The SST-1M gamma-ray mini-array - results of early operations

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Ministry of Education and Science
Université de Genève
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
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State Secretariat for Education, Research and Innovation SERI
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Swiss National Science Foundation
MŠMT
Ministerstvo školství, mládeže a tělovýchovy

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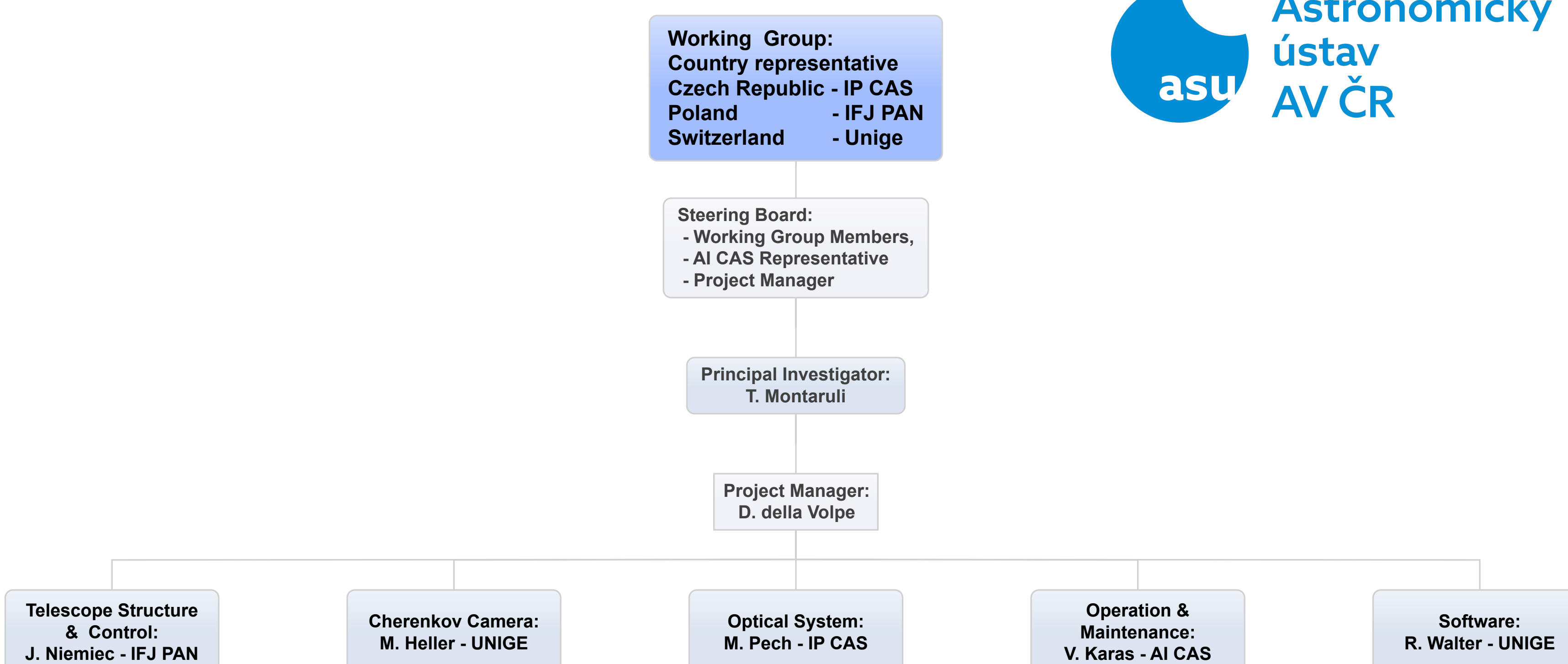
SINGLE-MIRROR SMALL-SIZE TELESCOPE (SST-1M) PROJECT

- Consortium of research institutions from Czech Republic, Poland, and Switzerland
- Operates a mini-array of two IACTs of a Davis-Cotton design
- Initially developed for Cherenkov Telescope Array as prototypes of SSTs; reviewed and satisfied all CTA requirements
- SST-1M telescopes are installed at the Ondrejov Observatory (CZ) for stereo tests and science commissioning

Nicolaus Copernicus Astronomical Center
Centrum Badań Kosmicznych Space Research Centre
The Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences
AGH University of Science
Université de Genève Faculté des Sciences
ISDC Data Centre for Astrophysics
Jagiellonian University in Krakow
FZU Fyzikální ústav Akademie věd České republiky
Uniwersytet Warszawski
asu Astronomický ústav AV ČR
Palacký University Olomouc



SST-1M Telescope Highlights

Optical properties	*Focal Length*	5600 ± 5 mm
	f/D	1.4
	Dish diameter	4 m
	Mirror Area (*)	9.42 m^2
	Mirror Effective Area(*)	6.47 m^2
	Hexagonal Mirror facets	780 ± 3 mm
	Preliminary on-axis PSF real optical parameters	0.07°
	PSF (80% of FoV@ 4° off-axis)(**)	0.21°
Camera Characteristics	*Camera (depth x width)*	70 cm x 90 cm
	Total pixel number	1296
	Pixel linear size	23.2 mm
	Pixel angular size	0.24°
	FoV	9.1°
	Photosensors PDE	> 30%
	Sampling frequency	250 MHz
	Readout rate	0.6-1 kHz
	Time Spread RMS	< 0.25 ns

- Davies-Cotton proven optical design
  - Innovative SiPM-based camera
  - Digital electronics with fully digital trigger and readout architecture
  - Fully programmable
  - Highly performing large-area SiPMs with dedicated slow control
- Low Cost
- Lightweight (~ 8.6 t) and compact structure; drive system and control software harmonised with Medium-size Telescopes of CTA
- Optimized for gamma-ray sensitivity above 500 GeV in stereo mode
- Designed for fully robotic operation with minimal maintenance in harsh environment

TELESCOPE DESIGN DRIVER

Conditions:

Dish = 4 m

FoV > 8°

f/D = 1.4

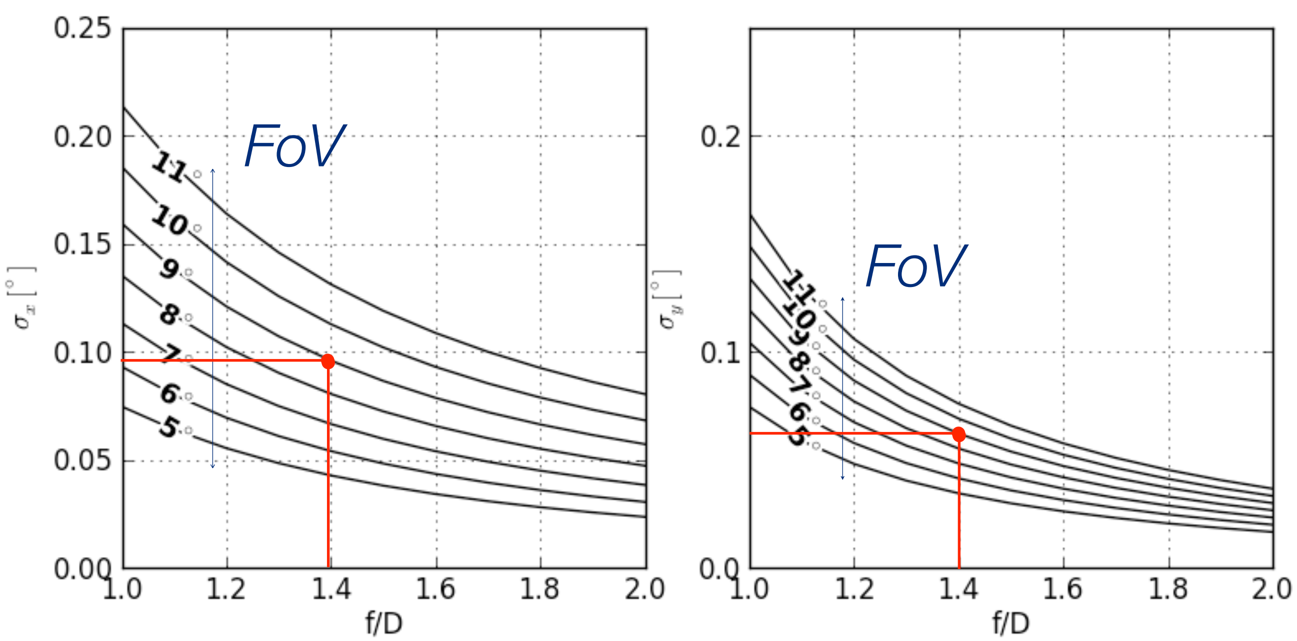
Pixel size = 4· min(σ_x, σ_y) = 0.25°

Camera size (D_c) = 88 cm

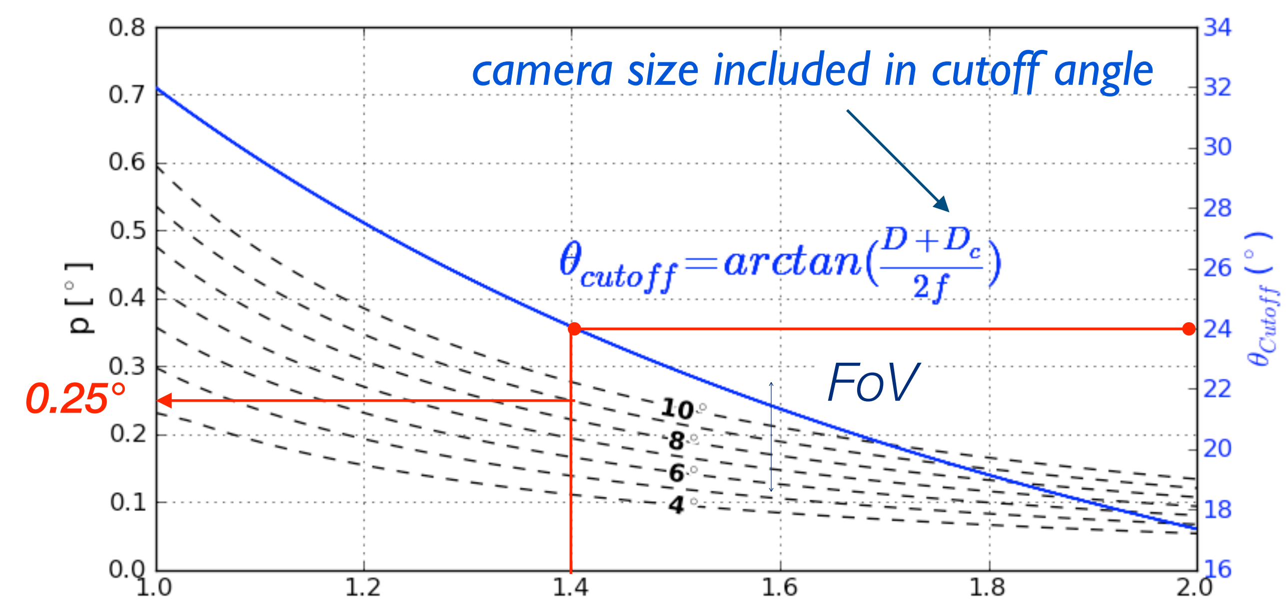
Pixel size (linear) = 2.44 cm

n_p = 1296 pixels

Too big for a SiPM.
A light funnel needed



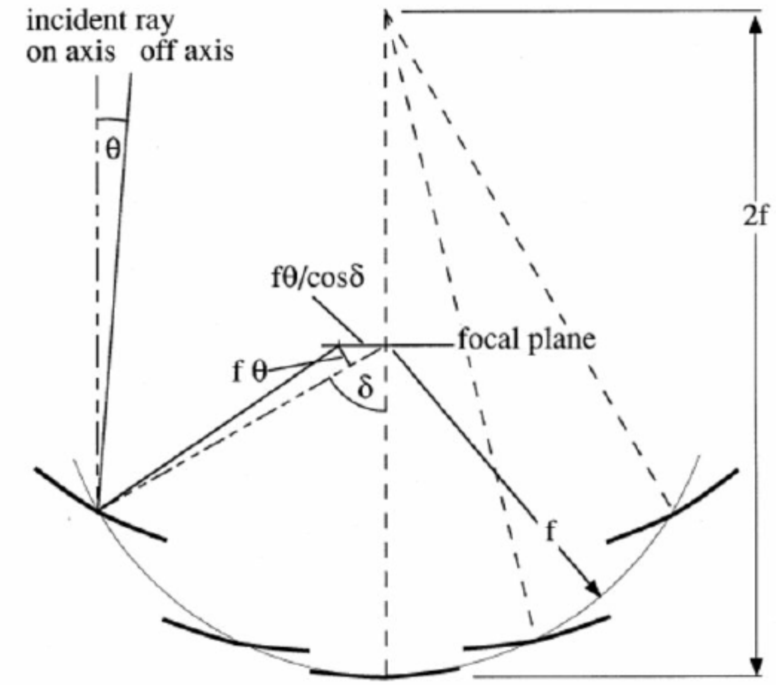
Vassiliev et al. [arXiv:astro-ph/0612718v2]



TELESCOPE STRUCTURE

- Robust steel mechanical structure that can sustain forces and torques as generated by strong winds and earthquakes
- Stand-alone control cabinets
- Cables/cooling pipes/fibers routed almost entirely inside telescope mast and tower
- Integrated cooling system for control cabinet and camera

TELESCOPE OPTICS



Davies-Cotton design principle

Telescope dish

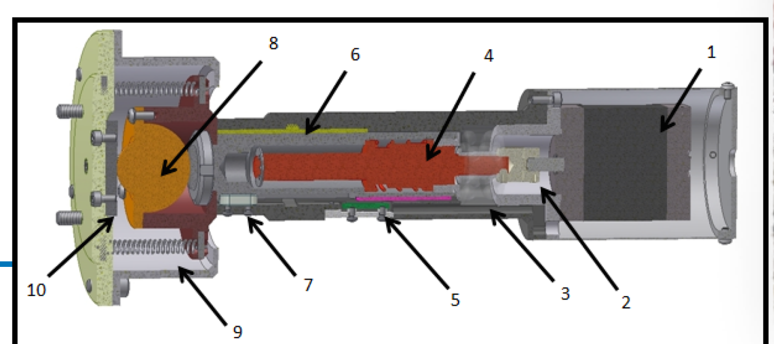
- Segmented mirror dish with D=4 m and flat detector surface
- Focal length F=5,6 m; F/D=1.4
- Enable low signal time spread < 1.5 ns
- Total reflective area: 9.4 m^2
- Effective mirror area (without shadowing): 7.6 m^2
- Wide FOV (9.1°) with small PSF (<0.25°, <0.1° on axis)

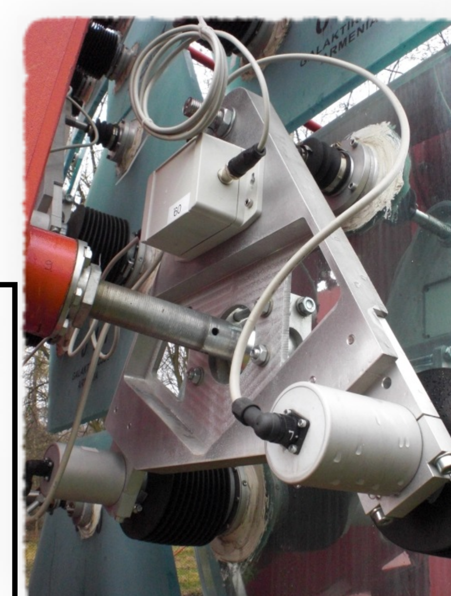
Mirrors

- 18 spherical mirrors with RoC=11.2 m
- Hexagonal 780 mm flat-to-flat, thickness 12-14 mm
- Mirror reflectance > 85% @ 300-550 nm
- Borosilicate glass substrate (DOTI + Jointlab, CZ)
- Al + SiO_2 composite coating (Jointlab, CZ)

Actuators

- Designed and produced at SRC, PL
- Wireless communication

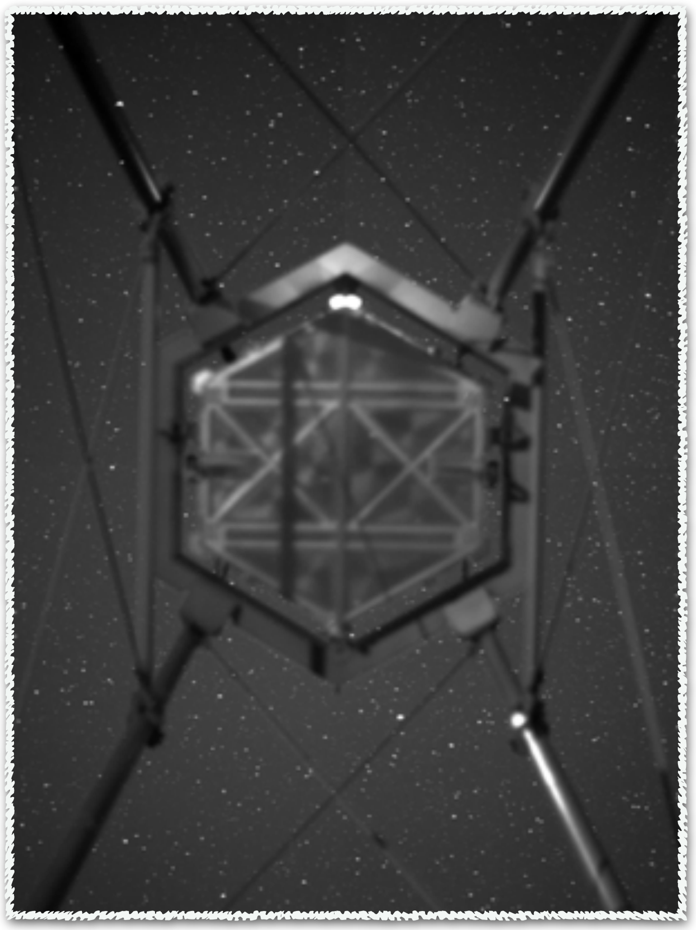




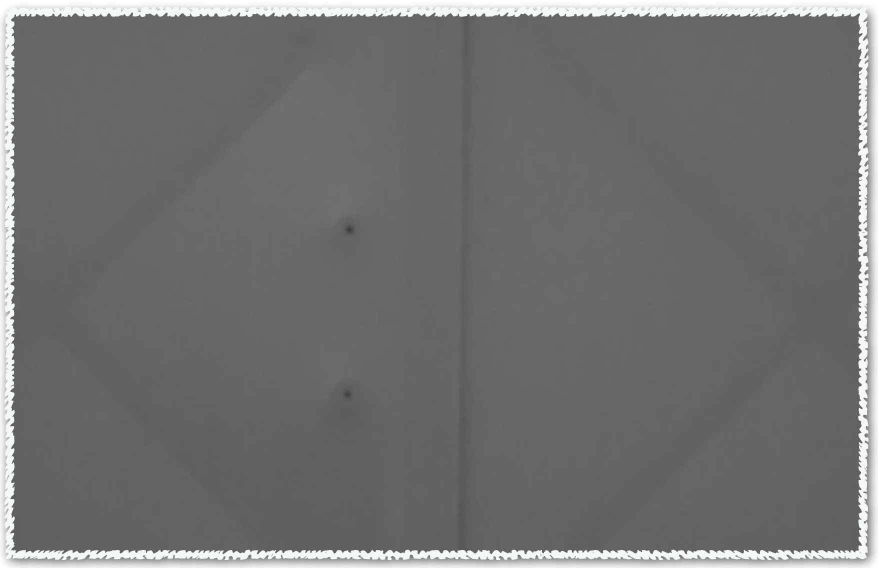
TELESCOPE ALIGNMENT AND POINTING

- Alignment and pointing systems based on LID and Sky CCDs on the same support structure to ensure relative alignment
- 3-step alignment (2F and Bokeh pre-align., fine alignment with dedicated PSF screen)
- Star projection pointing

