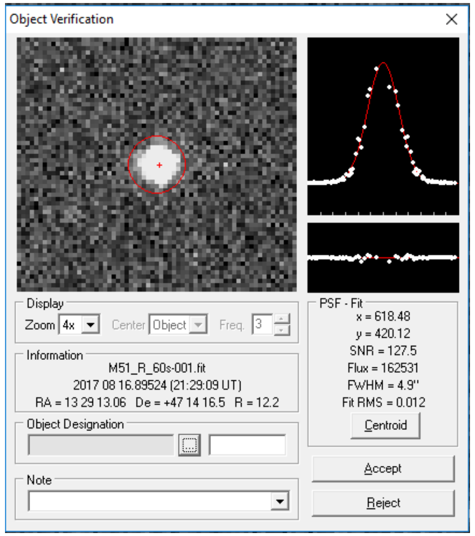


Figure – Example of an aperture measurement. Image generated by using Astrometrica S/W tool.

Segmentation, object search and centroiding

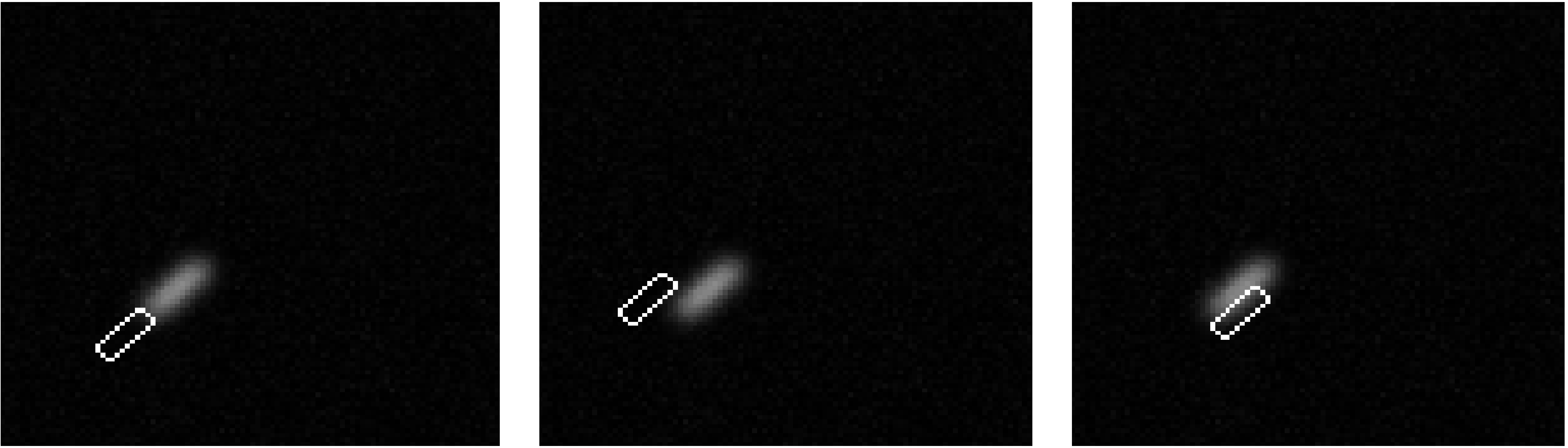


Figure – Example of an aperture measurement detection algorithm. Image generated by using internal FMFI synthetic image generator and "Search and centroiding" algorithm.

Segmentation, object search and centroiding

- Two types of data need to be extracted from frame object once detected
  - Center coordinates X, Y of the frame objects in camera (CCD) reference frame [pix]
  - Total intensity of the frame object (the source) [ADU]

- Most used approaches are:

  - Centroiding / Center-of-Gravity – all the pixels defined in the array will be used to calculate the "center-of-gravity" where the weight will be the pixel intensity value (also referred to as gray value) (ADU)

  - PSF fitting – all the pixels in the defined area, usually circular shaped aperature, will be fitted by a function called Point Spread Function (PSF), a 3D function which is usually based on the Gaussian or Cauchy distribution, the output of these methods are the coordinates X,Y, total intensity and shape of the profile defined via FWHM (Full-Width of Half Maximum)

Segmentation, object search and centroiding

- Center-of-Gravity

$$(x_b, y_b) = \left(\frac{\sum_{ij} I_{ij} x_{ij}}{\sum_{ij} I_{ij}}, \frac{\sum_{ij} I_{ij} y_{ij}}{\sum_{ij} I_{ij}} \right)$$

- PSF fitting

$$f\left(x_i, y_j, \beta\right) = a e^{\frac{-(x_i - x_b)^2}{2\sigma_x^2}} e^{\frac{-(y_j - y_b)^2}{2\sigma_y^2}}$$

