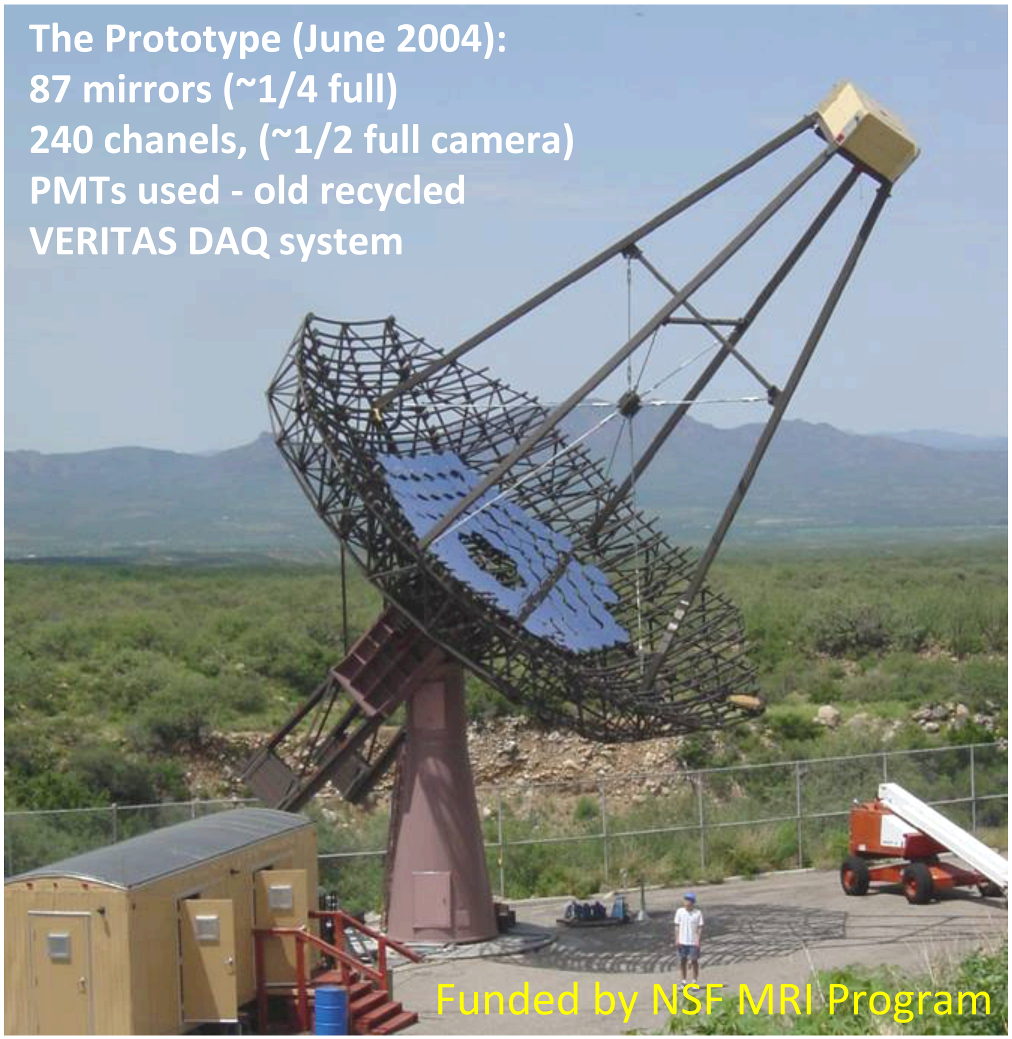
Schwarzschild-Couder telescope for ground-based gamma-ray astronomy

A replay of the most significant moments

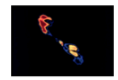
By
Vladimir Vassiliev
University of California Los Angeles

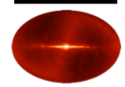
THE ORIGINS

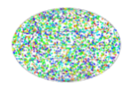
Prototype VERITAS Telescope

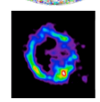


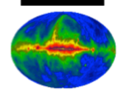
Science with VERITAS

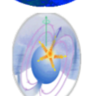
 Active Galactic Nuclei

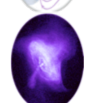
 Extragalactic Background Light

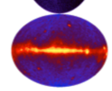
 Gamma Ray Bursts

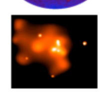
 Shell-type Supernova Remnants

 Galactic Diffuse Emission

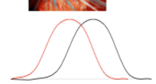
 Gamma-ray Pulsars

 Plerions

 Unidentified Sources

 Dark Matter (Neutralino Annihilation)

 Cosmic Ray Origin

 Lorentz symmetry violation

James Smithson and VERITAS

The meeting place cannot be changed…

1765-1829

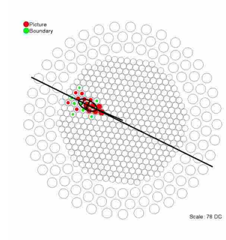
"And now... my mission is ended and I deliver into your hands ... the remains of this great benefactor of the United States." Alexander Graham Bell, 1904

Difficult times before 2004.
SAGENAP Review, Washington DC, 2004

Much was discussed about the trade offs between pixels size, field of view, telescope aperture, number of telescopes etc. to optimize VERUITAS through simulations and fit the budget.

What is the right pixel size?

Whipple 10M



Prototype VERITAS Telescope

Referring to J. Finley talk: “you have to learn this mistake twice”… trice

Perhaps the most critical decision for VERITAS

The Basecamp Four
Telescope Alternative

An
Unattractive but Possible
Temporary Option

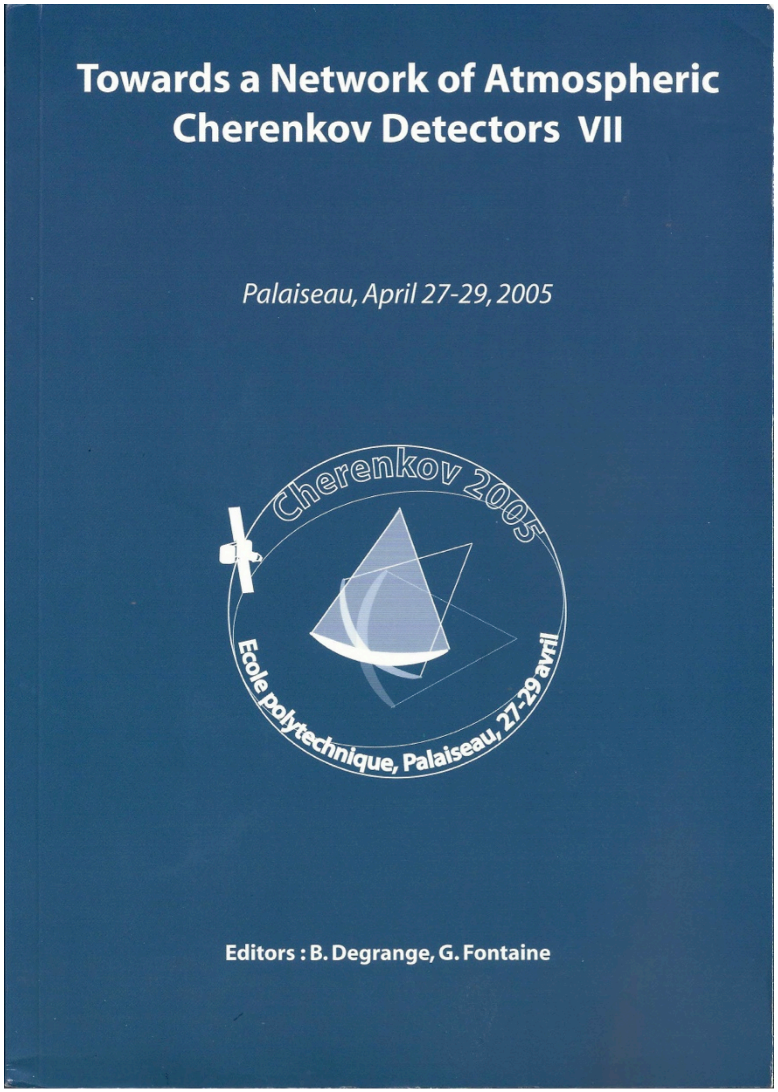
Timescale

- If we were to agree to proceed with this unattractive option, then we should do so ASAP. The value of this option decreases with time.
- Is there any other option whereby we can guarantee that VERITAS can achieve its scientific goals and be completed within the budget and on schedule?

VERITAS was delivered on budget, on schedule, and its scientific program has demonstrated tremendous success during last 10 years and will continue to do so for years to come.

Yet VERITAS project evolution and experience we gained with it, has started our quest for "What is Beyond VERITAS?"

Large IACT arrays: The Origins



Multitudes of ideas, which collectively contributed to the foundation of CTA.

Session 4: The future of ground-based VHE astronomy

- The next generation of IACT arrays *F. Aharonian*
- MAGIC-II *M. Teshima*
- Performance Limits for Cherenkov Instruments *W. Hofmann*
- High Energy All Sky Transient Radiation Observatory (HE-ASTRO) V. *Vassiliev and S. Fegan*
- …

Session 5: Developments in instrumentation for Cherenkov telescopes

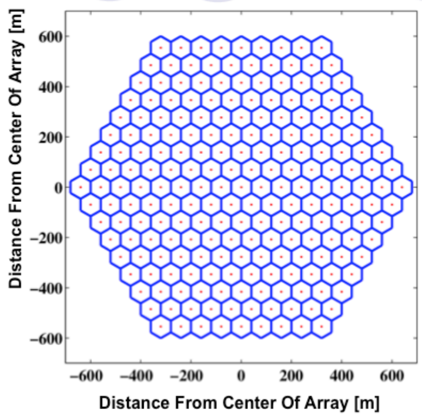
- The Domino System: a compact low power sampler and data readout for Cherenkov Telescopes *N. Turini*
- Application of Silicon photomultipliers in IACTs *N. Otte, R. Mirzoyan, M. Teshima, B. Dolgoshein*
- A smart pixel camera for future Cherenkov Telescopes *G. Hermann et al.*
- …

Advantages of large IACT arrays

(HE-ASTRO Example, 2005)

#1. New "event containment" operation regime is realized;

Baseline Design

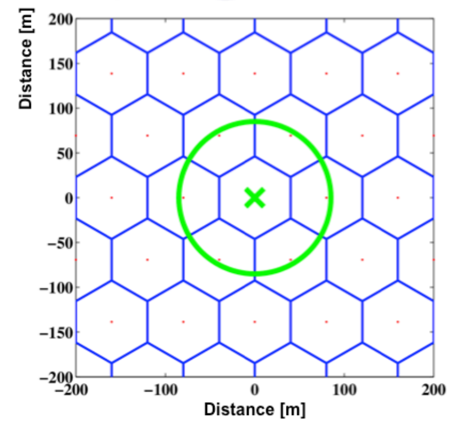


Array
1. 217 telescopes
2. 8 hexagonal rings + 1
3. 80m separation

Telescope and Detector
1. ø10m equivalent
2. QE = 0.25 (Bialkali)
3. 15° field of view

Facts and Figures
1. Outer radius: 640m
2. Single cell area: 5543m^2
3. Total area: 1.06km^2

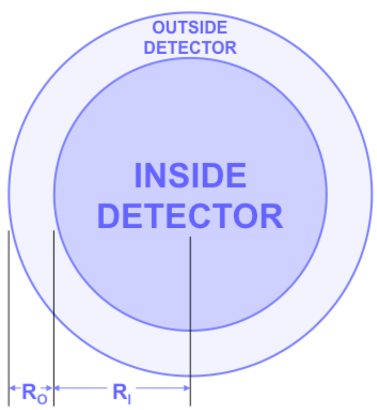
Cell Effect – Small Impact Parameter



Infinite Array Of Telescopes
1. 3500m ASL
   $\rightarrow R_{Cherenk}$ = 85m
2. D_{Scopes} = 80m

Geometry Dictates That
1. Impact point of every shower is in *some* cell
2. B_{Max} = 47m
3. At least 3 telescopes contained in Cherenkov light pool

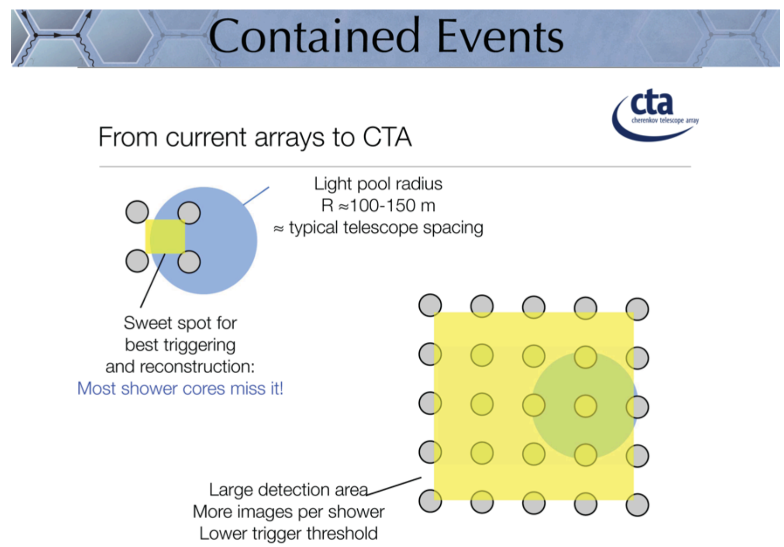
Cell Effect – Collecting Area



Gamma-rays INSIDE detector
Instrument has efficiency ε(E) such that effective area is:
$A_I = \varepsilon(E)\pi R_I^2$

Gamma-rays OUTSIDE detector
Instrument detects γ's to radius $R_O(E)$ such that effective area is:
$A_O = \varepsilon(E)\pi R_O(E)(2R_I + R_O(E))$

Energy Dependence
ε(E): 0.4 @ 20 GeV
0.8 @ 40 GeV
$R_O(E)$: <80m @ 20 GeV
600m @ 10 TeV

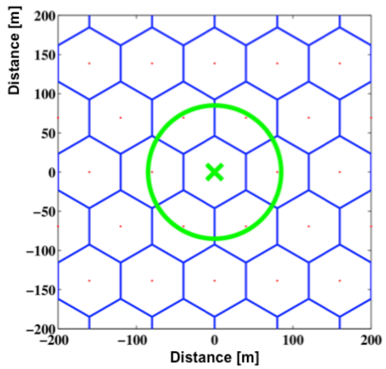


Advantages of large IACT arrays

(HE-ASTRO Example, 2005)

#2. Energy threshold decreases even IACT aperture remains the same;

Cell Effect – Small Impact Parameter



Infinite Array Of Telescopes

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Geometry Dictates That

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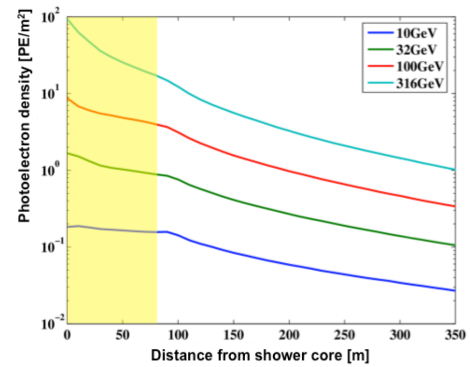
Cell Effect – Cherenkov PE Density