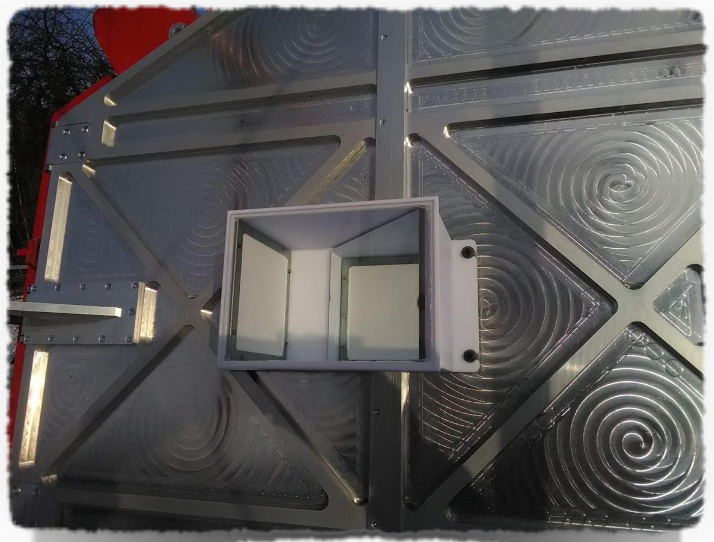
LID and Sky CCDs in the middle of telescope dish



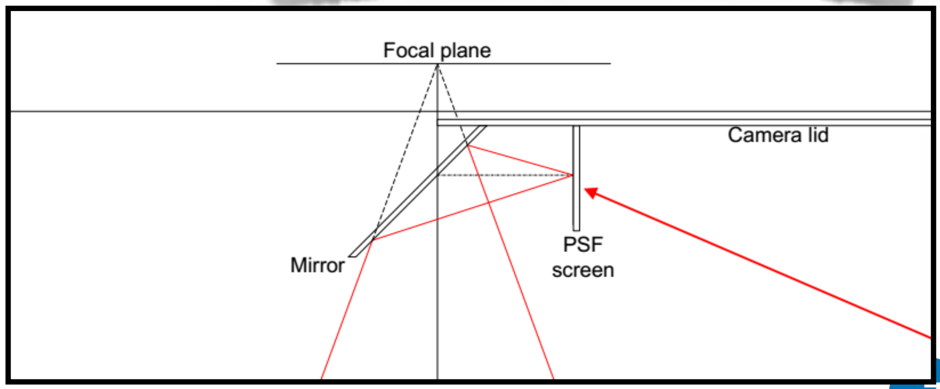
Sky CCD view



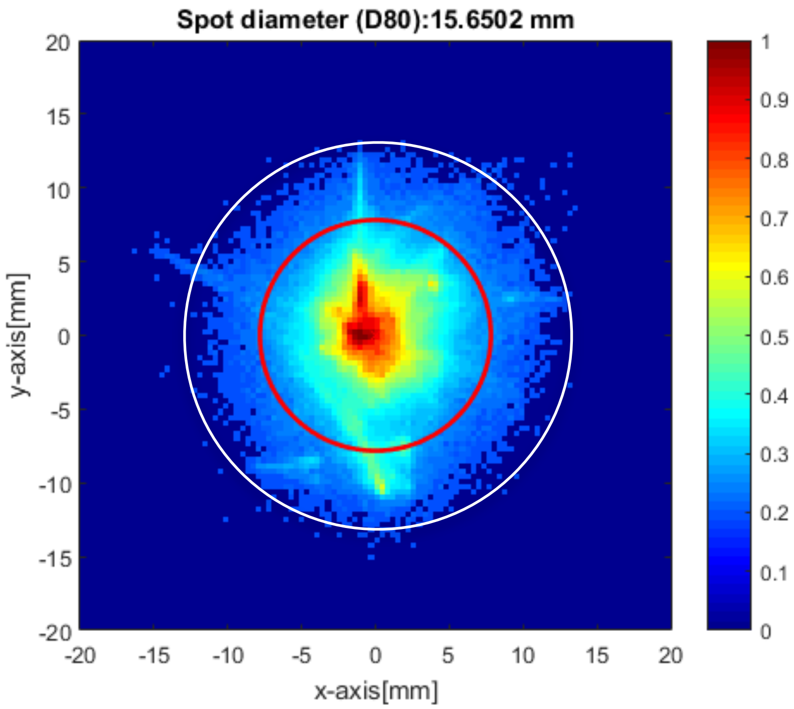
LID CCD view



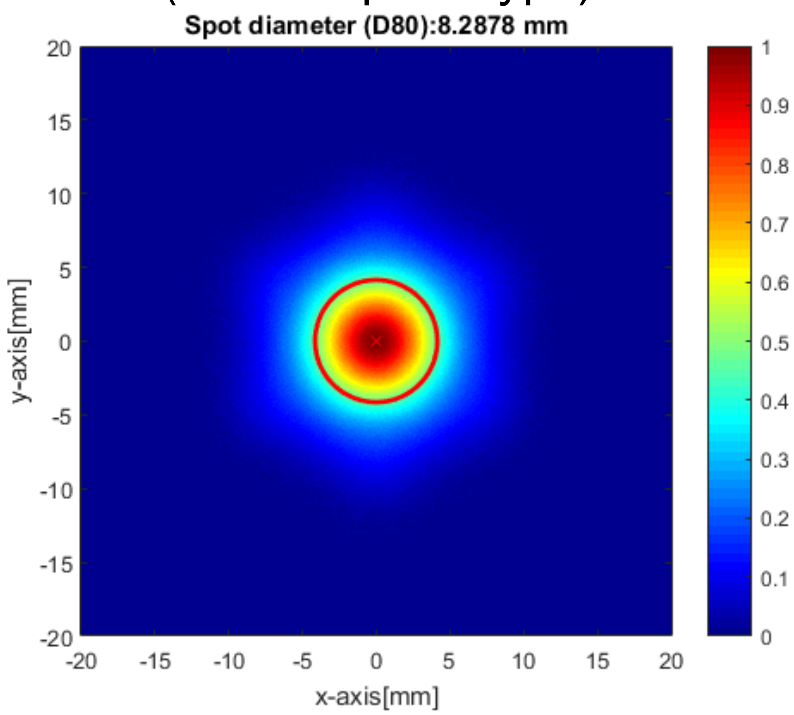
PSF screen



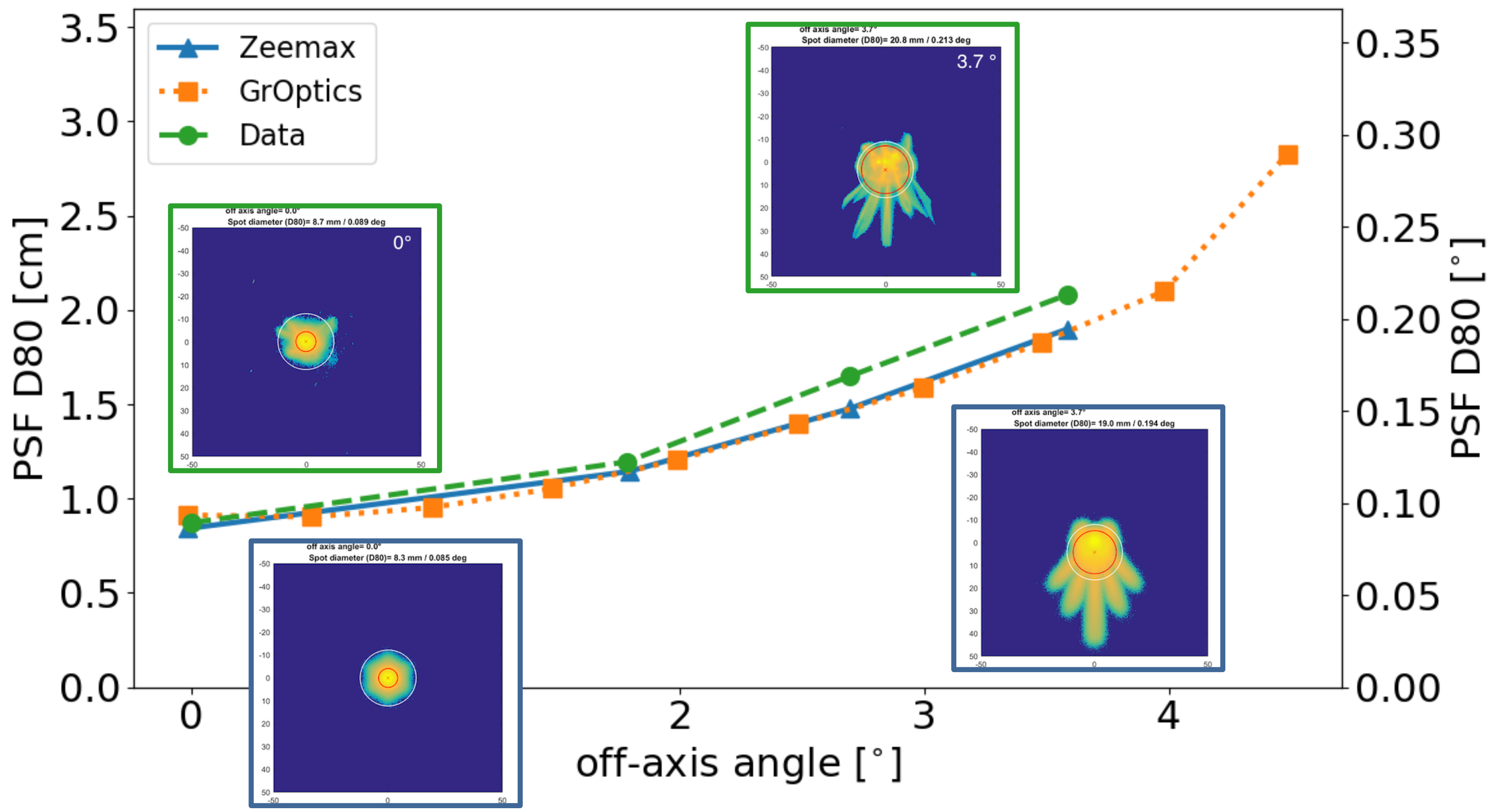
TELESCOPE PSF AFTER FINE ALIGNMENT



Measured telescope PSF
(Krakow prototype)