- PSF fitting

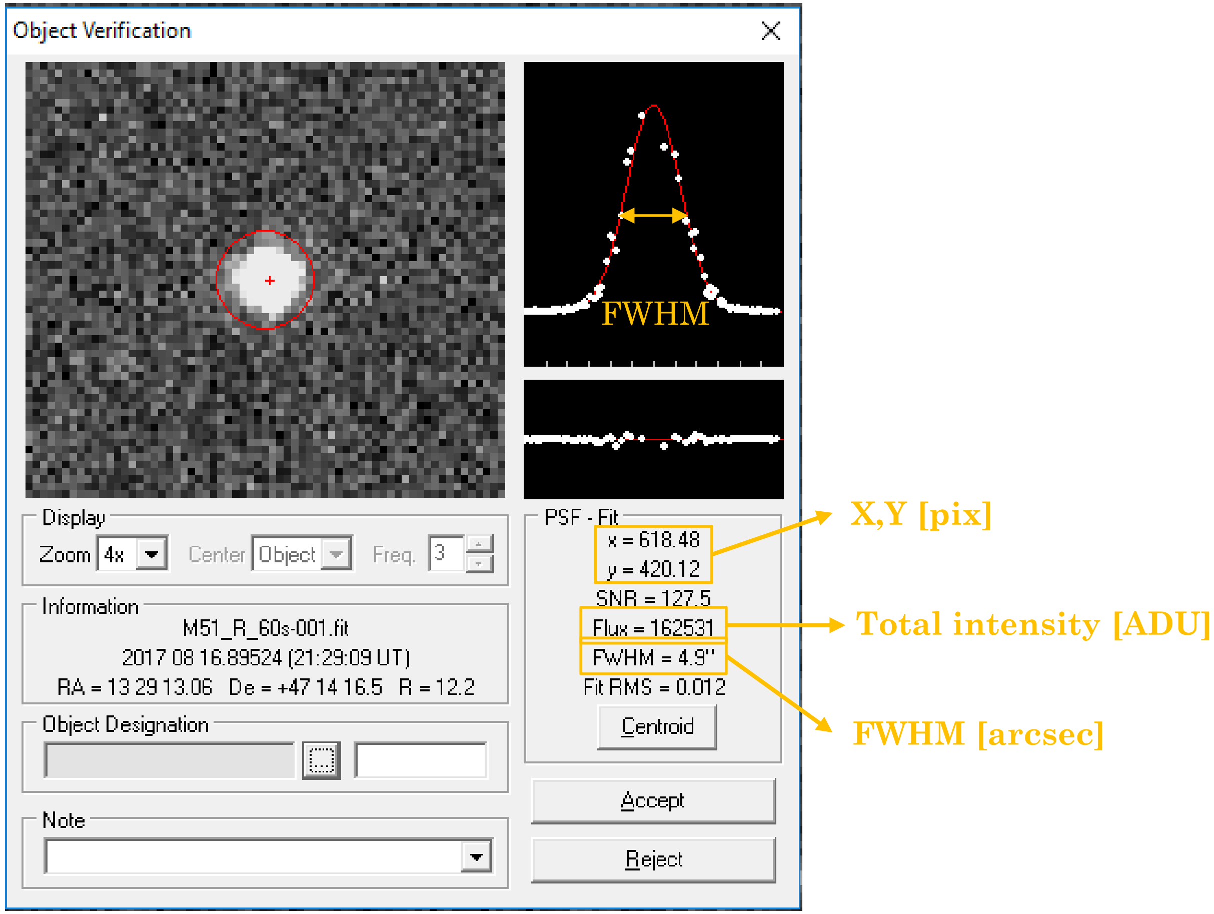


Figure – Example of a PSF fitting algorithm results. Image generated by using Astrometrica S/W tool.

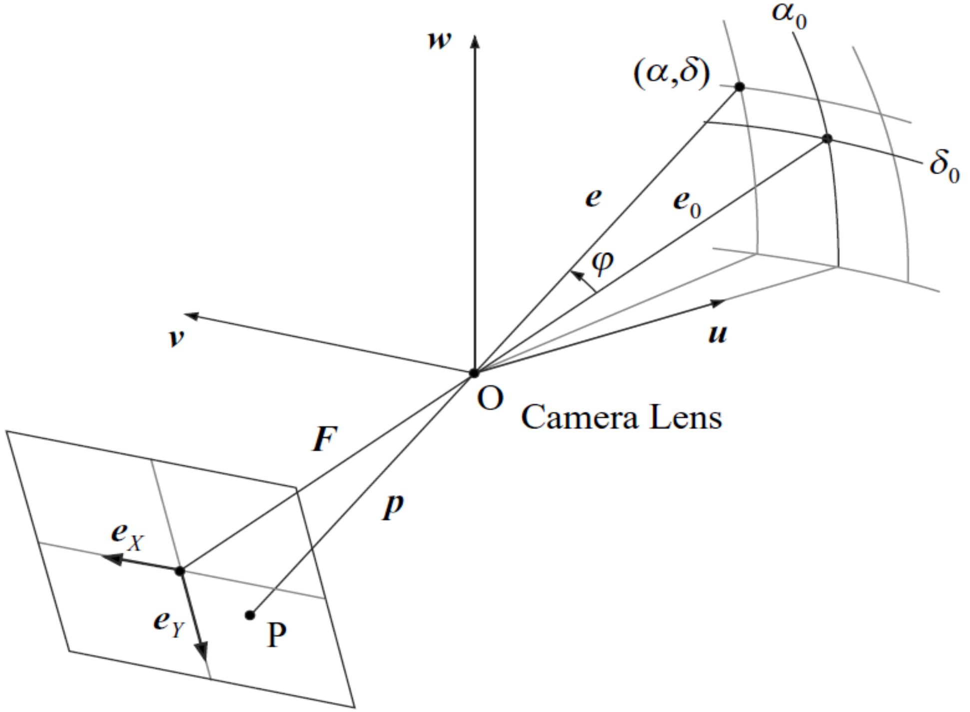
Astrometric reduction, star field identification

- Part of the image processing is to convert the measured coordinates within the frame 2D Cartesian coordinates, (x,y), to the required celestial sphere coordinates, preferably to equatorial coordinates right ascension (RA and α) and declination (DEC and δ).

- The key element of the astrometric reduction is to find the plate constants. In general, there are defined three different coordinate systems:
  - a) The measured 2D Cartesian coordinates (x,y)
  - b) The standard 2D Cartesian coordinates (X,Y)
  - c) The equatorial coordinates (α,δ)

$$\alpha = \alpha_0 + \tan^{-1}\left\{\frac{-X}{\cos\delta_0 - Y\cos\delta_0}\right\}$$

$$\delta = \sin^{-1}\left\{\frac{\sin\delta_0 + Y\cos\delta_0}{\sqrt{1 + X^2 + Y^2}}\right\}$$



Astrometric reduction, star field identification

- The standard coordinates (X,Y) are used as a basis for the plate reduction. To obtained these coordinates from the measured coordinates (x,y) we have to use following equations:

$$X = \sum_{p,q} A_{pq} x^p y^q \, ; \qquad p \geq 0; \; q \geq 0; \; p + q \leq A_{order}$$

$$Y = \sum_{p,q} B_{pq} x^p y^q \, ; \qquad p \geq 0; \; q \geq 0; p + q \leq B_{order}$$

where A_{pq} and B_{pq} are polynomial coefficients for polynomial terms $x^p y^q$ and coefficients A_{order} and B_{order} define the polynomial order, e.g. for first-order (linear) polynomial A_{order}=B_{order} $= 1$, for second-order (quadratic) polynomial A_{order}=B_{order} $= 2$ and for third-order (cubic) polynomial A_{order}=B_{order} $= 3$.

- For linear function there are six plate coefficients to be solved, namely A_{10}, A_{01}, A_{00}, B_{10}, B_{01}, and B_{00}. For quadratic and cubic polynomials it will be in total 12 and 20 coefficients, respectfully

$$X = A_{10}x + A_{01}y + A_{00} \qquad Y = B_{10}x + B_{01}y + B_{00}$$

Astrometric reduction, star catalogues

- Several different catalogues used for astrometry, e.g.:
  - Hipparcos catalogue
  - Tycho catalogue
  - Gaia catalogue
  - USNO-A and USNO-B catalogue
  - UCAC4 catalogue
  - etc.