PE density after:

1. Atmosphere
2. Mirror reflection
3. Photocathode

Cell Geometry

Consider only the density within 80m of core

Midsized telescopes

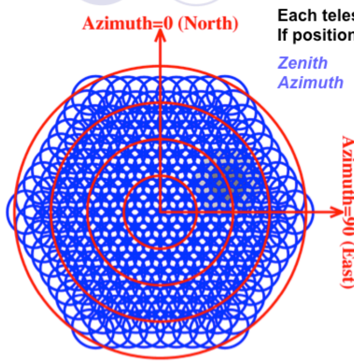
ø10m, A=78m²
E=32 GeV, b=80m
$\rightarrow n_{PE}$=78

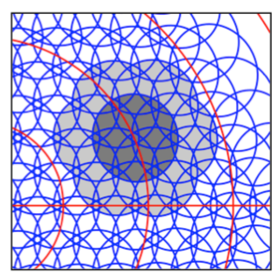
#3. Enable diverse operation modes: Collecting area <-> Solid angle ("divergent mode");

All Sky Coverage: "Fly's Eye" Mode

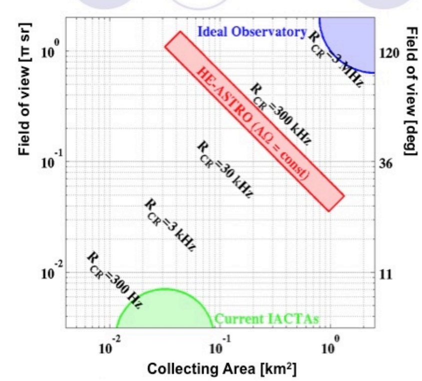
Each telescope points in different direction.
If position of telescope *n* on ground is (x_n, y_n)

Zenith $= \xi \times (x_n^2 + y_n^2)^{1/2}$
Azimuth $= \tan^{-1}(x_n / y_n)$





Collecting Area vs. Field Of View



Current IACTAs

Narrow field of view
<0.01 km² @ 40 GeV
0.05-0.1 km² @ 100 GeV
0.2-0.3 km² @ 10 TeV

Square KM Array

Continuum of modes
Trade area for solid angle

Parallel mode

Narrow field of view
1 km² @ 40 GeV
2 km² @ 100 GeV
4-5 km² @ 10 TeV

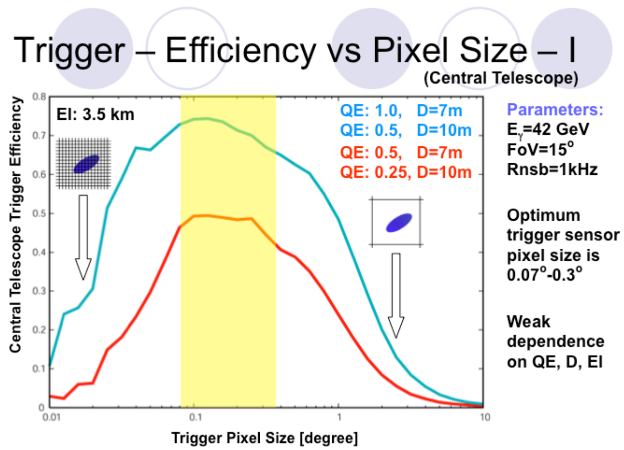
"Fly's Eye" mode

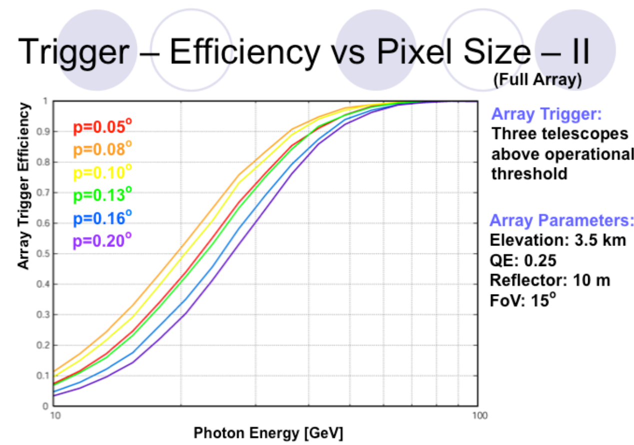
Wide field of view
0.02-0.03 km² @ 40 GeV
0.1-0.2 km² @ 100 GeV
3-4 km² @ 10 TeV

Advantages of large IACT arrays

(HE-ASTRO Example, 2005)

#4. Triggering and imaging are different functions of IACT requiring significantly different optimal pixel sizes (0.08°, <0.04°);





#5. Much better imaging resolution significantly improves gamma-ray angular resolution;

#6. New concept of array trigger (distributed array trigger) may be required to maintain high data rates (F. Krennrich, A. Weinstein);

#6. “Cleaning” methods are of crucial importance to fully realize low energy operation performance potential;

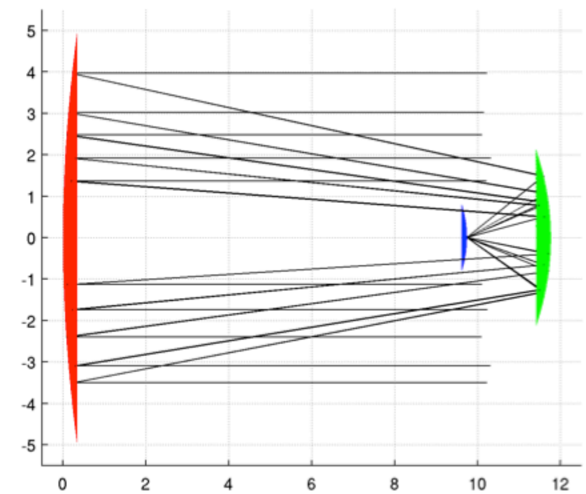
#7. …… To be discussed later in the context of AGIS concept.

New Telescope OS

The telescope OS used in HE-ASTRO simulations studies was ideal, and once real OS such as VERITAS was used many important conclusions diluted.

To fully utilize advantages offered by a large IACT array a new wide field high angular resolution telescope with moderate aperture and new focal plane photo-sensors is needed.

Modified RC – "Best Design"



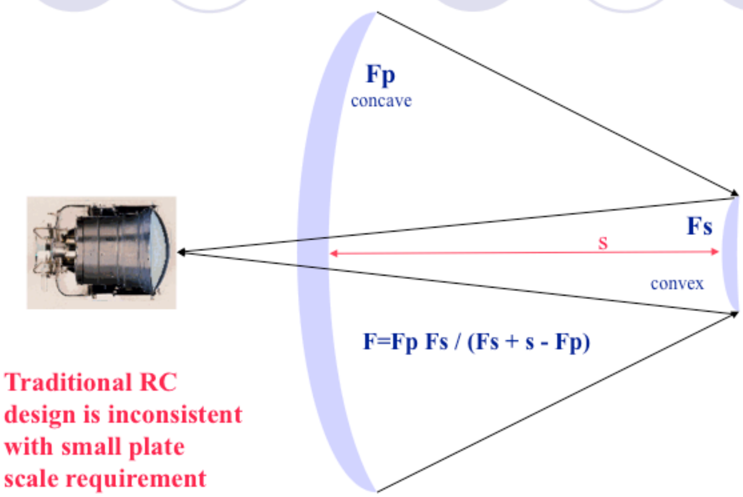
Example of detailed ray tracing in modified RC design

Dp=10m
Ds=4.1m
Df=1.6m

A(0)=0.81 x pi $D^2/4$
A(7.5)=0.55 x pi $D^2/4$

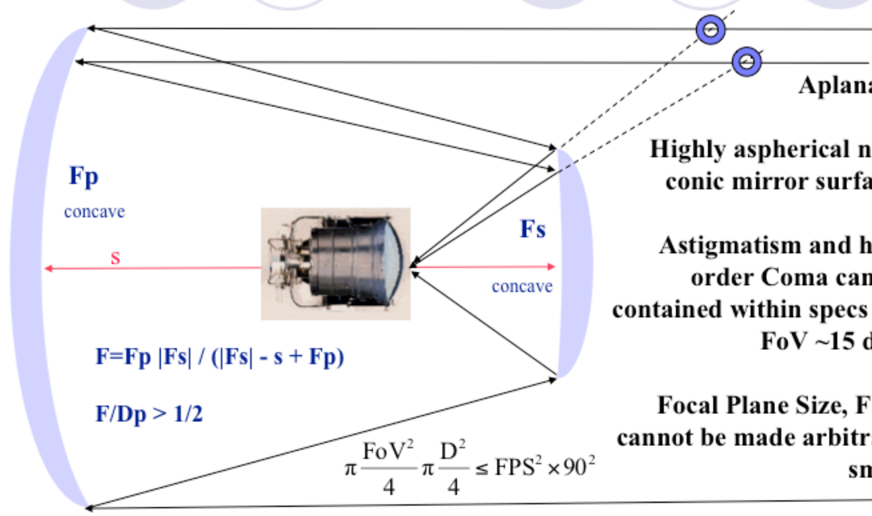
Spot size can be a few arcmin at the edge of the FoV

Two Mirror Designs – RC



Traditional RC design is inconsistent with small plate scale requirement

Two Mirror Designs – Modified RC



Aplanatic

Highly aspherical non-conic mirror surfaces

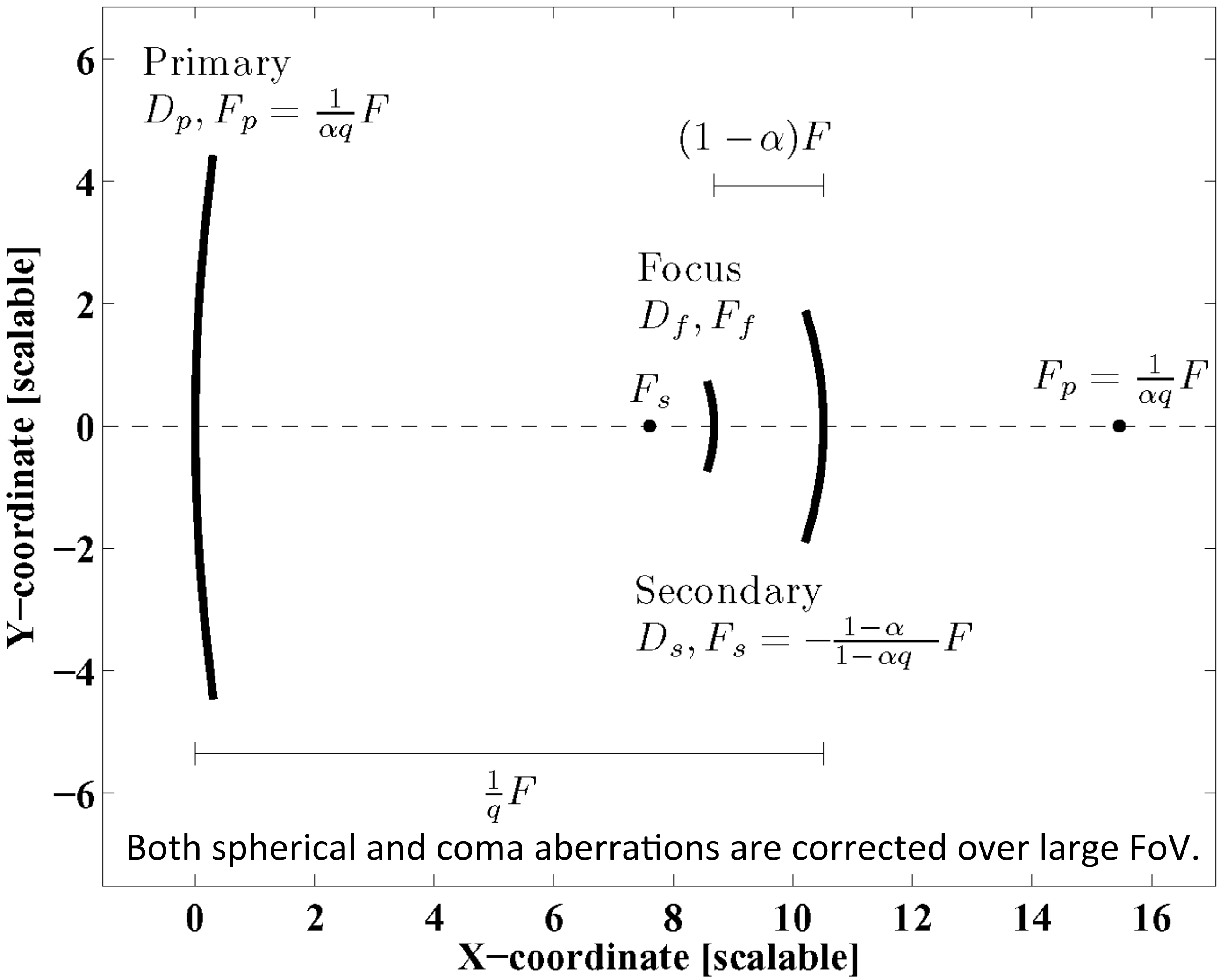
Astigmatism and high order Coma can be contained within specs for FoV ~15 deg.

Focal Plane Size, FPS, cannot be made arbitrary small

Abbreviation RC is for Ritchey-Chretien telescope. Will be important later (Author)

Aplanatic Telescope OS:

Schwarzschild-Couder Telescope (SCT)



1) Focal length **F** is fixed by geometrical and angular pixel sizes of SiPM;

2) α and **q** parameters are optimized for maximal light collecting area with minimal PSF at the edge of **FoV**;

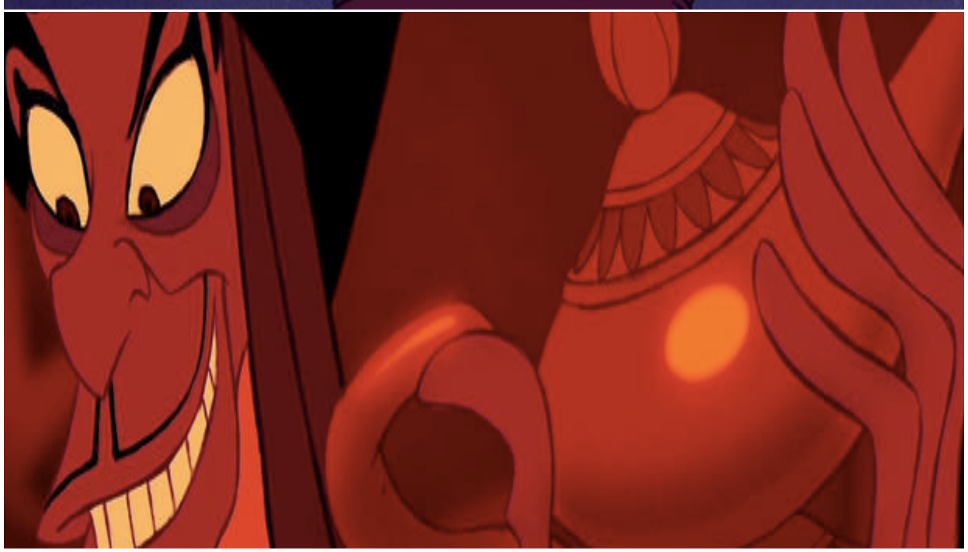
3) Diameter of the primary is determined by **F**, α, **q** with second derivative being zero at the edge;

4) Diameter of the secondary is determined by tolerable vignetting;

5) Focal plane is curved to minimize astigmatism.