Simulated telescope PSF
with actual mirror parameters



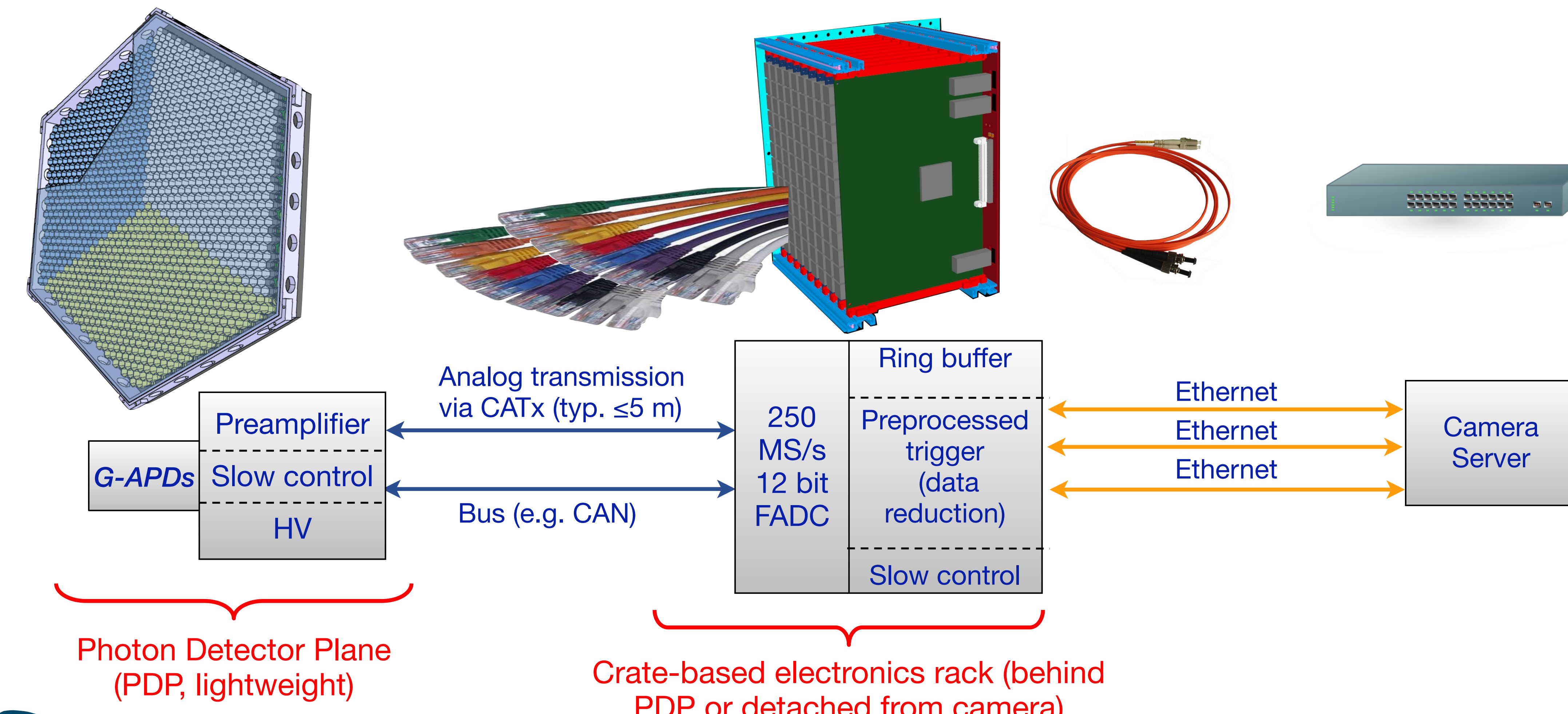
Comparison between data and simulation for the telescope PSF vs. off-axis angle

D_{80} = diameter containing 80% of total light

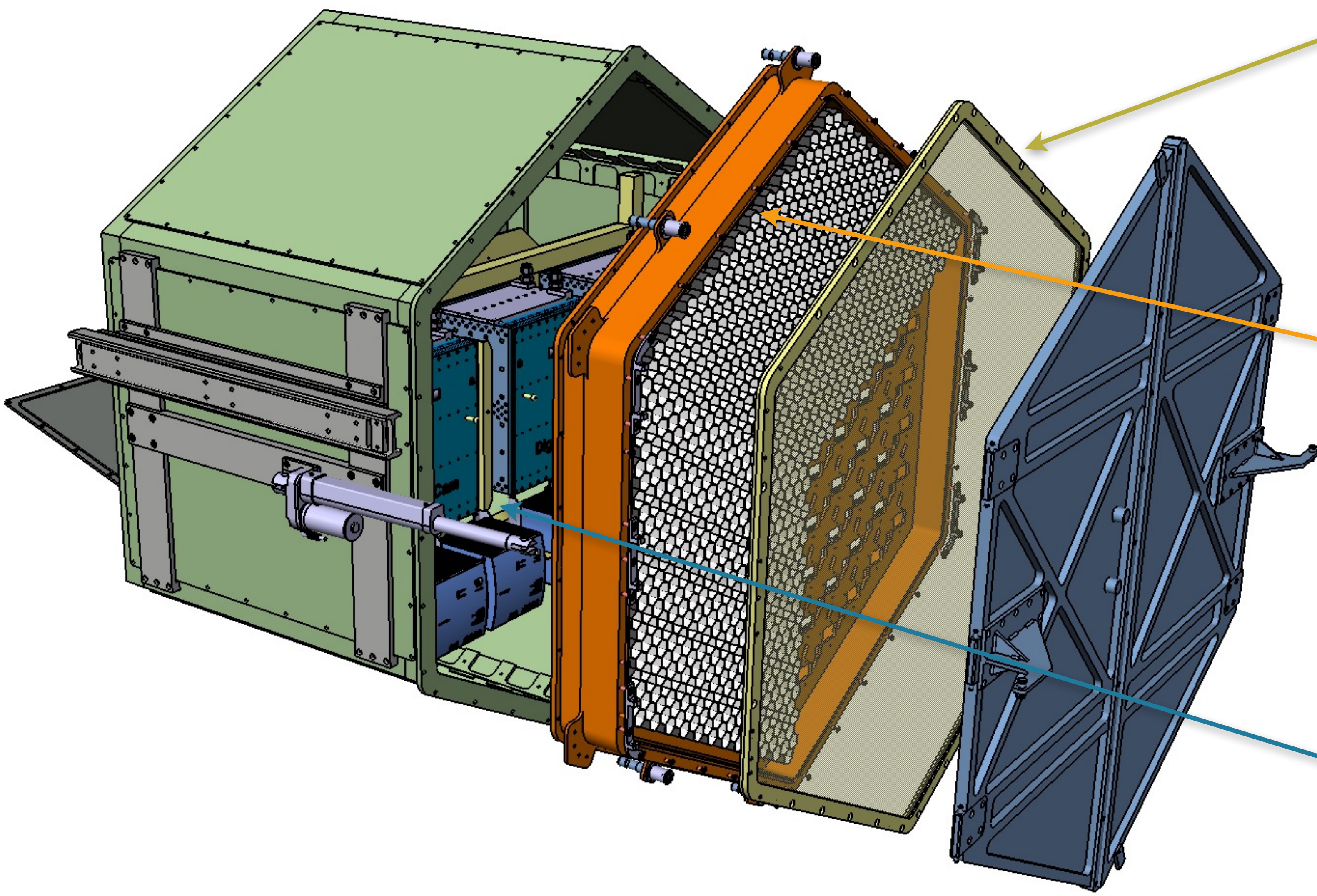
- Required D_{80} = 24.43 mm

SST-1M Camera concept

- New approach: use GAPD-based camera on a Davies-Cotton telescope.
  - Operation during Moonlight: ~30% larger duty cycle
  - Excellent single PE sensitivity
  - High Photo Detection Efficiency (Currently >35%)
- Fully Digital readout electronics
- Fully digital trigger path with reconfigurable algorithms and signal preprocessing
- Compact, robust, lightweight and self-contained – perfect for SST-1M telescope



SST-1M Camera

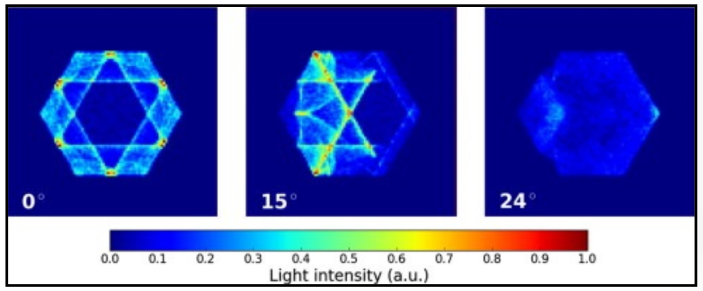


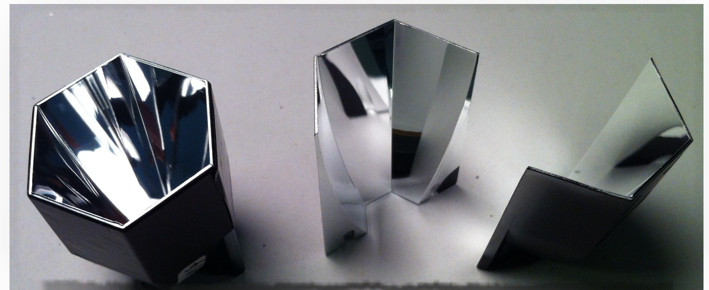
Entrance window:
- 3.3 mm Borofloat
- AR coating
- Cut-off filter at 540 nm for NSB rejection