- Only few photometric catalogues:
  - Landolt standards
  - Henden sequences

Masking

- Method to remove the unwanted frame objects from the frame, once the stars identified and used, signal from to them related pixels set to “0”, left only “desired pixels” from objects of interest, e.g. debris, asteroid, etc.

- Mask generated by using info from astrometric reduction and applied to light image

- Output image then processed again for background estimation (refinement) and segmentaion/”object search & centroiding”

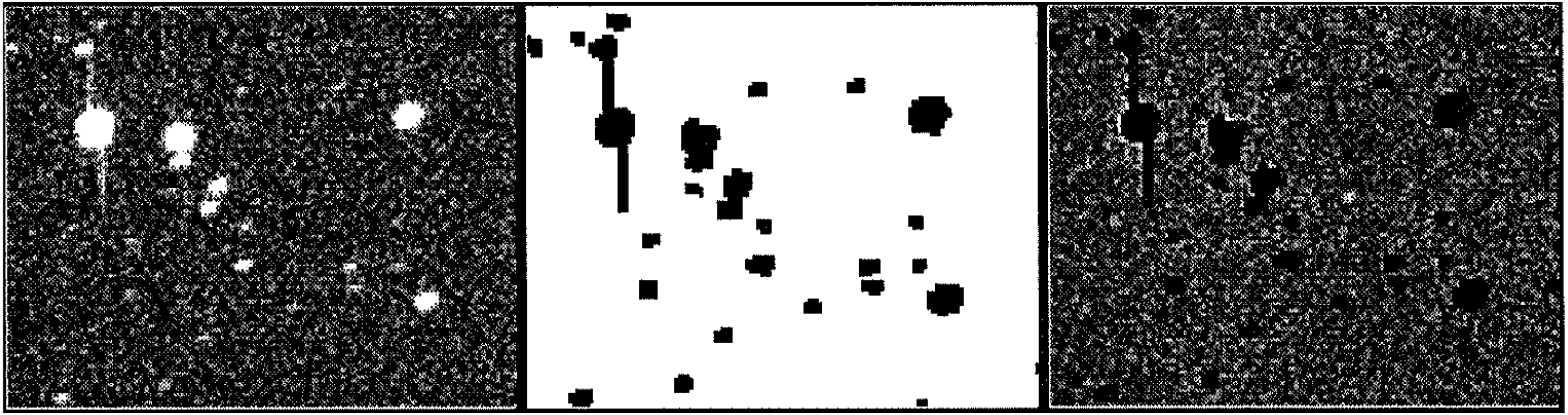


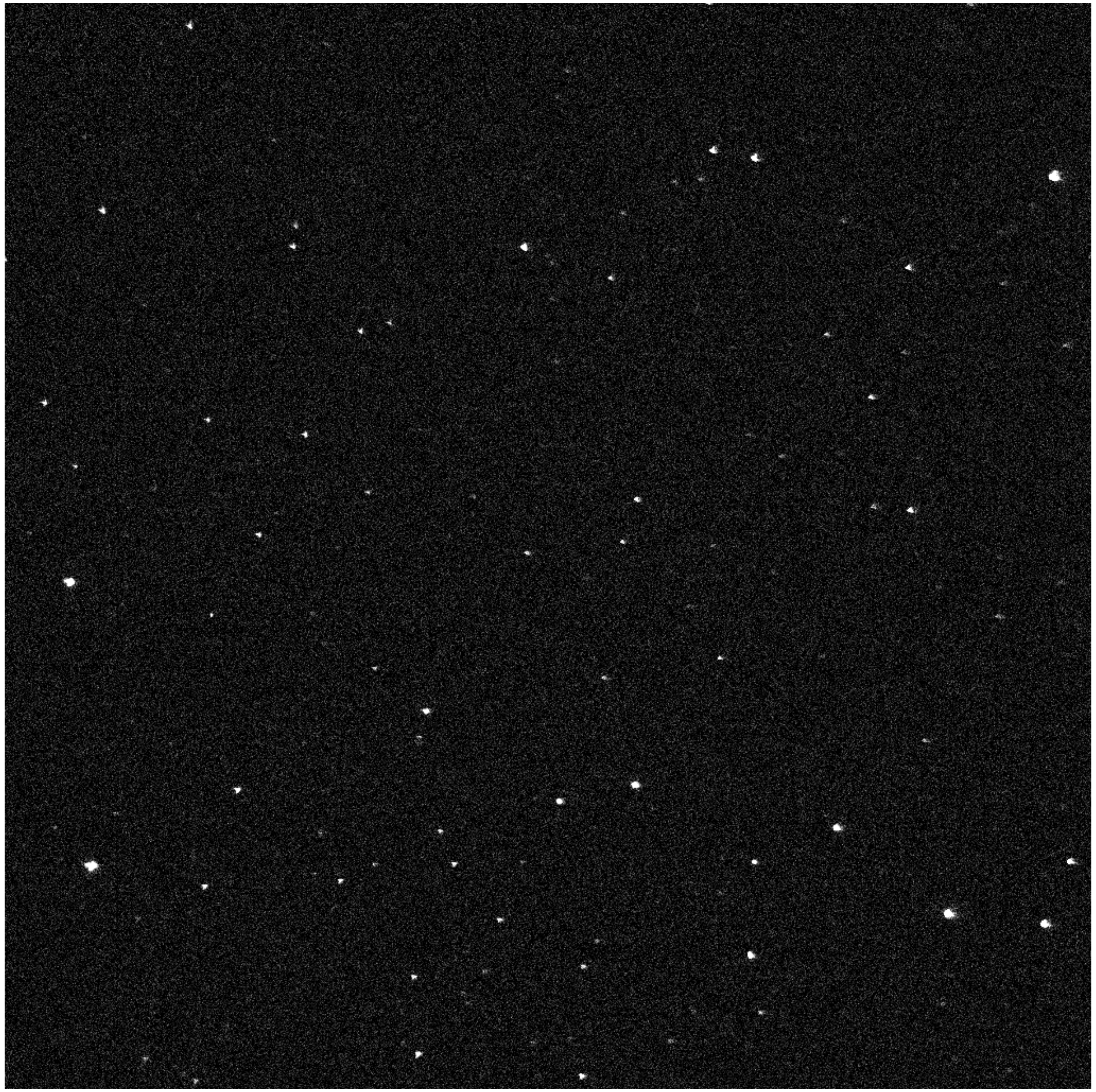
Figure – Reference frame (left), reference mask (middle), and masked frame (right). The images were taken with the Zimmerwald 0.5 m Satellite Laser Ranging (SLR) telescope. The FOV = 14’ x 10’ and the exposure was 1.5s. Taken from Schildknecht et al. (1995).