V. V. Vassiliev, S. J. Fegan, P. F. Brousseau Astropart.Phys.28:10-27,2007

Genei left Alladin lamp (2006)

Disney.wikia.com

Aplanatic Telescope Paper was reviewed by

Werner Hofmann
Tadashi Kifune
3rd unknown reviewer

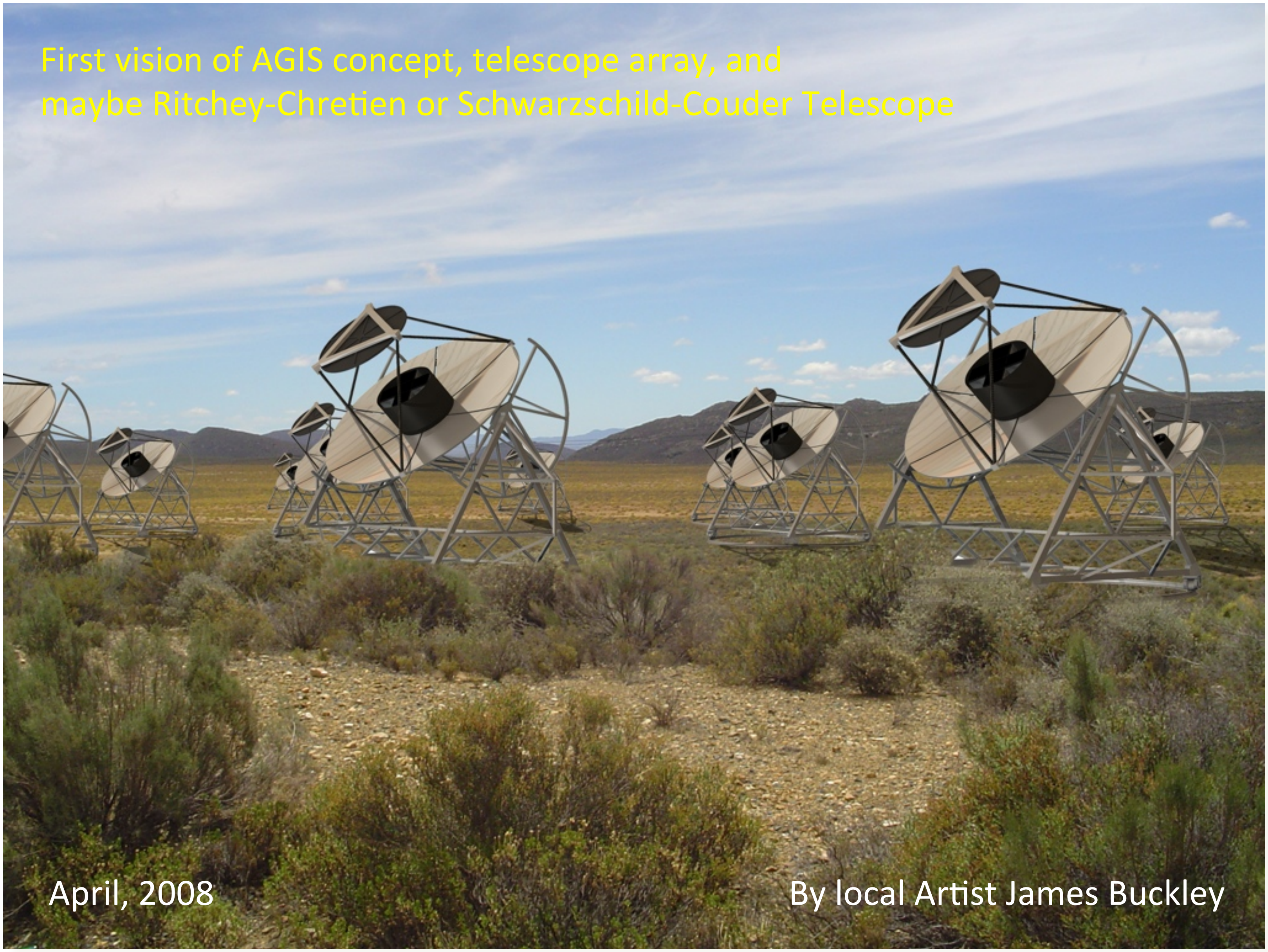
Amount of email communications significantly exceeded this 18-pages long paper;

Contribution of the reviewers to the paper must be recognized by making them the co-authors;

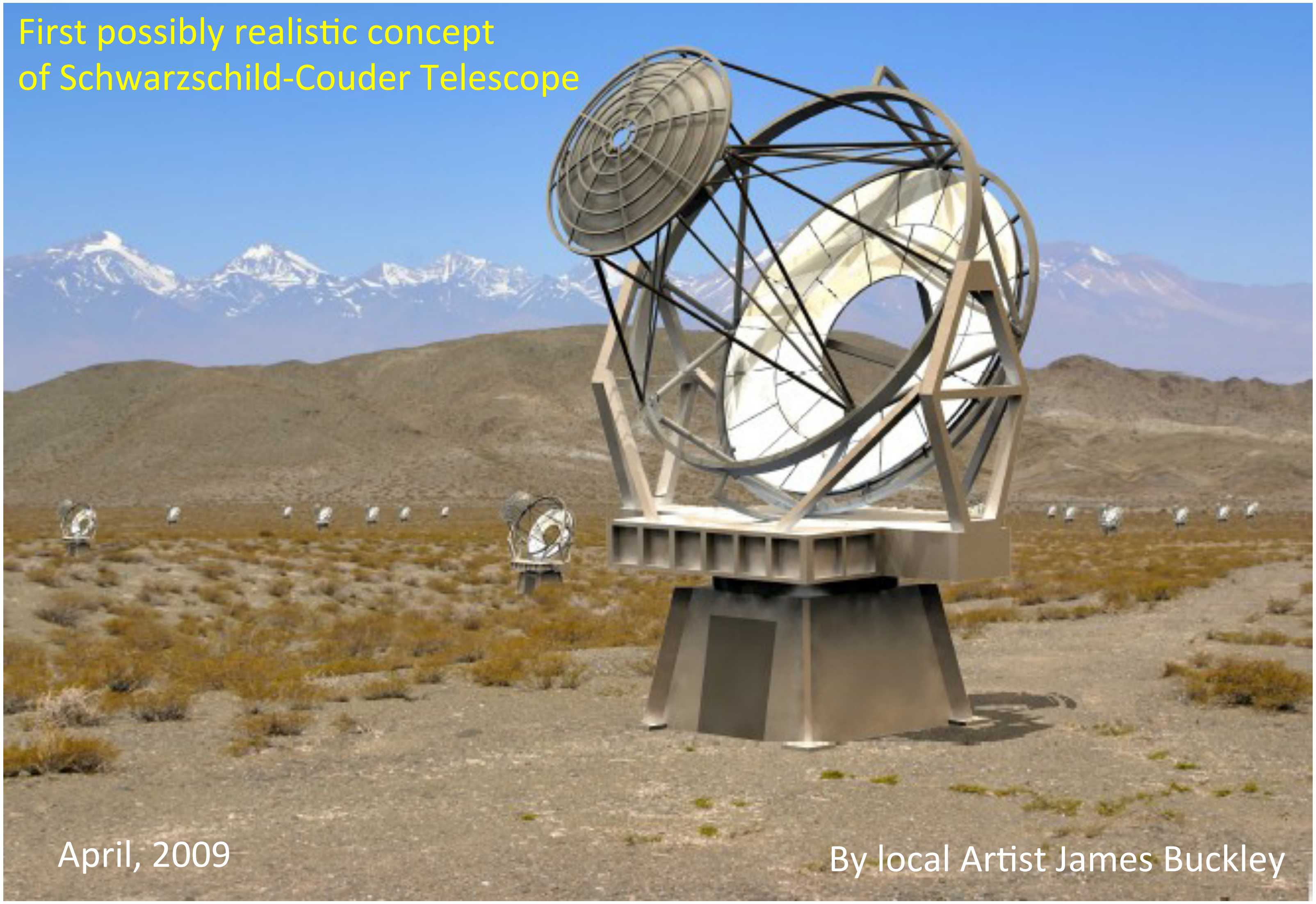
..but,
unknowingly at that time,
this paper may have started the trouble for CTA.

SCT IN AGIS

Here comes the AGIS



Advanced Gamma-Ray Imaging System (AGIS)

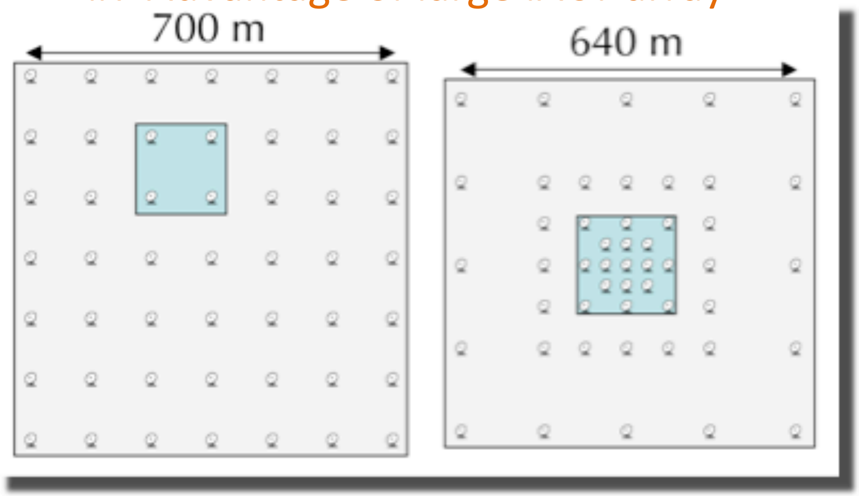


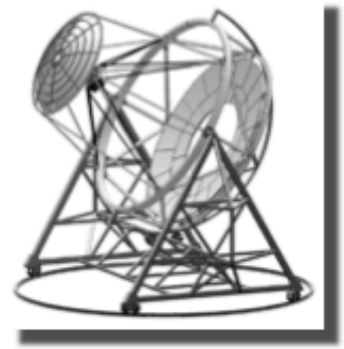
Not long before AADS2010

The concept presented to AADS2010

AGIS Summary

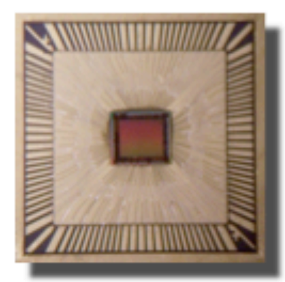
#7 Advantage of large IACT array





Novel optical designs for angular resolution and FoV

- ~50 telescopes, $100M
- ~40 GeV threshold
- ~km^2 effective area
- arcminute angular resolution
- FoV four times larger than HESS
- 10 times sensitivity of VERITAS/HESS



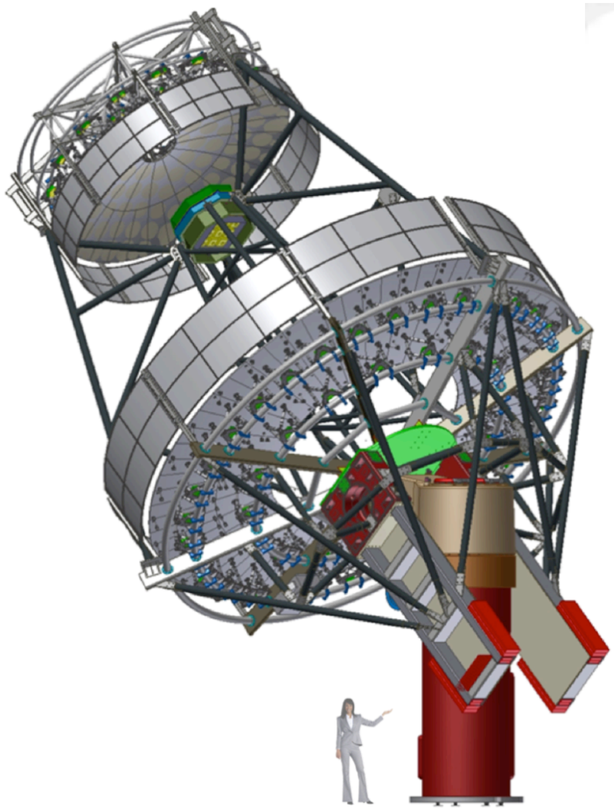
Gigasample waveform sampling ASICs for cost reduction to $20/channel

AADS2010 Reccomendation

Both the U.S. and the European communities are developing concepts for a next-generation array of ground-based telescopes with an effective area of roughly 1 square kilometer. The U.S. version of this facility (AGIS, the Advanced Gamma-ray Imaging System) was evaluated by the survey and the total cost, estimated to exceed $400 million, was considered too expensive to be entertained, despite technical risk being medium low. The European Čerenkov Telescope Array (CTA) is in a more advanced stage, and there is advantage in sharing the costs and operations in a Europe-U.S. collaboration. The committee recommends that the U.S. AGIS project join CTA for collaboration on a proposal that will combine the best features of both existing projects. Funding availability is likely to permit U.S. participation only as a minor partner, but the promise of this field is so high that continued involvement is strongly recommended. U.S. funding should be shared among DOE, NSF-AST, and NSF-PHY, as happened with VERITAS, and a notional $100 million spread between the agencies over the decade is recommended. Given the large project cost uncertainties, the current lack of a unified project plan, the project ranking, and the likely budget constraints in the coming decade, it will be necessary for the agencies to work quickly with the AGIS/CTA group to define a scope of U.S. involvement that is both significant and realistic.

SCT IN CTA

SCT for CTA - MRI Success !!!



Numerous AGIS R&D and MRI proposals, although rejected, shaped the design of the SCT.

The US NSF approved construction of prototype SCT through program MRI starting September 2012!