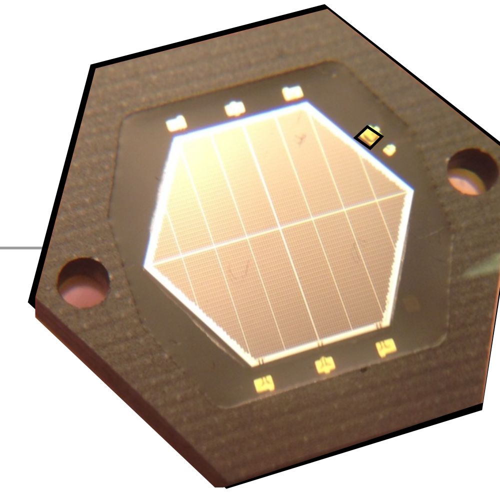
Photo detection plane:
- 1296 pixels
- 0.24° angular size
- Power consumption 500 W

Digital electronics (DigiCam):
- 12 bits FADC @ 250 MS/s
- Fully digital trigger
- 1 trigger decision every 4 ns
- Power consumption 1200 W

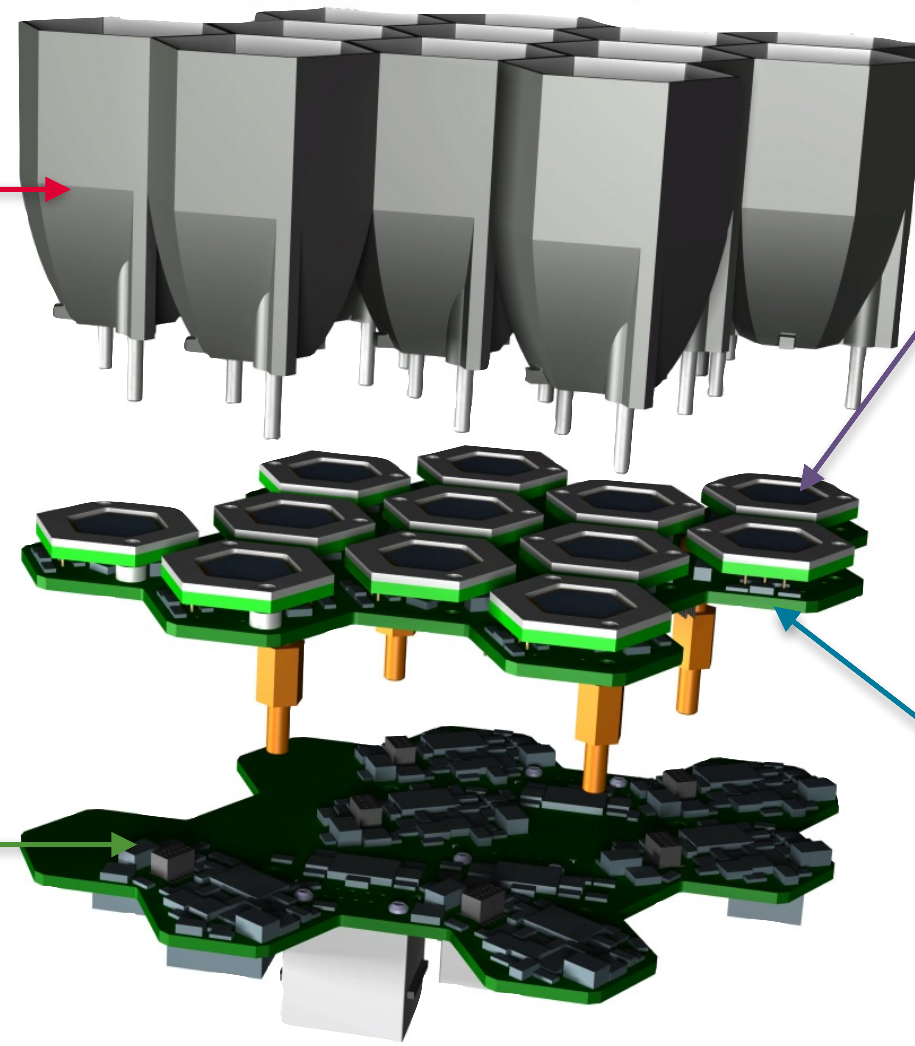
PHOTO DETECTION PLANE (PDP)







Hollow light guides:
- Plastic substrate
- AlSiO2 coating
- Cut-off at 24°
- 2.32 cm linear size
- Compression factor of 6



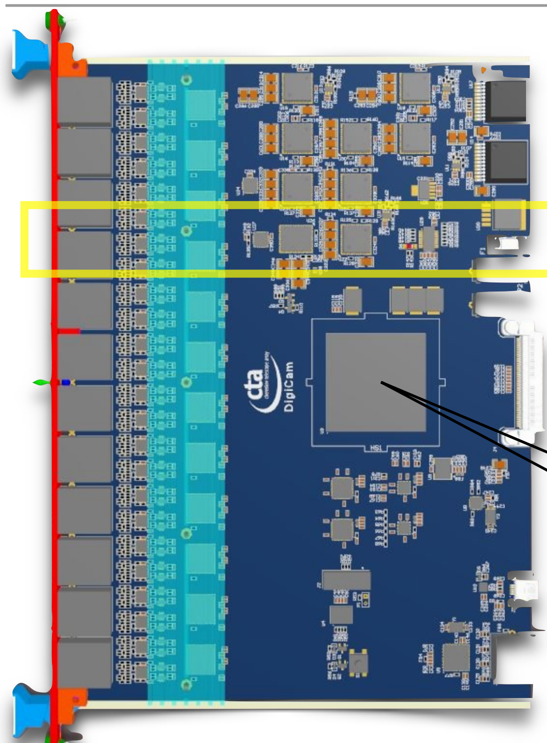
Sensor:
- Custom hexagonal Hamamatsu MPPC
- 4 anodes per pixel with one common cathode
- Embedded NTC temperature sensor

Slow control board:
- Temperature compensation loop (2 Hz)
- HV generation
- Differential output to DigiCam

Preamplifier board:
- Discrete components
- Trans-impedance topology
- 2 operational amplifiers per sensor to reduce pulse length
- DC coupling

DIGICAM CAMERA/TRIGGER TOPOLOGY

1 μ-crate per sector, 3 per camera

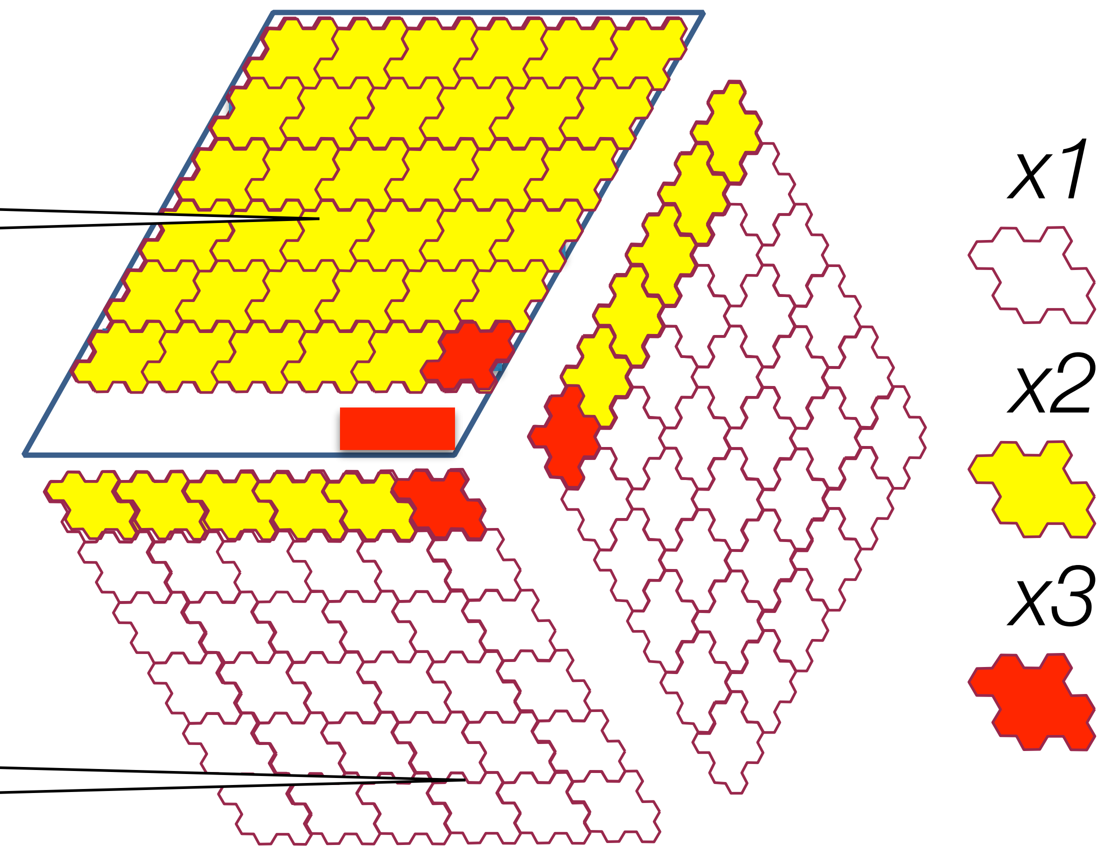


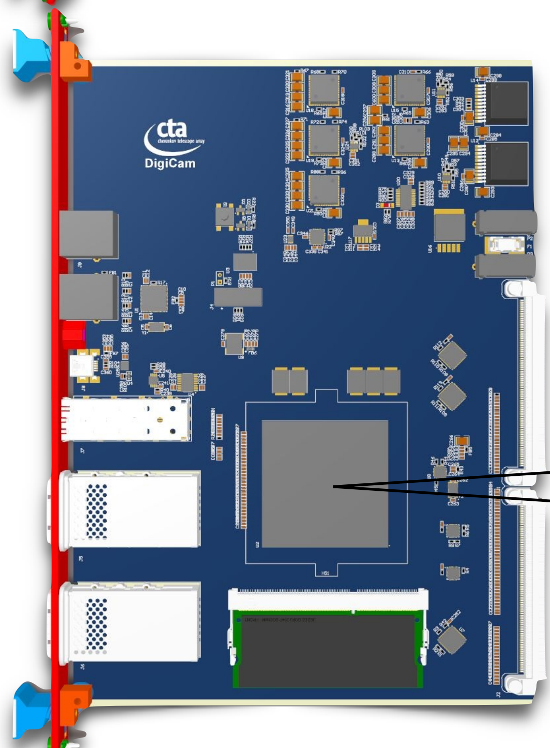
9 FADC Cards/μCrate
- 48 channels
- 12 bit FADC 250 MS/s
- Ring Buffers
- Preprocessed trigger
- Slow control