Tracklet building

- Tracklet building, also known as tracklet construction, is necessary for connecting the *frame objects* (excluding the identified stars) to series of observations, building so-called tracklet

- Otherwise just bunch of frame objects, including cosmics, hot pixels, object with no interest (e.g. functional satellite in FOV, faint stars), etc.

Tracklet building



- Simpler cases are when the sidereal (star) tracking or image (e.g. GEO) tracking is used
- Apparent motion of stars marginal or apparent motion of object is marginal, possibility to use linear regression on frame coordinates

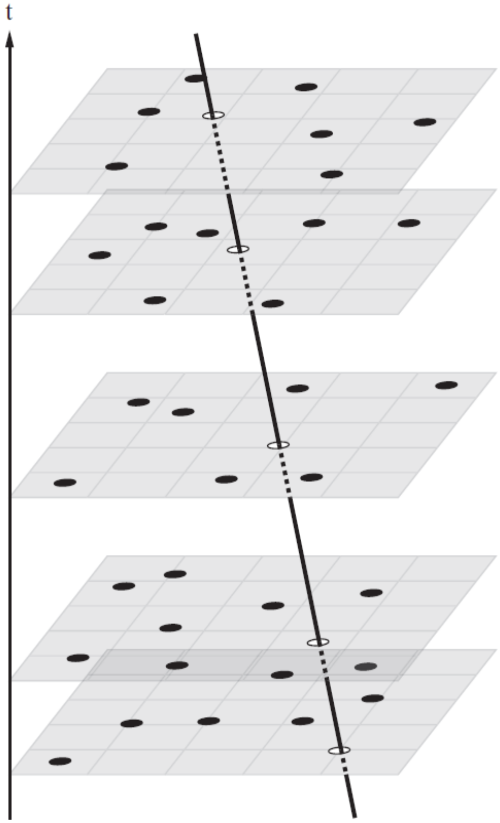
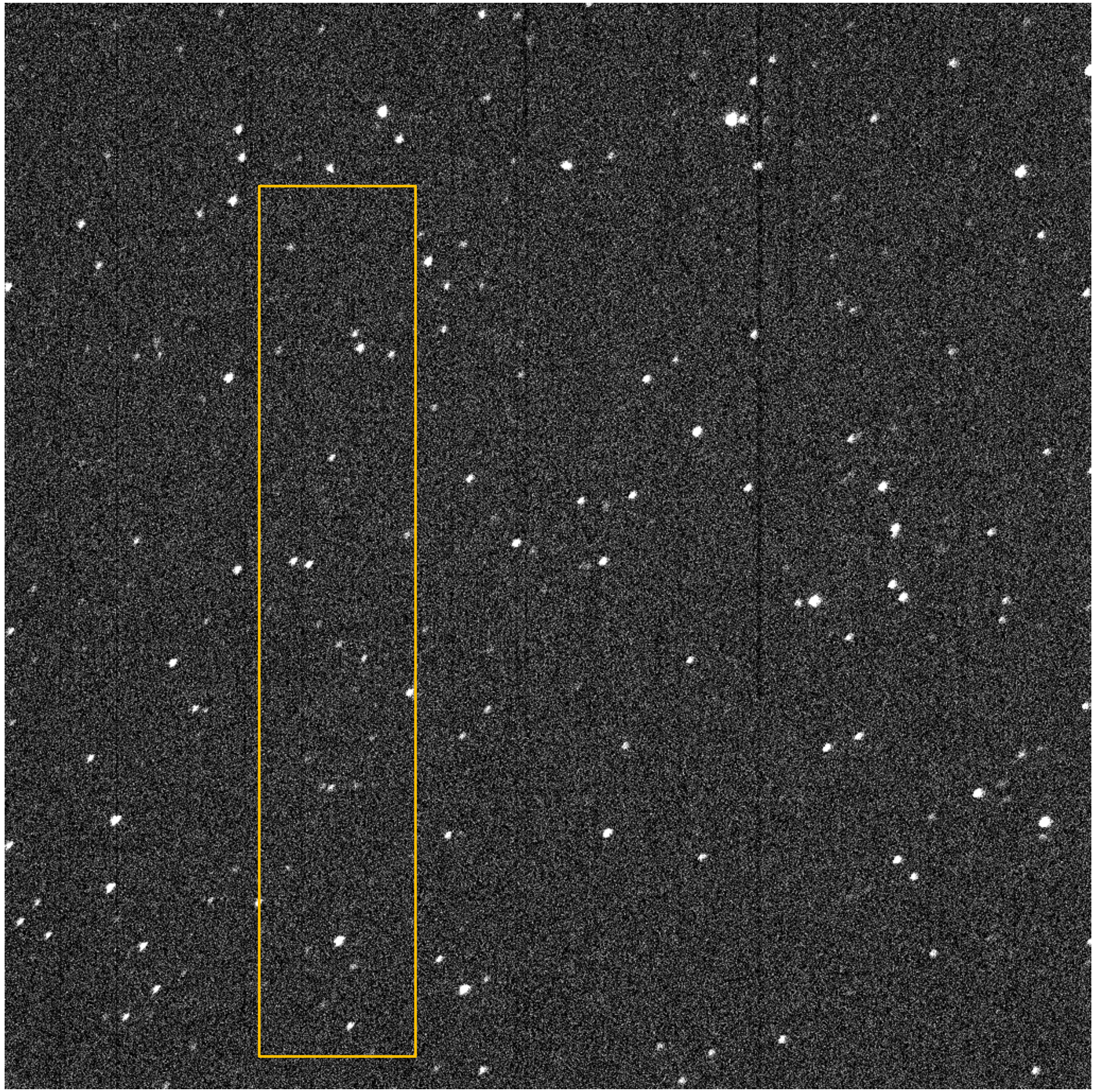


Figure – Concept of the uniform linear motion detection algorithm. Taken from Oda et al. (2014).