National Science Foundation
WHERE DISCOVERIES BEGIN

- Optical system: f/0.58, F=5.59 m
- S Aplanats: q=0.666; α=0.666
- Primary (M1) diameter: 9.66 m
- M1 type: aspheric segmented (16+32)
- Secondary (M2) diameter: 5.42 m
- M2 type: aspheric segmented (8+16)
- Field of View: 8 deg
- Focal plane diameter: 78 cm
- Effective collecting area: >35 m^2
- PSF less than: <4.5 arcmin (across the FoV)
- Photon detector: SiPM
- Number of pixels/channels in camera: 11,328
- Angular pixel size: 0.067 deg

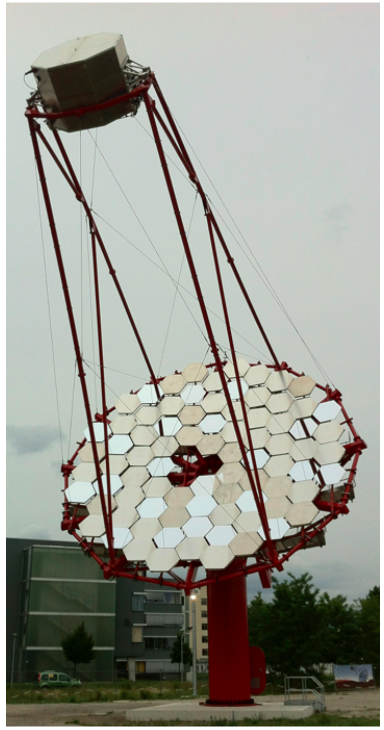
First Frustration and Kaleidoscope of Memories

"Combining…." DC-MST vs SC-MST

CTA DC-MST:

1. Well tested low risk DCT technology;
2. Improved angular resolution (F=16m, f/1.2);
3. Relatively low cost 12m aperture segmented spherical optics;

1. Very large (2.4m) and expensive PMT camera;
2. Pixel size and FoV are limited by the cost;
3. Doesn't fully utilize high angular resolution of MST array in CTA



Berlin, 2016

FLWO, 2017

Trade off
Camera cost <–> OS cost

CTA SC-MST:

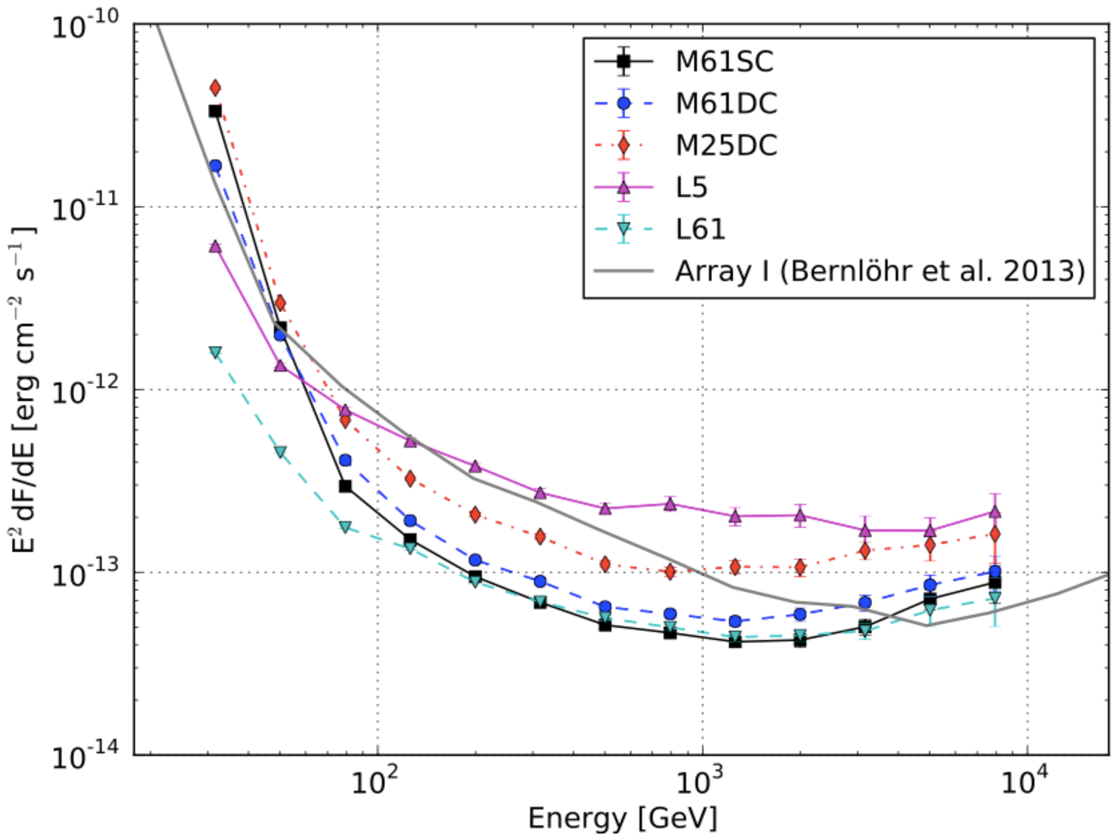
1. Excellent angular resolution;
2. Wide field of view combined with high resolution imaging;
3. Small plate scale (f/0.6);
4. Low cost per pixel utilizing SiPMs;
5. OS and camera costs are balanced;

1. Low cost aspheric mirror technology is critical;
2. New SC technology represents risk and requires prototyping.

If SC-MST is implemented in CTA baseline configuration it will operate nearly at the limit of IACTechnology

SC-MST performance benefits for CTA

Simulations



"The gain in point-source sensitivity comes primarily from the improvement in the gamma- ray angular reconstruction enabled by the higher resolution imaging of the shower axis."

Unless SC-MST is more than ~1.7 times more expensive than DC-MST (*unlikely at this stage of pSCT progress*), it will provide sensitivity benefit given the same cost of MST array construction. It will also provide superior angular resolution which cannot be matched by the DC-MST array.

"When considering arrays with the same number of telescopes, we find that the SC telescope design yields a 30-40% improvement in point-source sensitivity over the DC telescope design because of its superior imaging resolution."

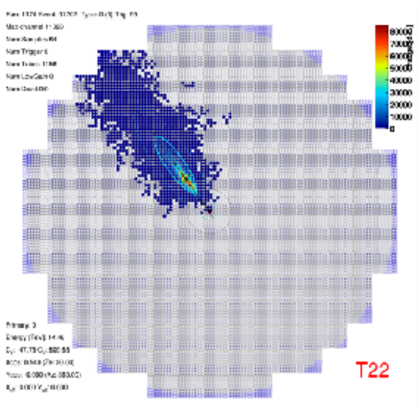
M.Wood, T. Jogler, J. Dumm, and S. Funk. *Monte Carlo studies of medium-size telescope designs for the Cherenkov Telescope Array*. Astroparticle Physics, 72:11–31, January 2016.

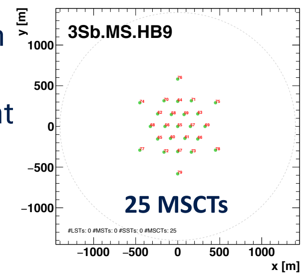
Recent Simulation Studies

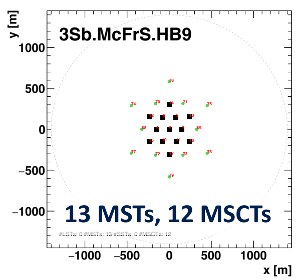
Dual-mirror mid-size telescopes

O. Hervet, D. Nieto, GM

- study impact of replacing Davies-Cotton MSTs by dual-mirror SC-MSTs
  - Paranal: full and partial replacement
  - La Palma: full replacement



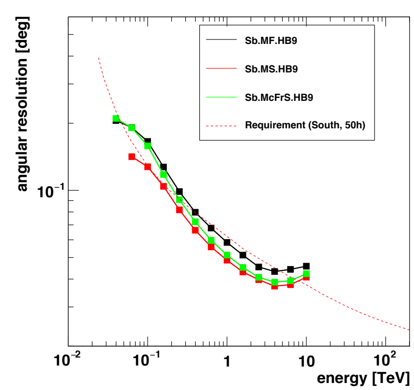


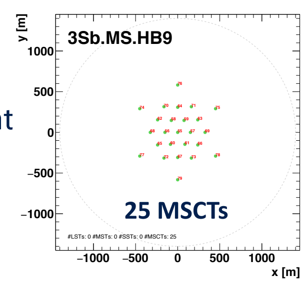


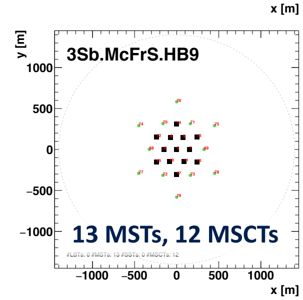
Last CTA consortium meeting Rio de Janeiro, May 2017

Dual-mirror mid-size telescopes

- study impact of replace Davies-Cotton MSTs by dual-mirror SC-MSTs
  - Paranal: full and partial replacement
  - La Palma: full replacement







Discover New Opportunities !

Many thanks to all people working on simulation studies of SCTs in CTA!

Combining the best features…

Perhaps the most important collaboration for the success of the pSCT project was developed with the DESY, Zeuthen group, which leads the DC-MST mechanical structure development for CTA.

Early in the pSCT project the most critical decision was made (with a lot of pain) to use nearly identical telescope positioning system so that both DC and SC versions of MST are basically identical from the point of view of telescope array control.

MST with upgraded OSS, Berlin, 2017

Tank you, DASY MST team!

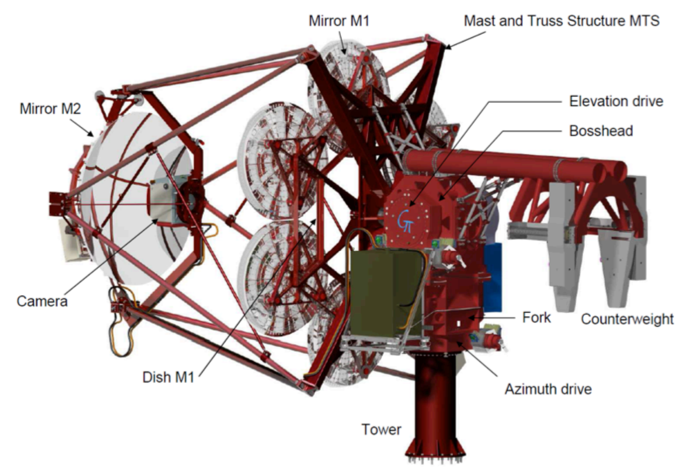
“Infecting” with the best features …

CTA SST array operates in the regime in which Cherenkov light detected is mostly produced by the electrons significantly deflected by the multiple Coulomb scattering from the direction of the primary photon. In this detection regime the reduction of the pixel size doesn’t lead to the improvement in the gamma-ray PSF. Although SC-SST doesn’t provide γ-ray angular resolution improvement, it arguably provides cost benefit for SST array sensitivity by balancing the reduced cost of the camera and the costs of structure and optical system. It also enables a possibility of using SiPMs in IACT cameras.

CTA DC-SST

<–>

CTA SC-SST
ASTRI

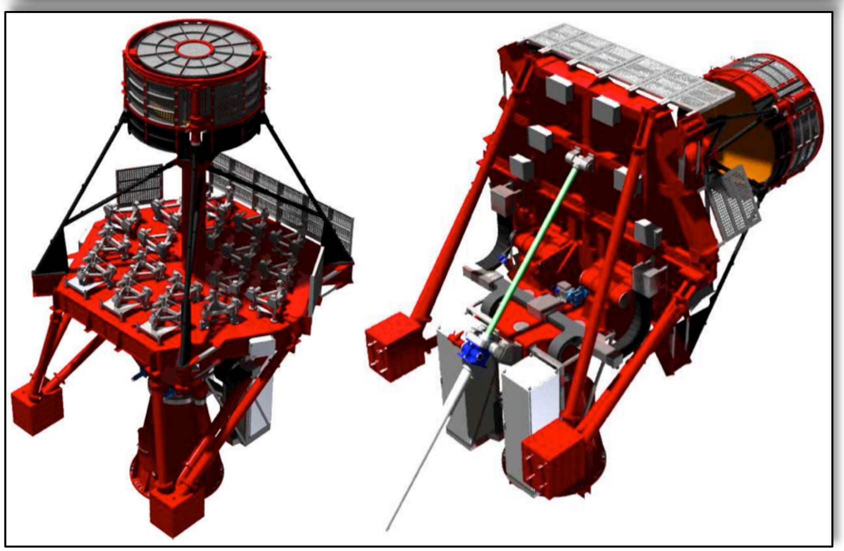


CTA SC-SST
GCT

Prototype SST-2M ASTRI inauguration

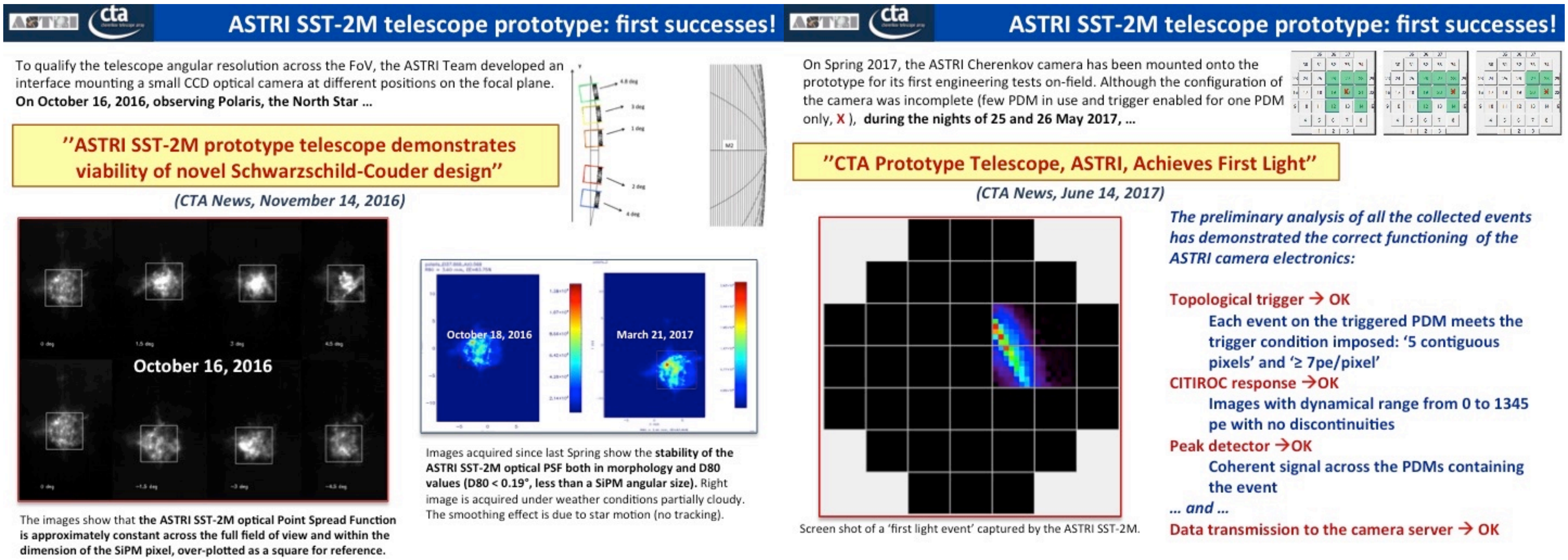
The **prototype SST-2M ASTRI** is installed at the INAF observing station 'M.C. Fracastoro' located in Serra La Nave (Mt. Etna, Sicily, Italy), at 1740 m a.s.l.