Xilinx Virtex 7

48 RX @ 4Gbit/s

4 TX @ 8Gbit/s





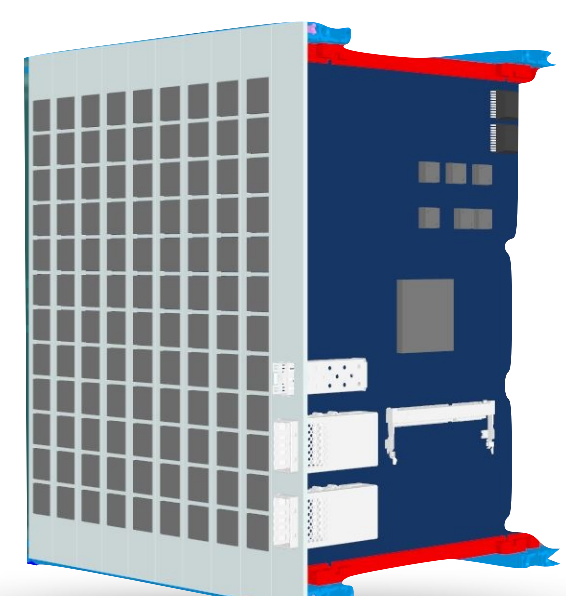
1 Trigger Card/μCrate
- Main Trigger
- Data Readout

Xilinx Virtex 7

48 RX @ 8Gbit/s

12 TX @ 8Gbit/s

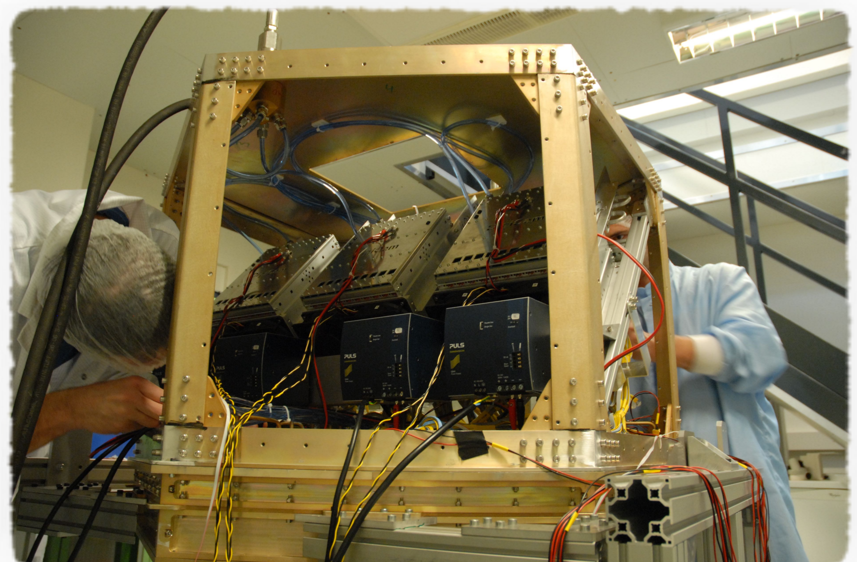
1 TRX @ 10.3Gbit/s

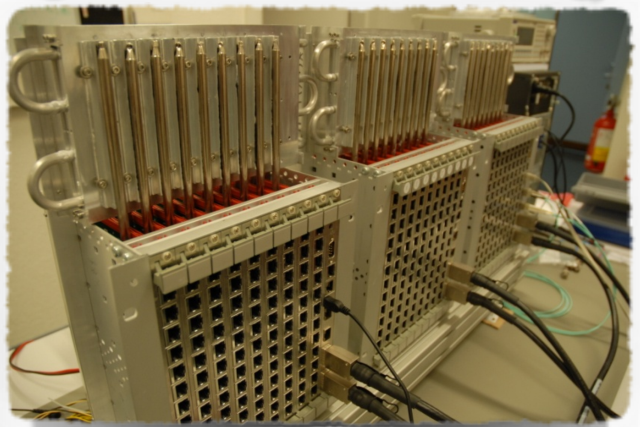


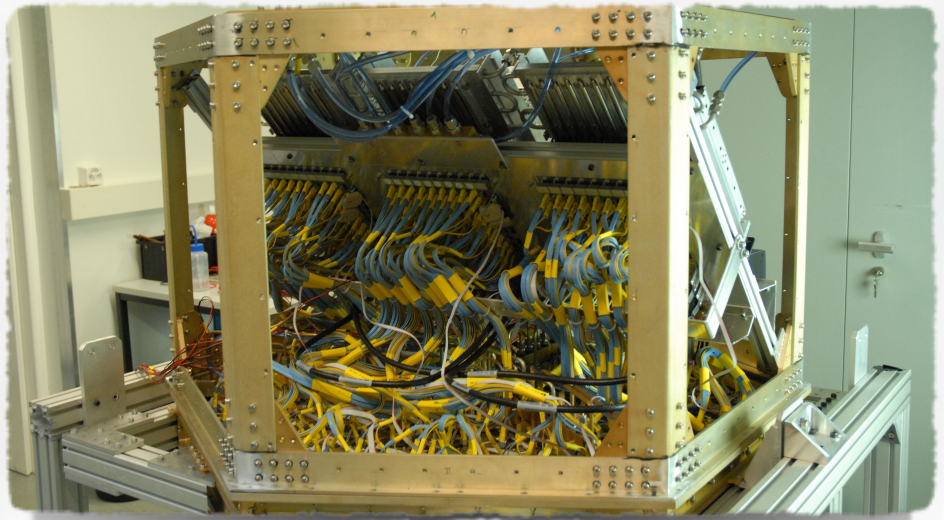
μ-Crate
10 slots

SST-1M CAMERAS

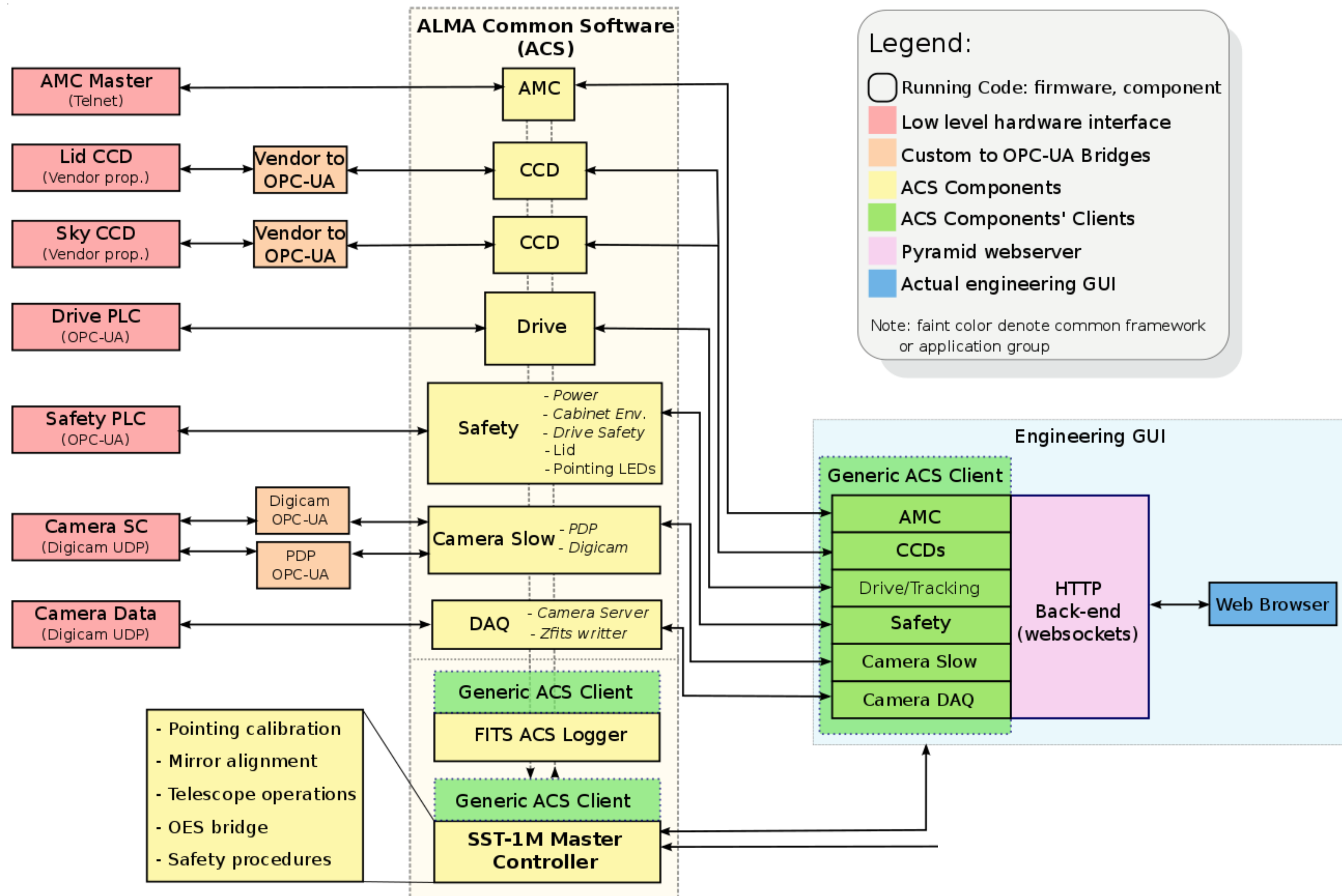
- Two cameras built, tested, and commissioned on the telescopes
- Design of the camera PDP, cooling system, and mechanics updated on the second prototype