Figure – Composition of 10 light images of GNSS satellite GLONASS 2016-032A. Images acquired by AGO70cm system. CCD temperature = -40°C. Exposure time = 0.1 s. Used R filter.

Tracklet building



- In reality tracking not necessary perfect or limited
- Apparent motion of stars and object is relatively high from frame to frame
- Necessary to perform astrometric reduction and use RADEC coordinates for tracklet building, currently following methods used:
  - Linear regression for RADEC coordinates, for small angular distance applicable
  - Apparent motion on great circle, fitting
  - Initial orbit determination

Figure – Composition of 40 light images of NEA 2018-CB. Images acquired by AGO70cm system. CCD temperature = -40°C. Exposure time = 0.5 s. Used R filter.

Tracklet building

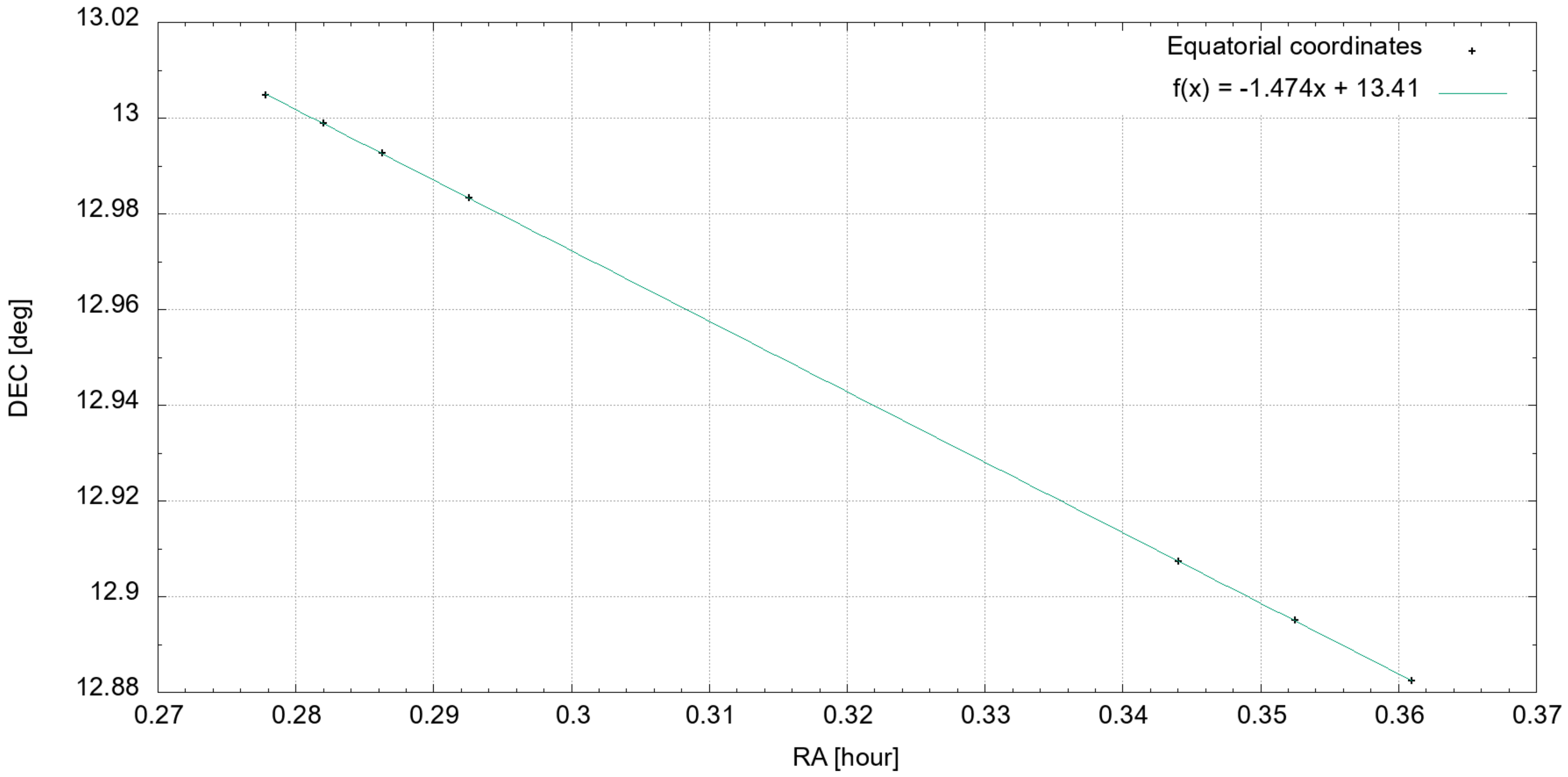


Figure – Example of a linear fit of data extracted for object E11299A observed by AGO70cm in 2017-08-03.

Object identification

- Identification of specific tracklet with catalogue objects. Necessary is to have:
  - Tracklet – reference epoch, RA, DEC → angular velocity, position angle
  - Catalogue – preferably in TLE format with the most recent reference epoch
  - Ephemeris – prediction of the position in the same coordinates (e.g. J2000, TEME) for the same observer

- Compared are following parameters:
  - Difference in positions for ref. epoch Δ [deg]: $\Delta = \cos^{-1}(\sin\delta_1 \sin\delta_1' + \cos\delta_1 \cos\delta_1' \cos(\alpha_1 - \alpha_1'))$
  - Difference in position angle [deg]: $\Delta PA = (PA - PA'),$
  - Difference in apparent angular velocities [deg/s]: $\Delta\omega_{radec} = \omega_{radec} - \omega'_{radec}$
  - Ratio between apparent angular velocities [deg/s]: $\omega_{radec,ratio} = \Delta\omega_{radec}/\omega'_{radec}$