SC-SST in CTA: ASTRI



- Optical system: f/0.5, F=2.15 m
- S Aplanats: q=0.72; α=0.76
- Primary (M1) diameter: 4.3 m
- M1 type: aspheric segmented (6+6+6)
- Secondary (M2) diameter: 1.8 m
- M2 type: aspheric segmented (monolithic)
- Field of View: 9.6 deg
- Focal plane diameter: 36 cm
- Effective light collecting area: 6 m^2
- PSF (D80) less than: < 9 arcmin (across the FoV)
- Photon detector: SiPM
- Number of pixels/channels in camera: 1,984

SST-2M ASTRI Highlights



ASTRI SST-2M project demonstrated for the first time that non-diffraction limit Schwarzchild –Couder Optics does work in the context of IACT application!
November, 2016

ASTRI SST-2M project achieved first light utilizing SiPM as photo-sensor and novel for IACT camera electronics design!
June 14, 2017

This event, however, is the second in the history of SC optics.

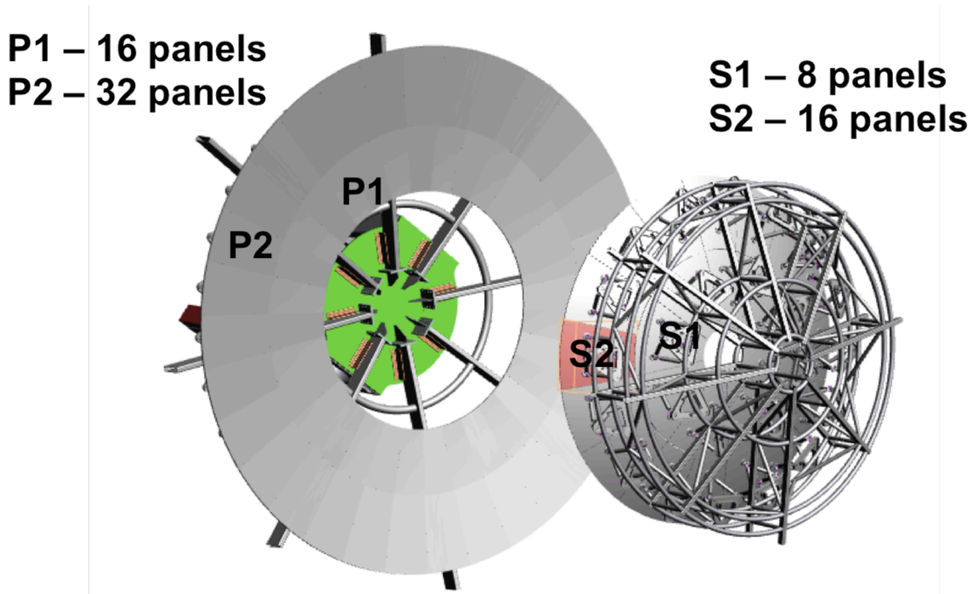
Combining the best features…

Another most important collaboration for the success of the pSCT project has been developed with the INAF de Brera observatory, which started almost immediately after the publication of the "Aplanatic Telescope…" paper, continued through AGIS era to the present with CTA.

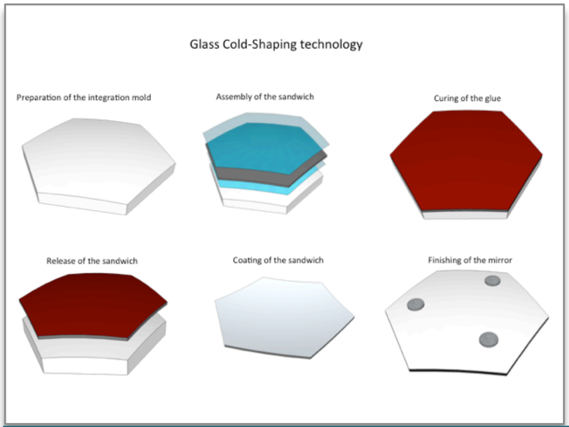
Combination of SCT ideas, originated in the US, with the inexpensive replication technology developed at INAF de Brera and Media Lario Technologies became particularly prolific for realization of highly aspheric segmented SCT optics.

ASTRI, the acronyms …
''Astrofisica con Specchi a Tecnologia Replicante Italiana''
(Astrophysics with Mirrors via Italian Replication Technology)

Segmented OS of pSCT



All P1&P2 panels manufactured and delivered to UCLA. The main technological risk of S1 and S2 production retired and these panels are currently under production.

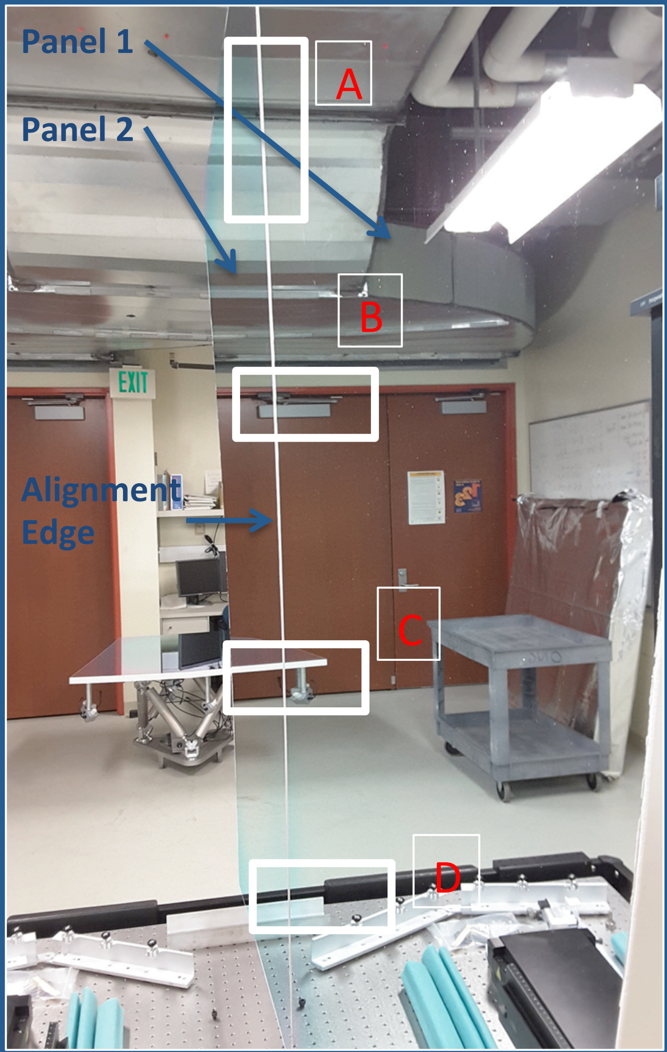


Tank you, INAF de Brera team!

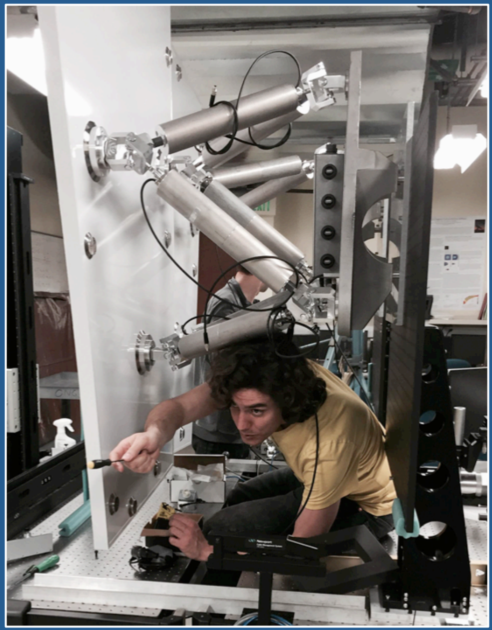
MPM Assembly & Calibration

1. Fabrication of all elements of panel-to-panel alignment system (P2PAS) is completed

2. The early results of integration of P2PAS with M1 panels are excellent;



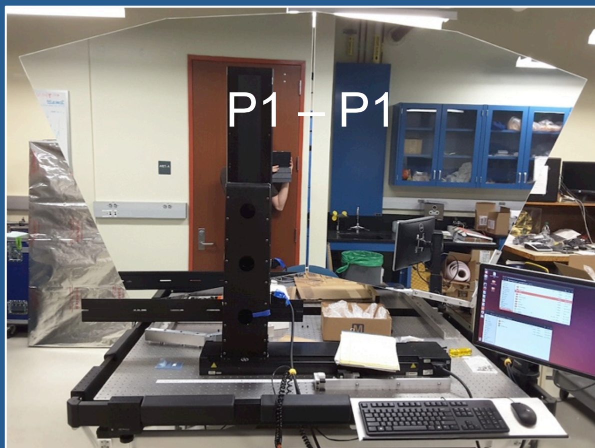
Two primary mirror panels aligned by P2PAS at UCLA Lab

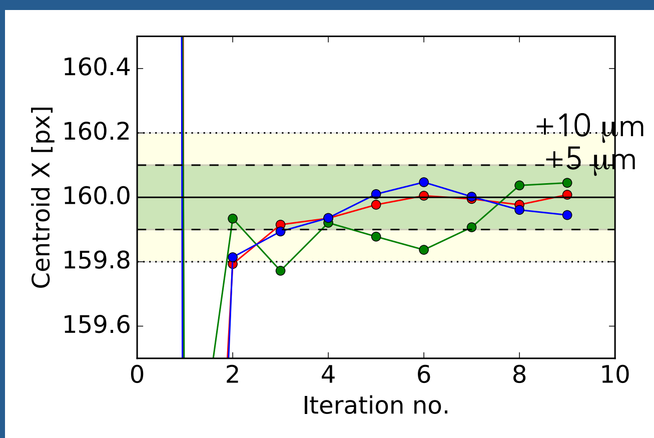


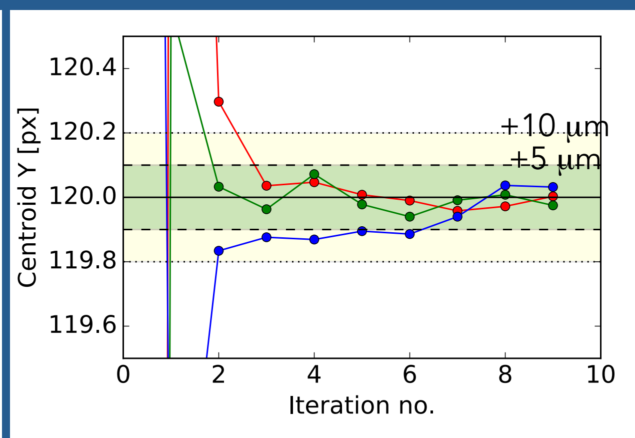
Assembly of MPESs

pSCT OS integration team at work

P2PAS Alignment Convergence





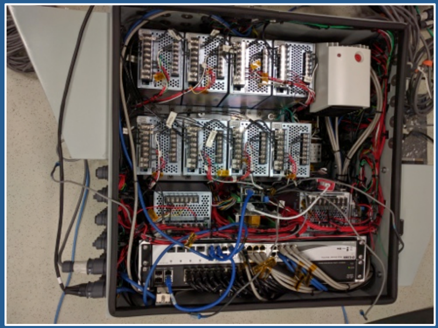


Two – four iterations align panels in both, X and Y, to better than 5 μm

GAS Sub-system Implementation

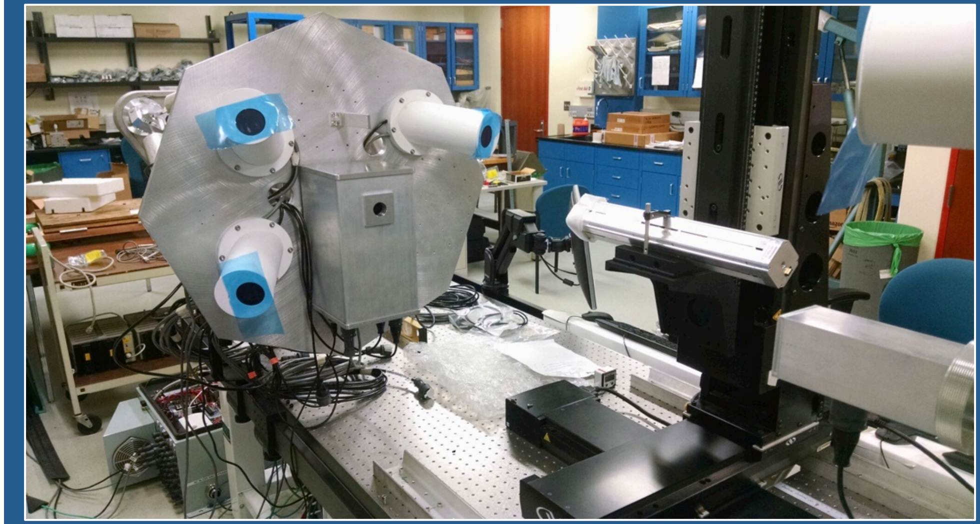
Parameter	Primary/Secondary	Secondary/ Focal plane
Δx, Δy	±0.25 mm	±0.25 mm
Δz	±8 mm	±1.2 mm
$\Delta\theta_x$, $\Delta\theta_y$	±25 µrad	

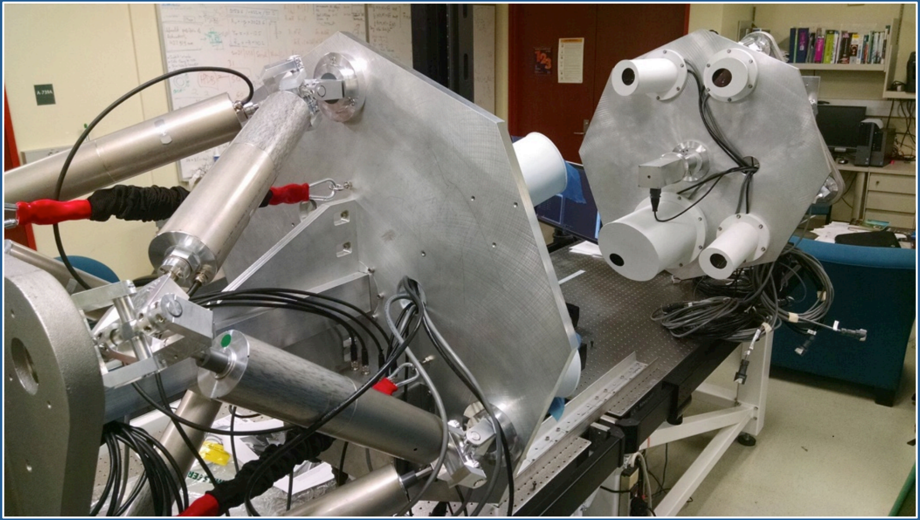
Global Alignment Specifications



M2 PEDB

pSCT GAS Optical Tables Assembled calibration





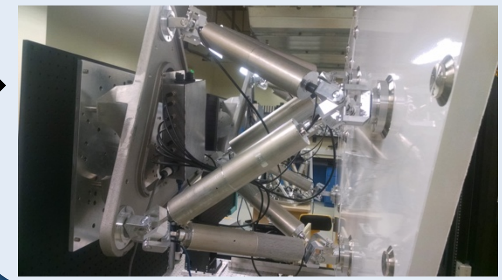
pSCT GAS Optical Tables on Calibration Stand