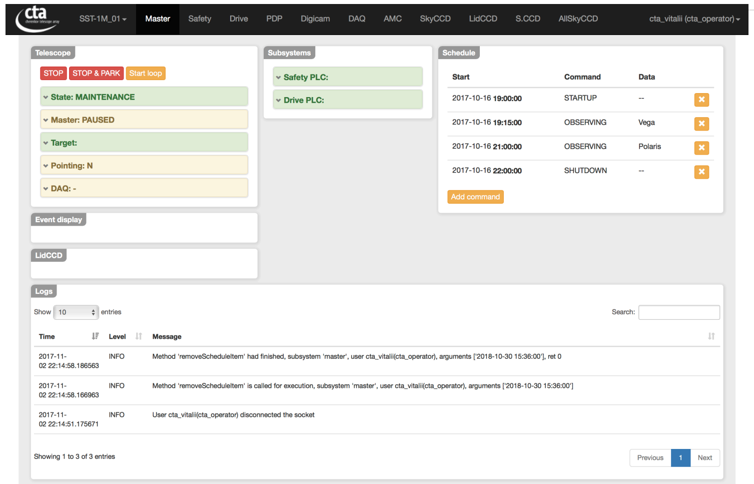


TELESCOPE CONTROL CONCEPT

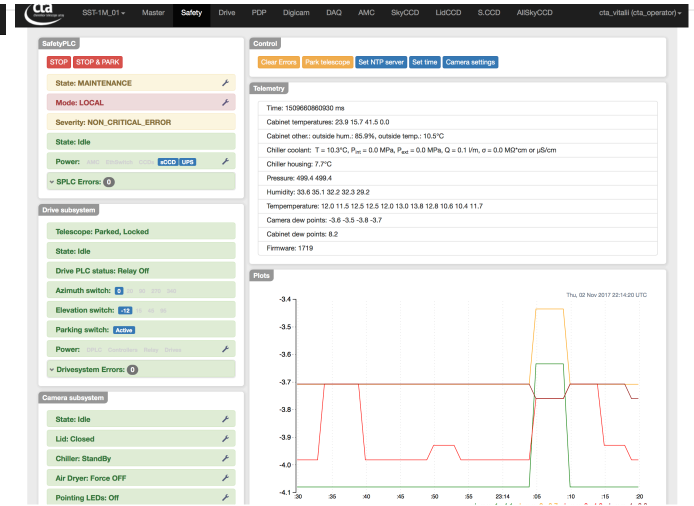


- Telescope control software is build around ALMA Common Software (ACS)
  - Each subsystem is represented by an ACS component connected via OPC UA to the hardware
  - Auxiliary services, e.g. FITSLogger, are also running as ACS components
- Web-based engineering GUI (eGUI) is used to connect, monitor and send commands to the ACS components

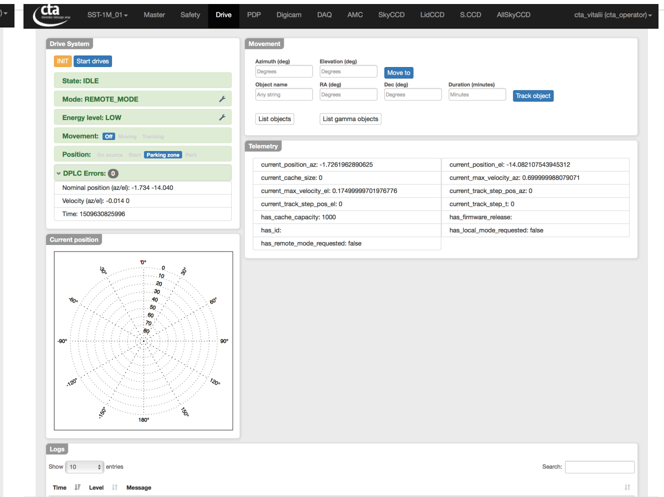
Engineering GUI - Full Control of Telescopes



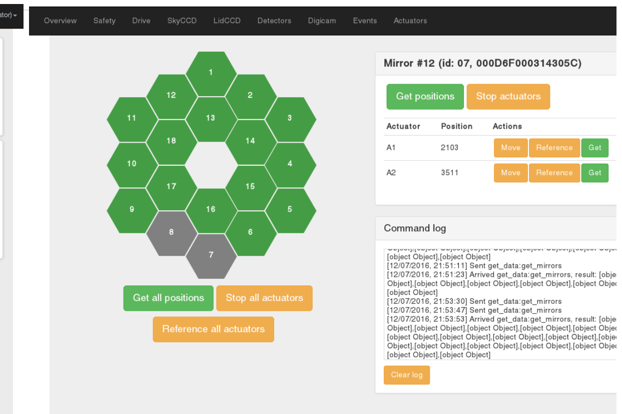
SST-1M master controller



Safety PLC subsystem



Drive system control



Active mirror control

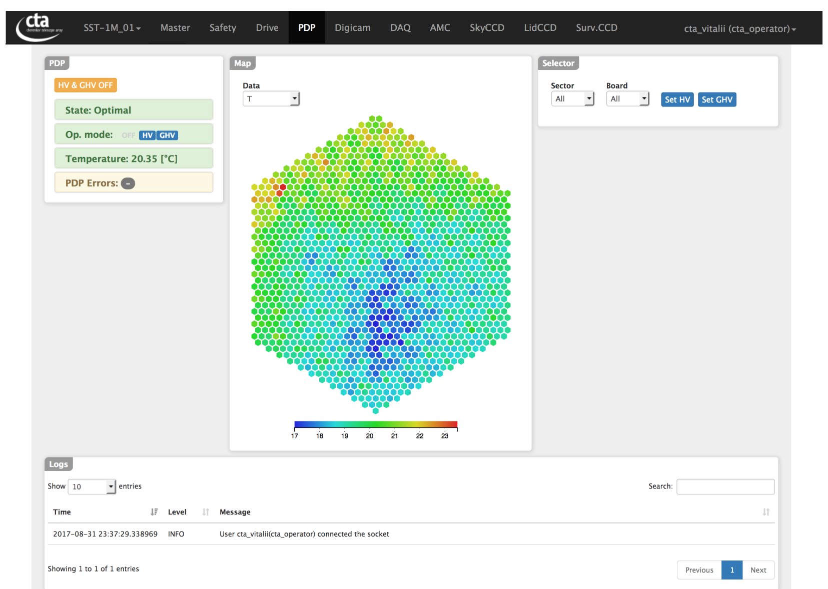
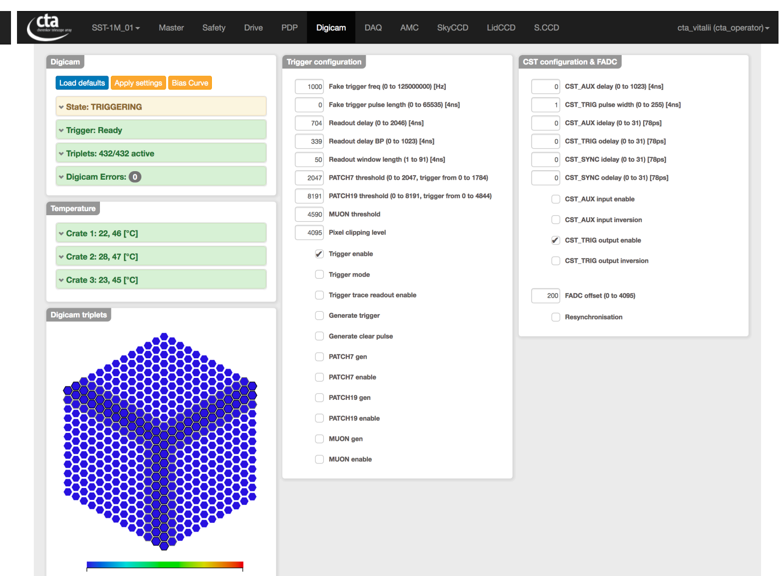
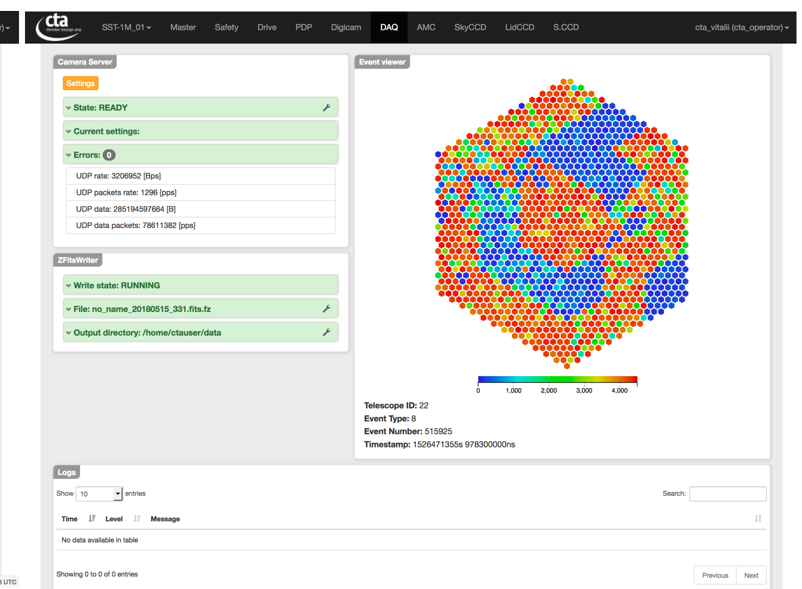