Object identification

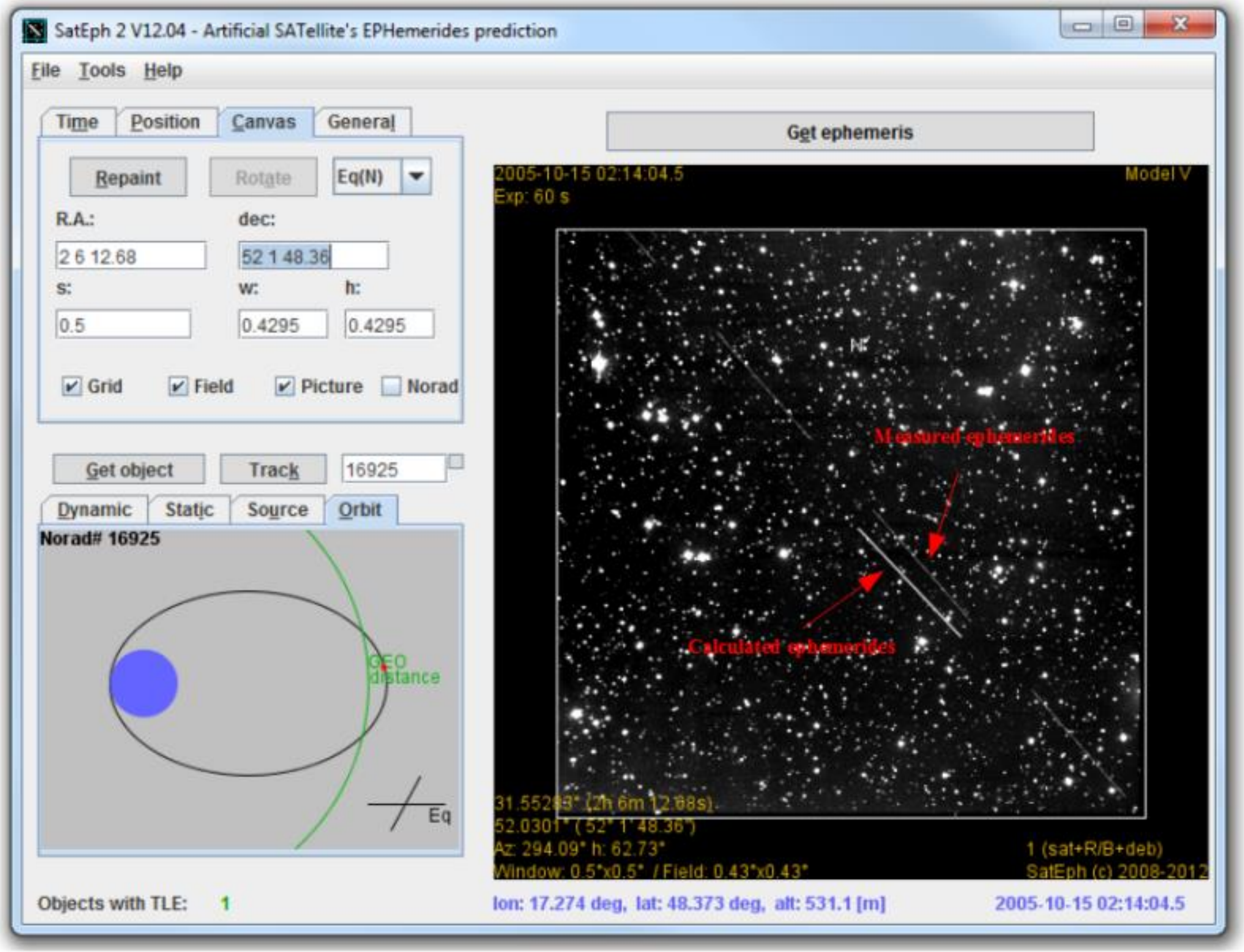


Figure – Visual real time object identification by using SatEph program.

Data conversion, data formats

- Several different data formats:

- Astrometry:
  - MPC (Minor Planet Center) – format for MPEC submission for small solar system bodies such as minor planets, comets, TNOs, etc., also extra-solar system bodies, e.g. hyperbolic comets, asteroid 1I/2017 U1 ('Oumuamua), simple format with metadata and data
  - CCSDS TDM (Tracking Data Message) – used in space surveillance, including ESA, standard still evolving, complex data format with metadata and data
  - AIUB's OBS – internal format used by AIUB, simple format with data only
  - Other formats such as HUN, ISON format, etc.
- Photometry:
  - No common format defined, important to have metadata part and in data part the information such as reference epoch and total intensity must be present
  - Some definition by IADC, AIJ's format, MPC format, FMPI's internal format, etc.

Data products, science products

- As discussed before, the science data products are:

  - **Tracklets** - cataloguing, orbital elements and their evolution, Area-to-Mass Ratio (AMR)
  - **Light curves** – apparent rotation period, change of period, phased light curve shape, amplitude, change of shape over time, change of shape as a function of phase angle
  - **Calibrated brightness** – colors, color indexes, CI change over time, CI function of phased light curve, physical size of the object, albedo, spaceweathering

Image processing tools

Image processing tools

- Distinguished are tools focusing on astrometry and tools with focus on photometry

- Astrometric S/W tools:
  - Astrometrica – commercial standalone S/W, possible to process point like objects only, S/W performs segmentation, star field identification, astrometric reduction
  - Astrometry.net – group of scripts, free of charge, possible to process point like objects only, S/W performs segmentation, star field identification, astrometric reduction
  - Astrometry24.net – webservice currently under validation, possible to process point and streak like objects, S/W performs segmentation, star field identification, astrometric reduction and object identification
  - etc.

- Photometry S/W tools:
  - AstroImageJ – standalone tool, free of charge, performs image reduction, centroiding
  - MaximDL – commercial standalone tool, expensive license, performs image reduction, centroiding
  - IRAF – group of IRAF scripts, free of charge, performs image reduction, centroiding, outdated and not supported, widely used in astronomical community
  - SExtractor – group of Python scripts, free of charge, performs image reduction, centroiding, background estimation and subtraction, etc.
  - stc.