Integration of MPMs (Workflow)

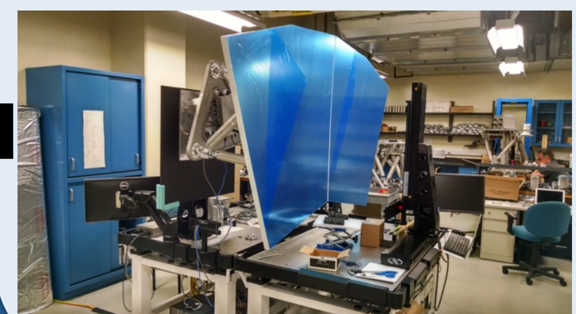
Assembly of actuators, controllers, edge sensors…

Delivery of mirror panels & edge sensors

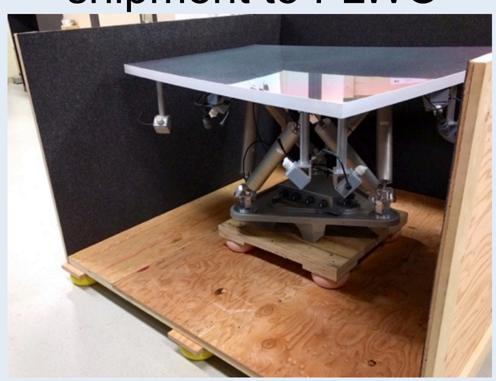
Assembly of panel modules



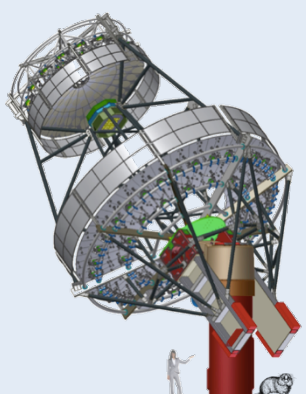
Calibration of each panels (+ metrology)



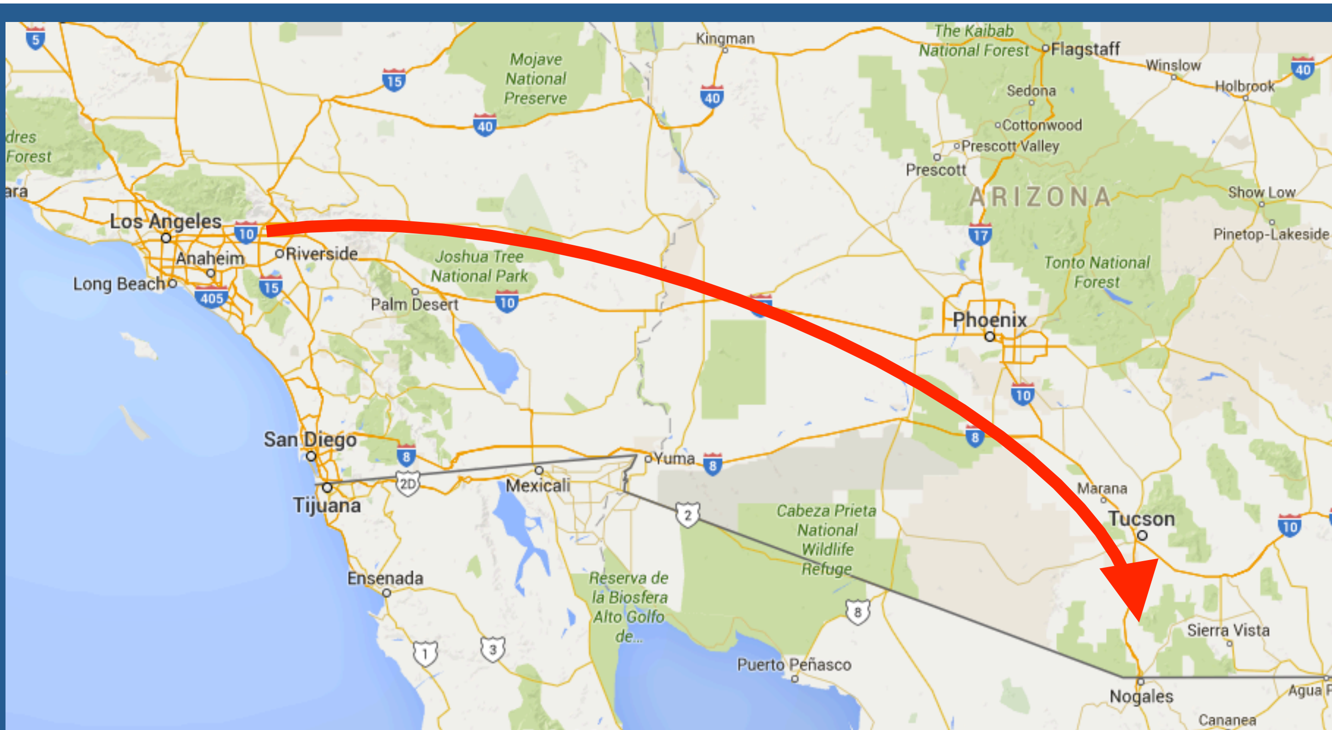
Custom crates for shipment to FLWO



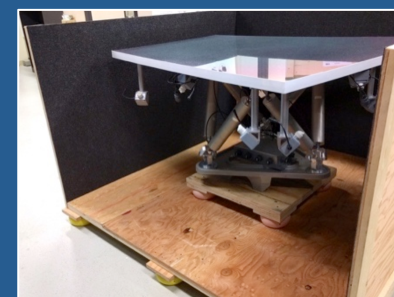
Integration on OSS



Shipping to FLWO

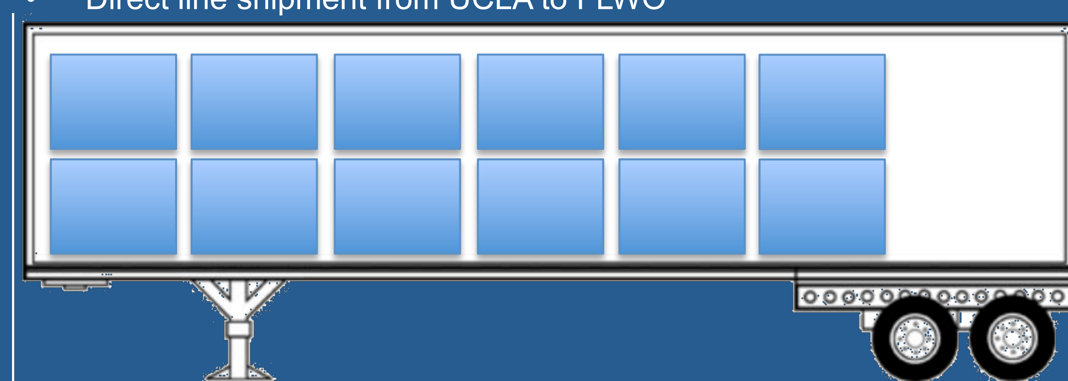


Assembled calibrated MPM



Custom made crate

- ~530 lb / crate; 12 crates per shipment (1/4 dish)
- 6 shipments needed (4 for M1, 2 for M2)
- Direct line shipment from UCLA to FLWO

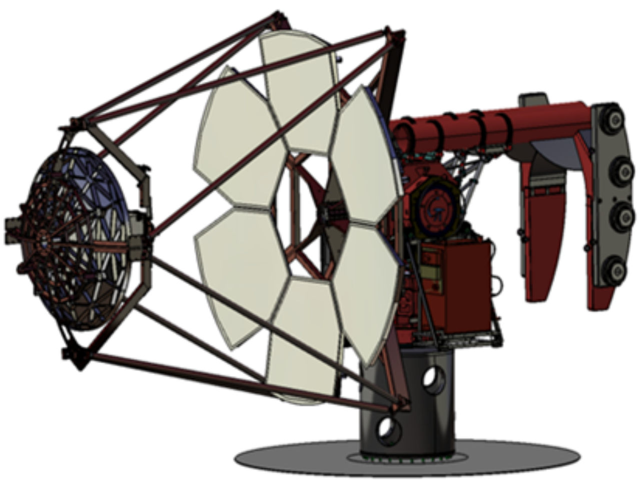


Prototype SST-2M GCT Inauguration

December 1, 2015

There is a special meaning of the Observatoire de Paris-Meudon in the history of the SC design

SC-SST in CTA: GCT

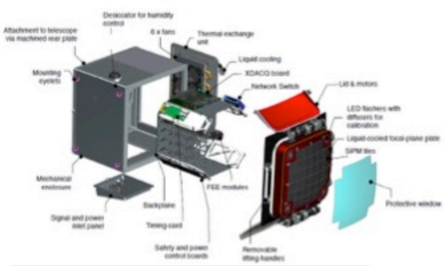


- Optical system: f/0.58, F=2.283 m
- S Aplanats: q=0.64; α=0.78
- Primary (M1) diameter: 4 m
- M1 type: aspheric segmented (6)
- Secondary (M2) diameter: 2 m
- M2 type: aspheric segmented (monolithic)
- Field of View: 8.5 -9.2 deg
- Focal plane diameter: 36 cm (9 deg)
- Effective light collecting area: 6.8 m^2
- PSF (D80) less than: < 9 arcmin (across the FoV)
- Photon detector: SiPM
- Number of pixels/channels in camera: 2,048

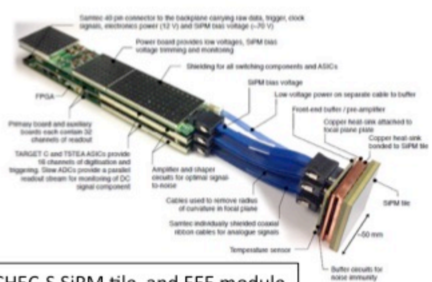
SST-2M GCT Highlights

SST-2M-GCT CHEC prototypes

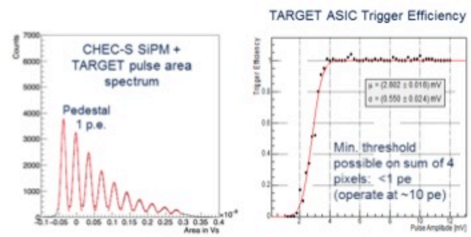
CHEC-M: tests nearly concluded. Now routine observations in Meudon to better investigate stability and reliability
CHEC-S: all components under intensive lab tests. Camera fully completed in the coming months.
(Australia, Germany, Japan, Netherlands, UK)

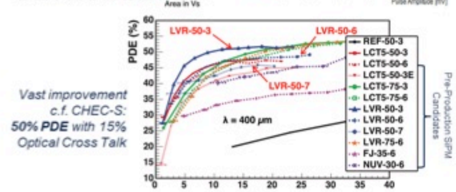


CHEC-S CAD model with key elements

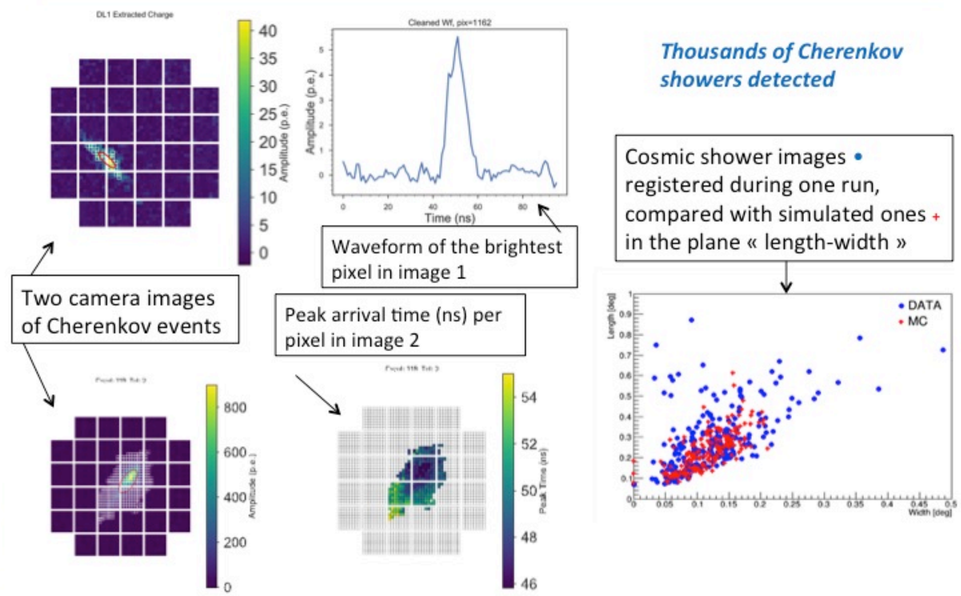


CHEC-S SiPM tile and FEE module





2nd GCT prototype observing campaign March-April 2017

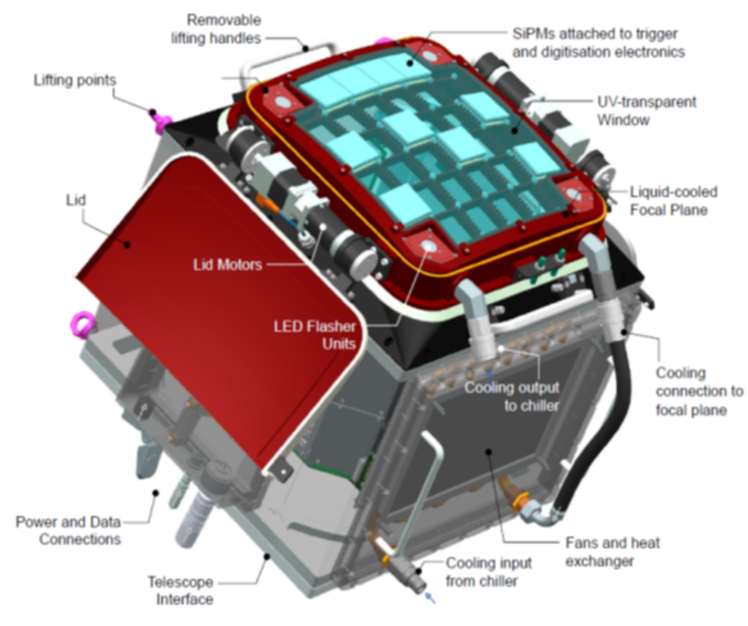


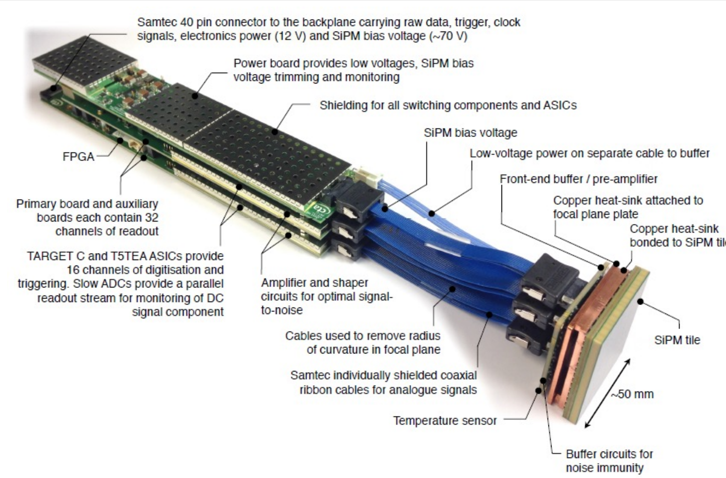
GCT team has been the first to demonstrate the detection of Cherenkov showers with the use of MAPMTs and SiPMS utilizing TARGET ASIC (switched capacitors array) based electronics. In a way the project disproved the common knowledge that one needs aligned optics and moving telescope to do this. Unlike ASTRI project the detection of Cherenkov images happened prior to inauguration event.