Photo detector plane



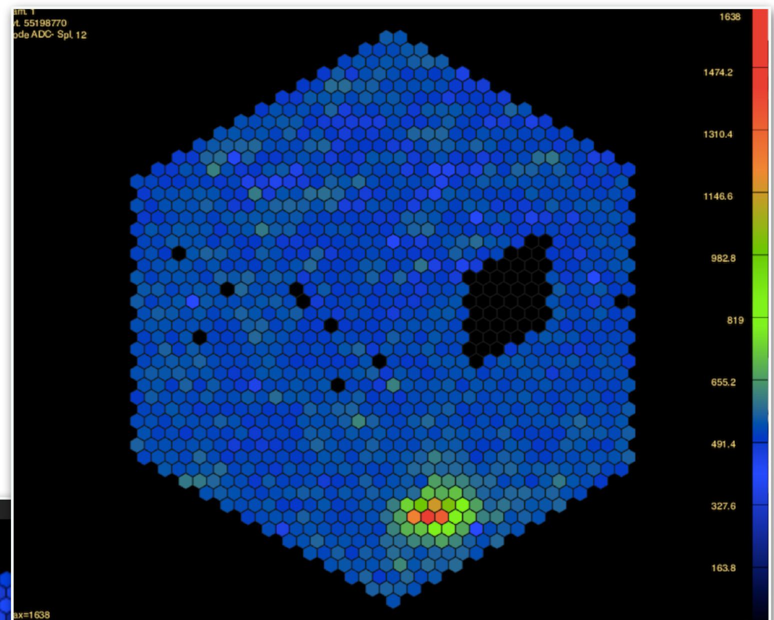
Digicam configuration and trigger view



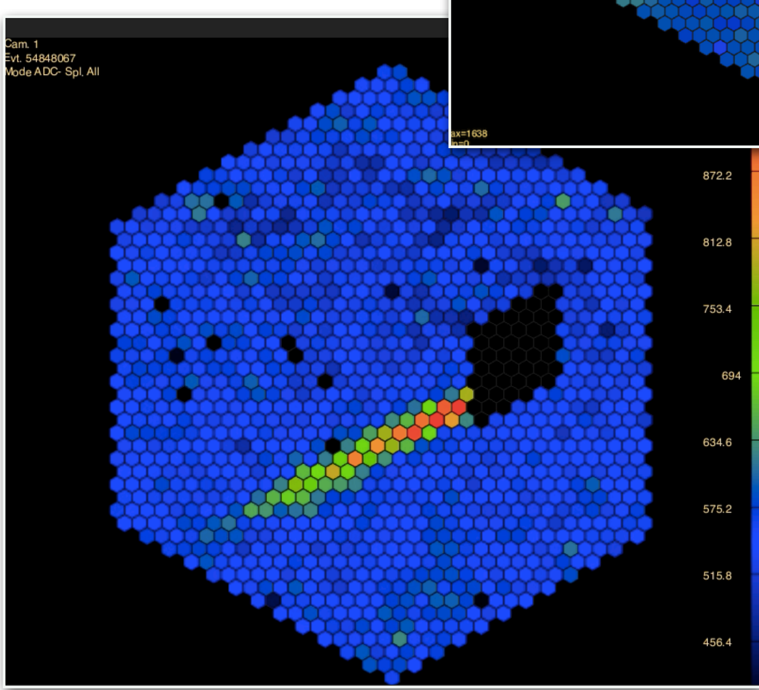
DAQ control and monitoring

MAJOR MILESTONES - 1

- First telescope structure assembled in October 2013 at the test site at IFJ PAN in Krakow; official inauguration in June 2014
- First camera installed in Krakow in August 2017; first commissioning campaign then started
- First light in September 2017



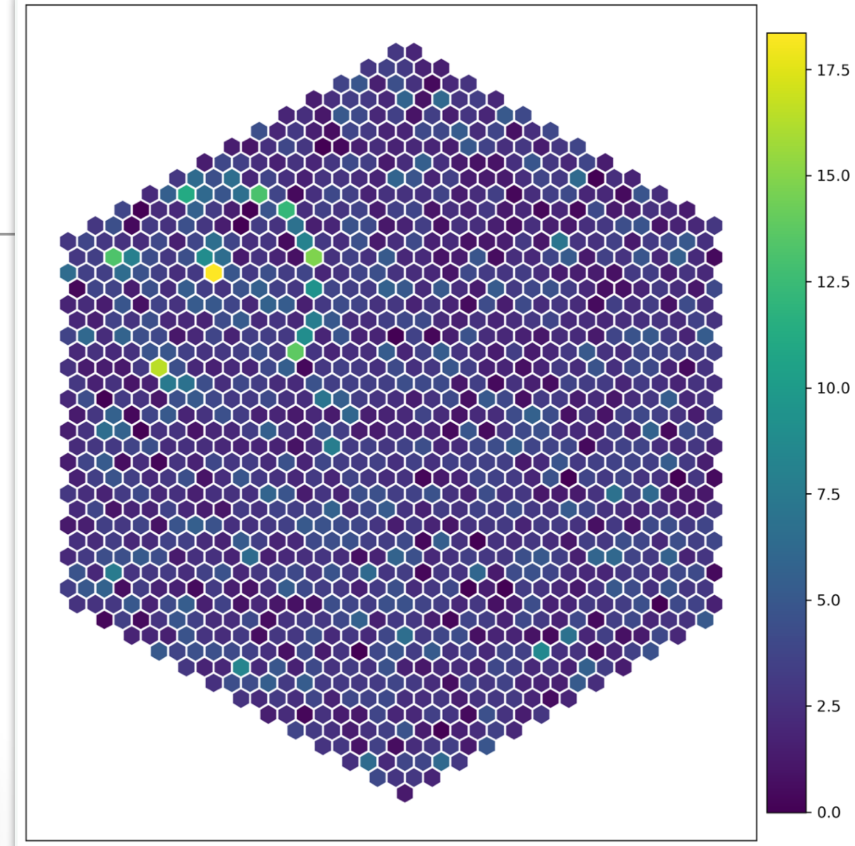
proton shower



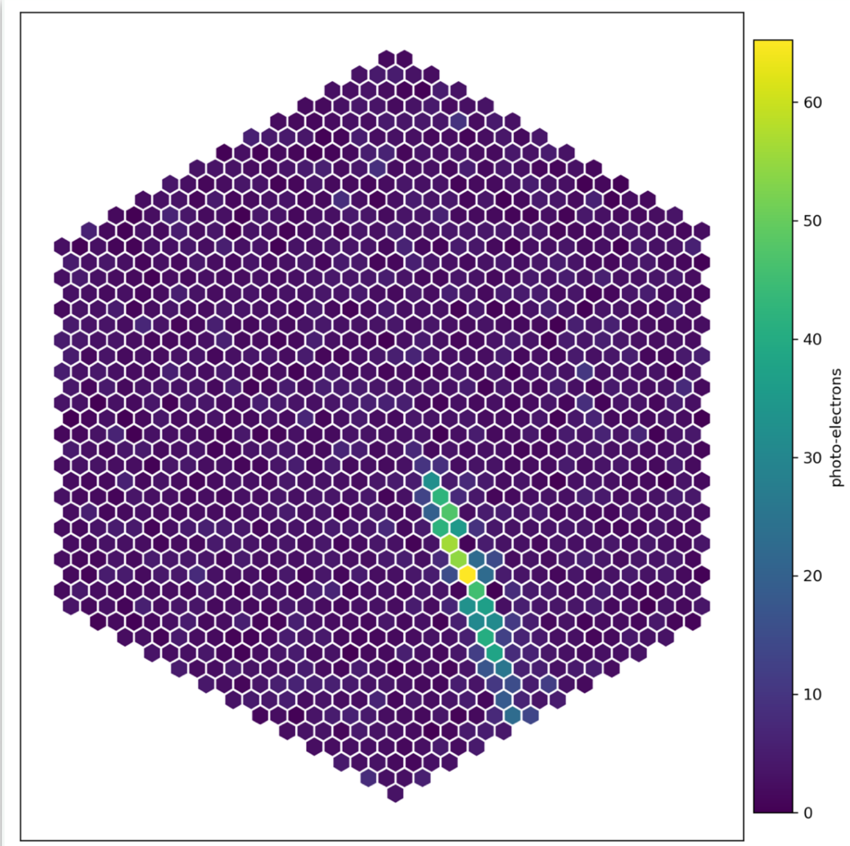
gamma-ray shower

MAJOR MILESTONES - 2

- Second telescope built in 2018-2021
- Two-telescope mini-array installed in the Ondrejov Observatory near Prague in Czech Republic in 2021
- First light with the new camera in February 2022
- First light with two telescopes observing the same source in April 2022 (stereo-like observations)



muon shower



gamma-ray shower

Current Status

- Commissioning and validation of telescopes together with regular data taking with two telescopes in mono-mode (stereo-like observations)
- Fully automatic operations - observations can already be taken by a single shifter
- Telescope optics after fine alignment; work on the bending model and the pointing system ongoing
- Master Telescope Control in preparation; stereo observations will start soon after White Rabbit-based synchronisation HW installed in early September; will allow fully automatic data taking during upcoming observational campaigns
- Monte Carlo production; Data-MC comparisons encouraging - simulated trigger rates and Hillas parameters compatible with data
- Update on the data analysis chain ongoing - implementation of the CTA data model with ctapipe, lstchain code for event reconstruction and gammapy for higher-level analysis

Summary and Future Prospects

- SST-1M Project operates a mini-array of two modern highly performant IACTs of Davis-Cotton design that host cutting-edge cameras with SiPMs and fully digital trigger and data readout electronics
- Telescopes are installed at the Ondrejov Observatory for stereo tests and science commissioning
- Telescopes can be fully operated remotely
- Observing campaigns will continue to monitor the Crab Nebula for calibration and bright blazar sources at energies above 500 GeV
- Large field-of-view of telescopes enables also surveys of large portions of the sky and observe extended sources
- Digital camera enables an easy implementation of the Stellar Intensity Interferometry