Image processing tools

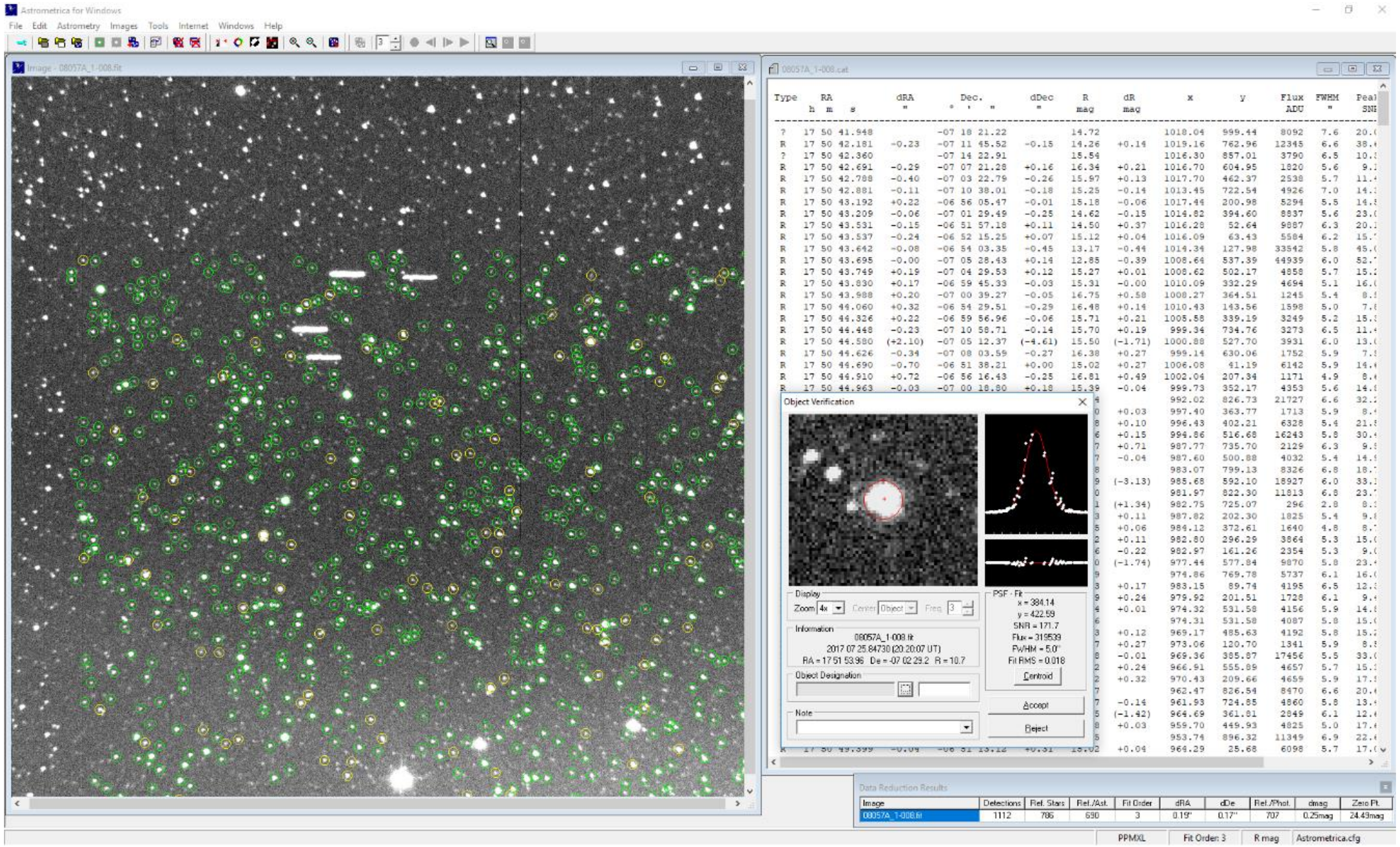


Figure – Screenshot of Astrometrica tool’s GUI. On the left is processed image with marked detected objects. On the left is the list of detected objects along with the extracted information. Plotted image has been acquired by AGO 70 cm with sidereal tracking and used exposure 5 s.

Image processing tools

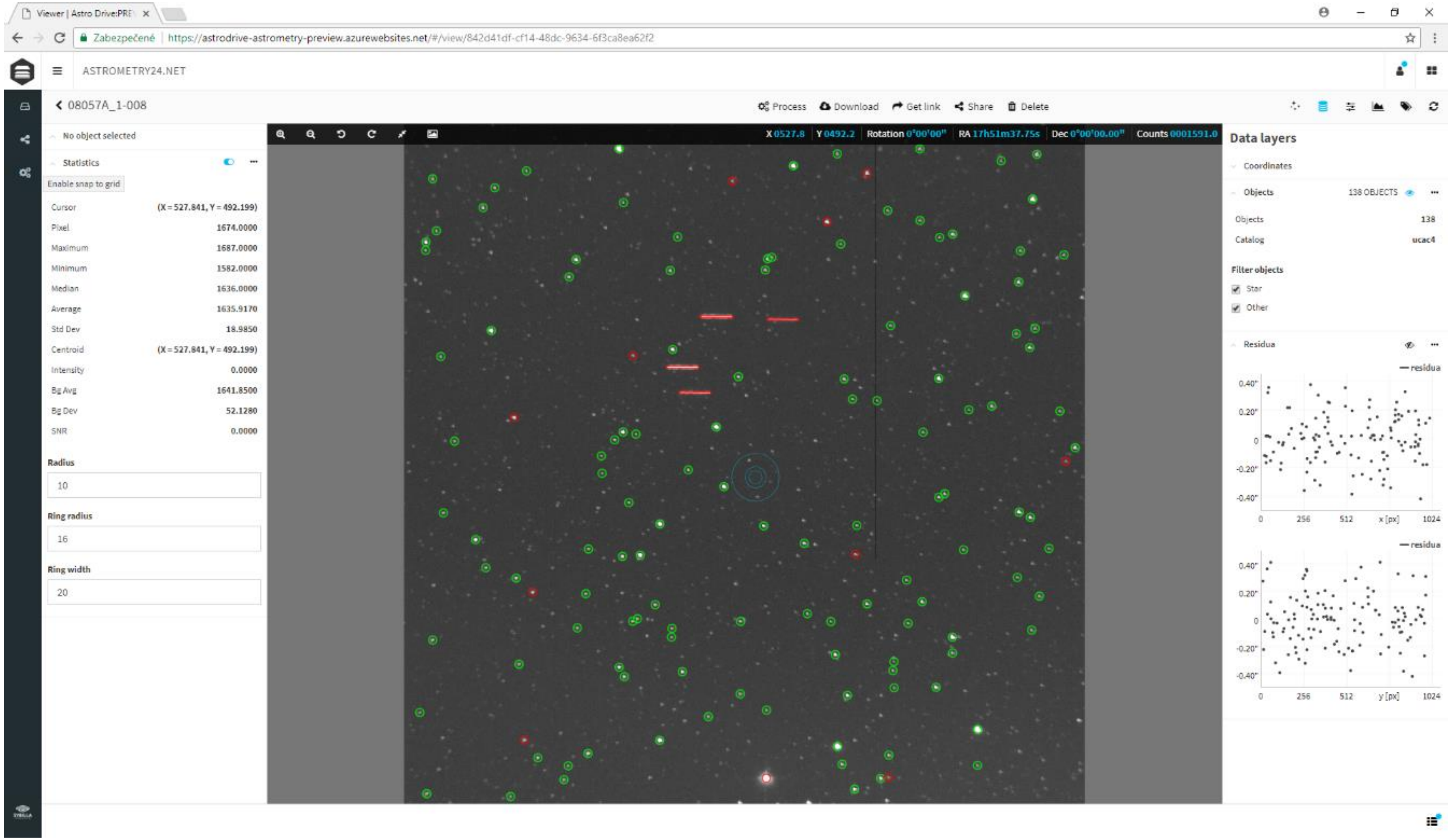


Figure – Screenshot of Astrometry24.net web interface. Plotted image has been acquired by AGO 70 cm with sidereal tracking and used exposure 5 s.