Combining the best features…

Yet, another most important collaboration for the success of the pSCT project has been developed with the MPIK and University of Erlangen, which started since early AGIS times and has increased at present with CTA.

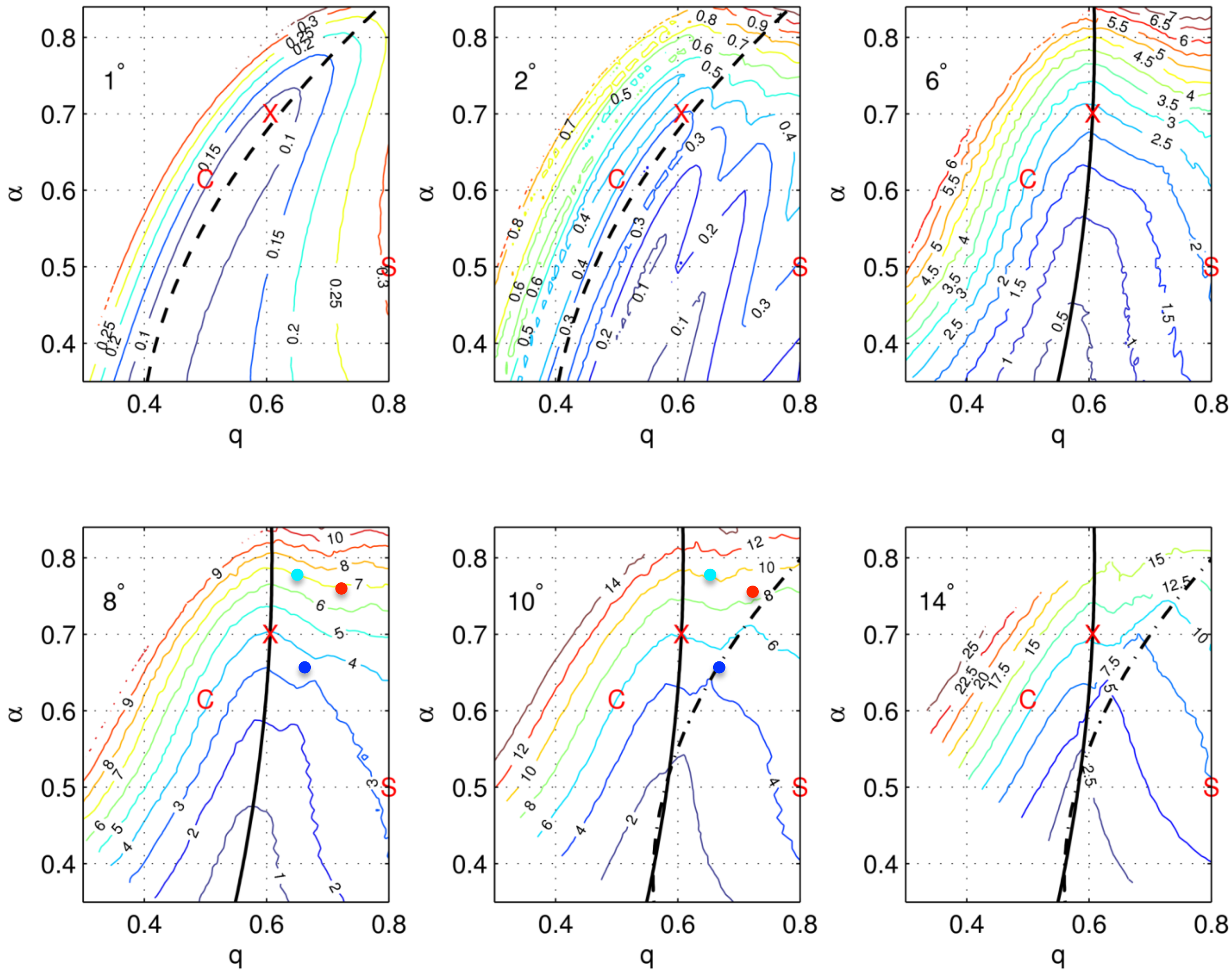
The TARGET ASIC technology, and the trigger backplane are common for both SCT and GCT-S cameras. Major camera components such as front end electronics modules as well as backplane are either identical or have significant common elements.





Tank you, GCT team!

Point Spread Function



Preferred solution for use in IACT applications has α=0.700, q=0.606

- SCT: α=0.666 q=0.666
- ASTRI: α=0.758 q=0.717
- GCT: α=0.777 q=0.641

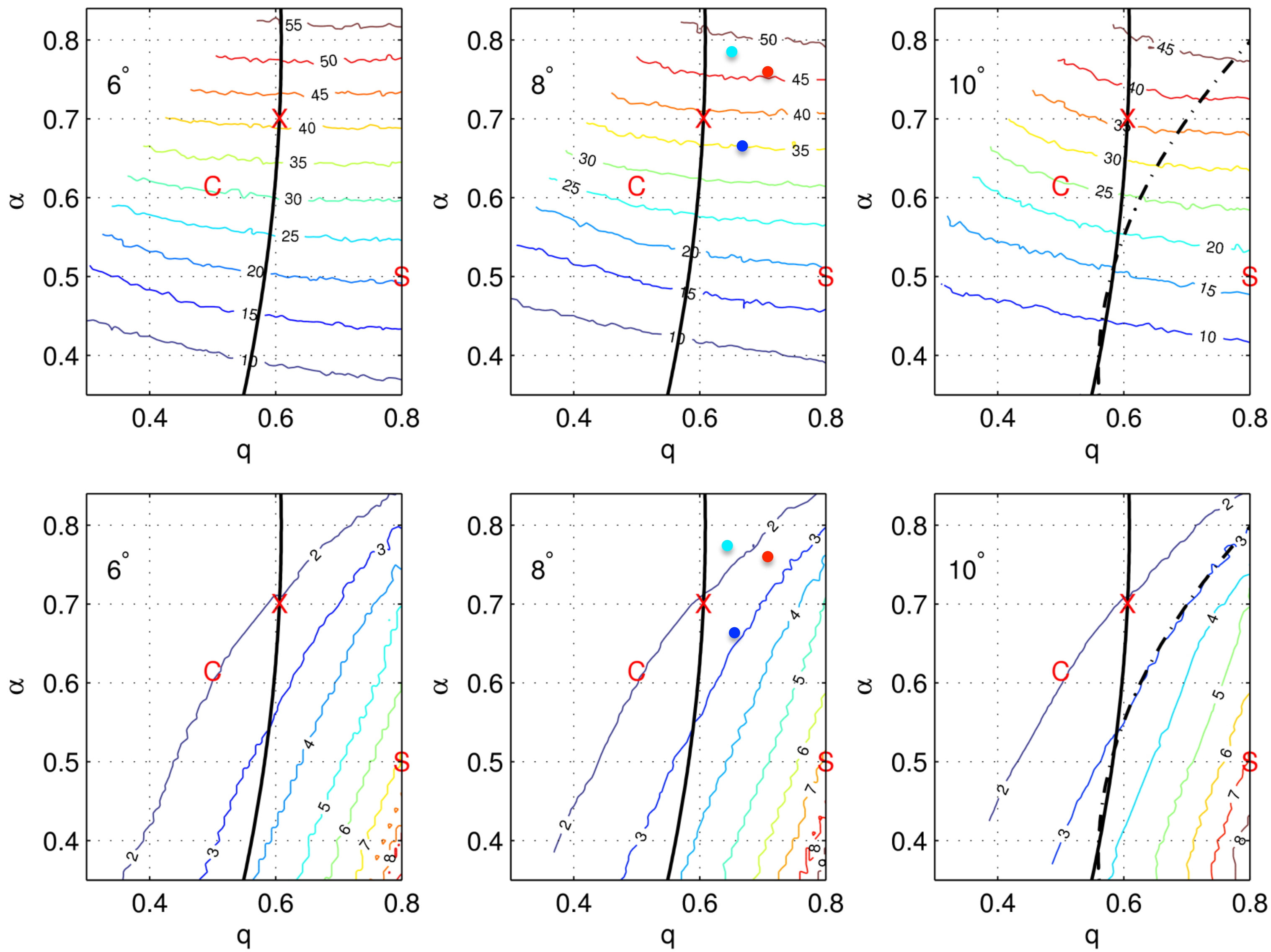
q->1
M2 is closer to M1
α->1
Camera is closer to M2

S minimizes distortion

C minimizes astigmatism

The lines show OSS with minimal astigmatism (optimized FP curvature) for a given value of α

Collecting Area and FP Curvature



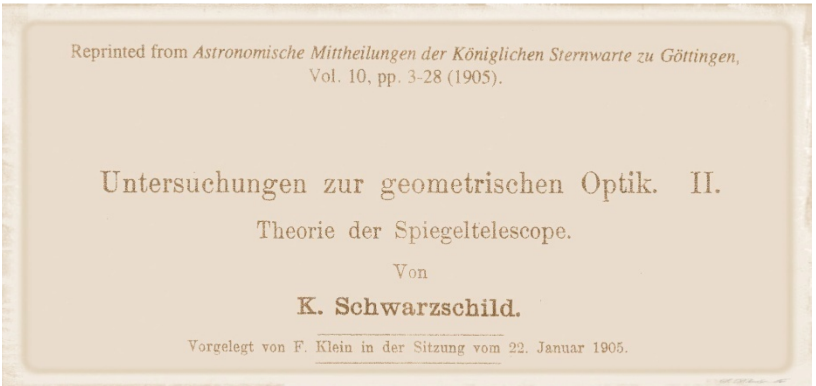
Light Collecting Area

Focal Plane Curvature

Example for F=500 cm

SC DESIGN IN HISTORY

Schwarzschild Telescope (1905)



Reprinted from *Astronomische Mittheilungen der Königlichen Sternwarte zu Göttingen,* Vol. 10, pp. 3-28 (1905).

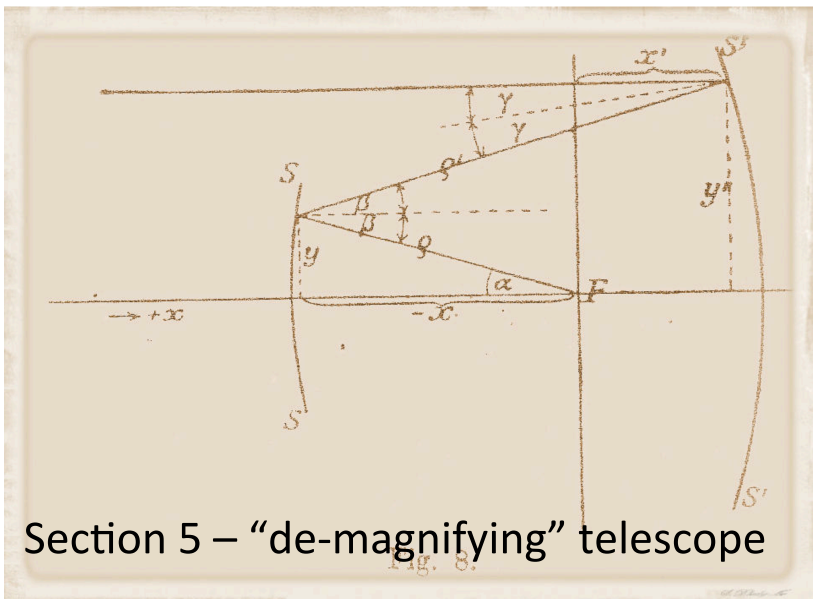
Untersuchungen zur geometrischen Optik. II.

Theorie der Spiegeltelescope.

Von

K. Schwarzschild.

Vorgelegt von F. Klein in der Sitzung vom 22. Januar 1905.



Section 5 – “de-magnifying” telescope

Karl Schwarzschild (1873 -1916)

Found exact solution for figures of two aspheric mirrors which corrected spherical aberrations and coma

K. Schwarzschild, Astronomische Mittheilungen von der Koeniglichen Sternwarte zu Goettingen, 10:3-28, 1905

"Miracle" of exact solution

These equations can be reduced to a single second order non-linear differential equation for the primary mirror sag function,

$$Z_{yy} = \frac{1}{2}\frac{\left(\left(\alpha\left(2+\eta\right) - Z - 1\right) Z_y + y Z_y^2 - \frac{1}{4}\right)}{\left(\alpha\left(2+\eta\right) - Z - 1 + \sqrt{1-y}\right)\left(1 - y + \sqrt{1-y}\right)},$$

which must be solved with the initial conditions $Z|_{y=0} = 0$ and $Z_y|_{y=0} = \frac{1}{4}\frac{1}{(1+\eta)}$. We found that the solution, $Z(y)$, has a unique, non-trivial property, which is likely related to the presence of a hidden symmetry in aplanatic optical systems, allowing it to be written

$$Z = \frac{\alpha}{4} q y - (1-\alpha)\,\Psi(y,q), \tag{27}$$

where $q^{-1} = \alpha(1+\eta)$ and $\Psi(y,q)$ is a function of only two independent parameters rather than the expected three: y, α, and $(1+\eta)$. This degeneracy requires that Ψ be a solution of a first order differential equation which can be readily obtained after some mathematical transformations

$$\frac{d\Psi}{dy} = \frac{1}{\sqrt{1-y} - 1 + \frac{2}{q}}\left(\frac{(1-\Psi)}{\left(\sqrt{1-y}+1\right)} - \frac{1}{2}\right).$$