Image processing tools

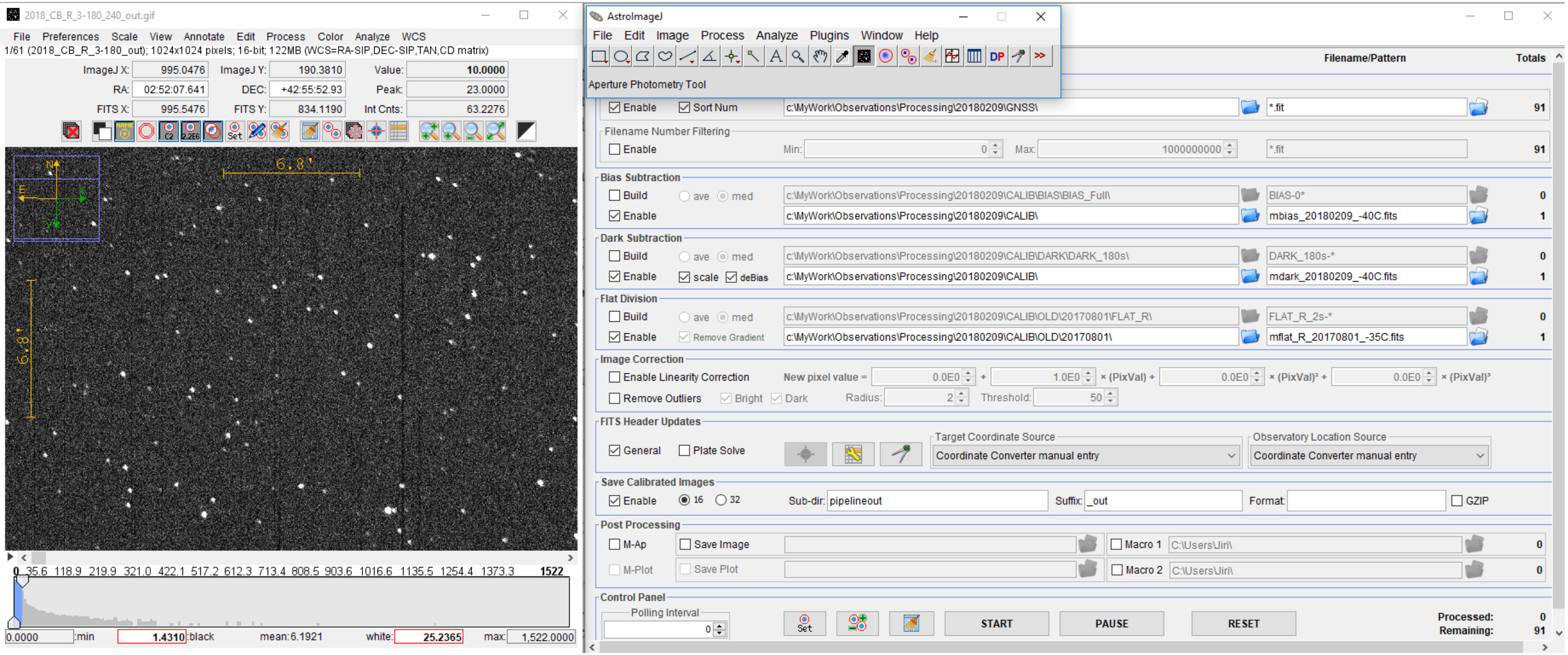


Figure – Screenshot of AstroImageJ S/W.

Projects and internships

Projects

- ESA / ESA PECS:
- Development related to products and telescope pointing and image processing development, astronomy + informatics

- APVV:
  - Primary focus is science

- VEGA:
  - Primary focus is science

Internships

- Erasmus+ (SPA): Student exchange between Slovak/Czech Universities and

- SAIA + AIUB (CHE):
  - up to 6 months, astronomy, space debris, programming, 6 optical telescopes operational

- SAIA + HTG (DEU):
  - Up to 6 months, programming, participation on ESA projects

- SAIA + Others?:
  - IWF (AUT)
  - Cooperation with Russian ISON (RUS)
  - POLSA/Sybilla (POL)
  - NASA (USA)
  - DLR (DEU)
  - …

Summary

Summary

- Department of Astronomy, Physics of the Earth, and Meteorology, Division of Astronomy and Astrophysics operates two types on instruments for space debris research:
  - **AGO 70cm** telescope – photometry, light curves (master thesis, physics), attitude determination and monitoring (master thesis, physics)
  - AGO 70cm telescope (+ 28cm or 60cm) – photometry, colors (master thesis, physics)
  - AGO 70cm telescope – astrometry/image processing (bachelor and master thesis, informatics)
  - Network of **8 AMOS cameras** – survey and photometry, experiment (bachelor + master thesis, physics)
  - Network of **4 AMOS-Spec cameras** – spectroscopy, experiment (bachelor, physics)
- Side projects possible, preparation for bachelor!
- Continuous development, e.g. AGO 70cm LEO tracking, AMOS-Deb network, etc.
- Possibility to cooperate with Astronomical Institute of University of Bern (AIUB) (CH) – 7 different sensors, astrometry, photometry, SLR, image processing, *spectroscopy,* etc.

Summary

Duties for AGO 70cm telescope:

- Observation planning
- Observation acquisition
- Observation processing
- Science data processing
- Publication activity
- Programming

Duties for AMOS/AMOS-Spec:

- Observation post-processing
- Science data processing
- Publication activity
- Programming

vs.

Thank you for your attention.

Questions?

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