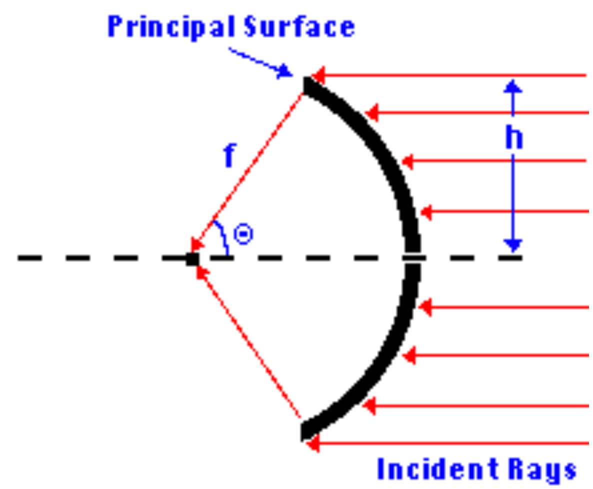
The solution satisfying $\Psi|_{y=0} = 0$ and expressed in quadratures is given by

$$\Psi(y,q) = \frac{1}{4} q \frac{y^2}{\left(\sqrt{1-y}+1\right)^2}\left[\frac{1}{2} - \frac{\left(q\left(\sqrt{1-y}-1\right)+2\right)^{1+\frac{1}{1-q}}}{\left(\sqrt{1-y}+1\right)^{-1+\frac{1}{1-q}}\left(\sqrt{1-y}-1\right)^2}\cdots\right.$$

$$\left.\cdots\int_{\sqrt{1-y}}^{1}\frac{(2-q)(s-1)^2}{(s+1)^{2-\frac{1}{1-q}}\left(q(s-1)+2\right)^{2+\frac{1}{1-q}}}ds\right],$$

or

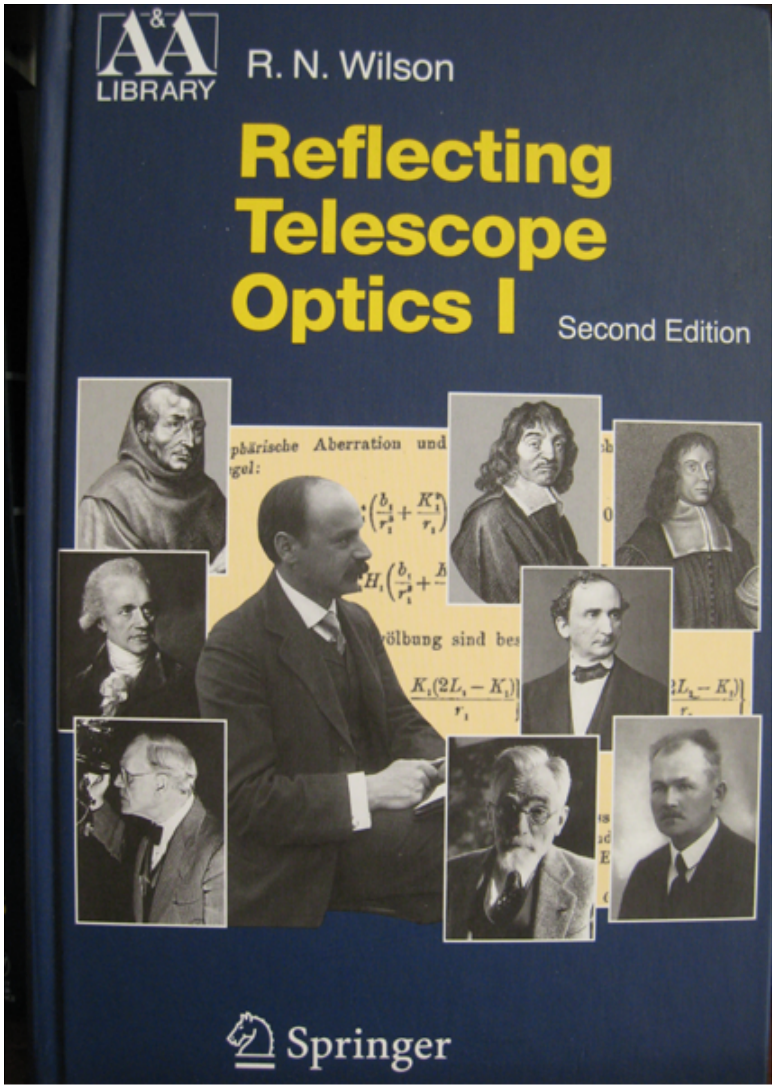
$$\Psi(y,q) = 1 - \frac{1}{2}\frac{\left(q\left(\sqrt{1-y}-1\right)+2\right)^{1+\frac{1}{1-q}}}{\left(\sqrt{1-y}+1\right)^{-1+\frac{1}{1-q}}}\left(\frac{1}{2} + q\int_0^y \frac{\left(\sqrt{1-x}+1\right)^{-1+\frac{1}{1-q}}}{\left(q\left(\sqrt{1-x}-1\right)+2\right)^{2+\frac{1}{1-q}}}dx\right). \tag{28}$$



Abbe sine condition

Integrable with the given specific initial conditions which of particular interest for aplanatic optics

Schwarzschild telescopes – History



K. Schwarzschild, Astronomische Mittheilungen von der Koeniglichen Sternwarte zu Goettingen, 10:3-28, 1905

In recognition of Karl Schwarzschild's contribution to optics development the analytical solutions for two-mirror telescopes are know as Schwarzschild aplanats

H. Chretien, Revue d'Optique Theorique et Instrumentale, 1, 49-64, 1922

Couder, A., Compt. Rend. Acad. Sci., Paris, 1926, 1276, pp 45-

A K Head, *Proc. Phys. Soc. B* 70 945, 1957 "The Two-Mirror Aplanat"-Finite foci system

D. Lynden-Bell Mon. Not. R. Astron. Soc. 334, 787–796 (2002) – claimed discovery of "exact optics" aplanatic solutions.

Karl Schwarzschild [1]
(Oct 9, 1873, Frankfurt – May 11, 1916, Potsdam)

- Born and grew up in Jewish community of Frankfurt;
- Published first two papers on the theory of orbits of binary systems (double stars) at the age of sixteen while still at the Frankfurt Gymnasium [influenced by Prof. J Epstein];
- Studied at the University of Strasbourg and obtained his doctorate at the University of Munich [Dissertation on the application of Poincare's theory of stable configurations of rotating bodies to tidal deformations of moons; supervised by Hugo von Seeliger];
- Worked at Von Kuffner Observatory (1896-1899) and at the University of Munich (1899-1901) on the apparent and visual brightness of stars realizing, correctly, that this was due to changes in the surface temperature and the radius of the variable star through its cycle;
- Discussed the possibility that space was non-Euclidean at a meeting of the German Astronomical Society in Heidelberg in 1900 (the radius of curvature of space > 0.8 kpc);

Karl Schwarzschild [2]

(Oct 9, 1873, Frankfurt – May 11, 1916, Potsdam)

- Was appointed as extraordinary professor at Göttingen and also director of the Observatory (1901-1909). Published on transport of energy through a star by radiation and on radiative equilibrium (instability) of a stellar atmosphere and fathered exact optics (1905). Collaborated with Klein, Hilbert and Minkowski.

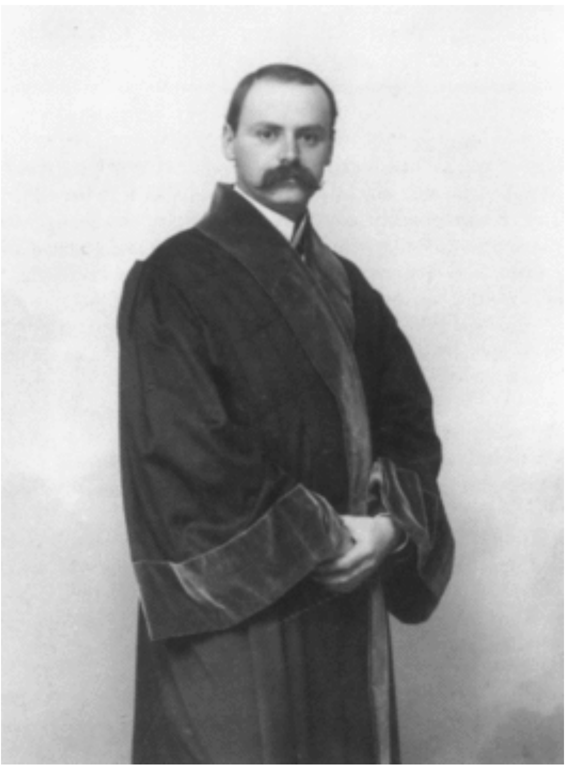
"… a man of his wide interests in all branches of mathematics and physics the surroundings must have been very congenial ..." Eddington

- Was appointed as director of the Astrophysical Observatory in Potsdam (1909), the most prestigious post available for an astronomer in Germany at that time, and studied photographs of the return of Halley's comet in 1910 taken by a Potsdam expedition to Tenerife;
- Elected to the Royal Astronomical Society of London (1909);

Karl Schwarzschild [3]

(Oct 9, 1873, Frankfurt – May 11, 1916, Potsdam)

- Elected to the Berlin Academy and to the German Academy of Sciences (1913). Extract from Schwarzschild admission speech



"Mathematics, physics, chemistry, astronomy, march in one front. Whichever lags behind is drawn after. Whichever hastens ahead helps on the others. The closest solidarity between astronomy and the whole circle of exact science. ... from this aspect I may count it well that my interest has never been limited to the things beyond the moon, but has followed the threads which spin themselves from there to our sublunar knowledge; I have often been untrue to the heavens. That is an impulse to the universal which was strengthened unwittingly by my teacher Seeliger, and afterwards was further nourished by Felix Klein and the whole scientific circle at Göttingen. There the motto runs that mathematics, physics, and astronomy constitute one knowledge, which, like the Greek culture, is only comprehended as a perfect whole.";

Karl Schwarzschild [4]

(Oct 9, 1873, Frankfurt – May 11, 1916, Potsdam)

- Volunteered for military service in August 1914 on the outbreak of WWI. Served in France where he was assigned to an artillery unit and given the task of calculating missile trajectories, and then was transferred to Russian front;
- While in Russian front wrote one paper on quantum theory (Stark effect) and two papers on Einstein's relativity theory (one of the papers provides first exact black hole solution of GR equations near point mass). Schwarzschild made it clear, however, that he didn't believe in the physical reality of BHs;
- Contracted a rare autoimmune illness while in Russia (pemphigus), was invalided home in March 1916 and died two months later.

  "The wide range of his contributions to knowledge suggests a comparison with Poincaré; but Schwarzschild's bent was more practical, and he delighted as much in the design of instrumental methods as in the triumphs of analysis. ... his joy was to range unrestricted over the pastures of knowledge…" Eddington

Cited from http://www-groups.dcs.st-and.ac.uk/~history/Biographies/Schwarzschild.html

Andre Couder

(1897-1979)

Andre Couder was young French Physicist who was appointed as the Director of the Dina Laboratory of the Paris Observatory in 1926 at the age of 29. In the same year he published brief paper (Couder, 1926) in which he started with Schwarzschild telescope (1905) optimized for minimal distortions in the flat focal plane and derived optical system (FoV 3 deg, f/3 of 0.8m aperture), which minimizes astigmatism (q=1/2) at the cost of introducing a curved focal surface.

Couder figured both mirrors for such a telescope (Fehrenbach 1980, Obituaries / Andre Couder) but they were never assembled and used because of the length of the tube (6m) and consequently expensive dome required for such an instrument. It is likely that the invention of the Schmidt camera in 1930 discouraged Couder from further work on this system. Andre Couder appears to have advocated the merits of his telescope only in the original paper (Couder 1926) and one book (Danjon & Couder 1935). To date no example has been successfully built in optical astronomy.

Other attempts of Schwarzschild's design

University of Indiana Kirkwood Observatory,
W.A. Cogshall made optical parts for 24-inch Schwarzschild reflector in 1928. Problems with the mounting have never been solved.

Ladd Observatory of Brown University, Providence, Rhode Island
C.H. Smiley made 12-inch mirror for Schwarzschild camera with f/3.5, no results were published.

G. W. Ritchey also worked at the Schwarzschild photographic reflector with aperture ratio of f/3 at Mt. Wilson Observatory (probably with Cretien) but this work was never completed.

"The principal reason for the neglect of the [Schwarzschild]-Couder telescope must surely be that astronomers of that time were not prepared, mentally, for such a large improvement in optical quality and focal ratio, nor was much of the technology available to take advantage of it. This must be a notable example of the operation of the <u>Principle of Unripe Time</u> (Cornford 1908)"   R. W Willstrop Mon. Not R. astr Soc. (1984) 209, 587

It is rather remarkable that SC-SST for VHE gamma-ray astronomy was constructed at the Paris Observatory, the place where one of the first attempts to construct Schwarzschild telescope was undertaken by A. Couder nearly 90 years ago.
In fact, there is more to this story…

RITCHEY-CHRÉTIEN TELESCOPE STORY

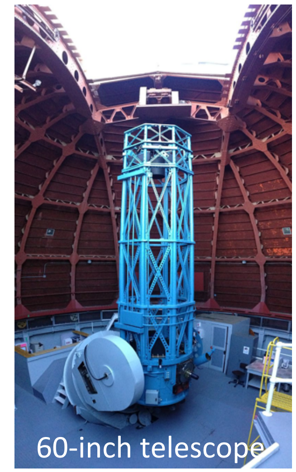
Ritchey-Chrétien telescope story

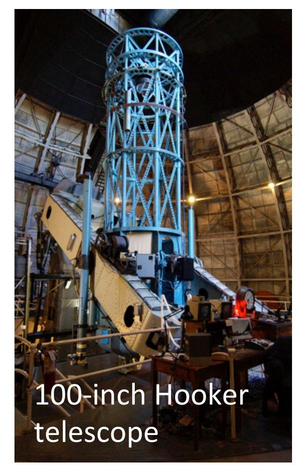
Andre Couder was appointed as the Director of the Dina Laboratory of the Paris Observatory in 1926 to replace George Wills Ritchey who was just fired from this position.

George Willis Ritchey (1864-1945)

His father was an amateur astronomer who fled Ireland for America during the potato famine of the mid 19th century.

- George Ritchey (American astronomer) prominently established himself in the development and construction of 60-inch and 100-inch telescopes of Mt. Wilson Observatory, CA, USA as director of Pasadena optical and mechanical shops.
- Ritchey met Henri Chrétien (French astronomer) in 1910 at Mt. Wilson Observatory, and begun work on building a prototype telescope based on the "new curves" (M1 diameter: 27 inches, M2 diameter: 9 inches).
- In 1914 the work on the prototype RC telescope had ceased due to deteriorating relationships between Ritchey and Hale (Mount Wilson Observatory's Director) when blueprints of the telescope mounting were nearly completed. In 1919 Ritchey was fired.





Cited from "Catchers of the Light: The Forgotten Lives of the Men and Women Who First …"

Ritchey-Chrétien telescope story

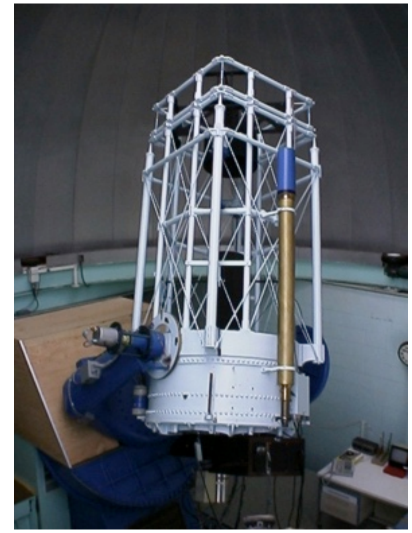
- Ritchey continued his work on the smaller version of RC telescope in his own workshop in Pasadena and was later invited to continue his work in France at the Paris Observatory (arrived in 1924).
- Within a month of his arrival Ritchey decided to construct the largest telescope ever built (5-6m segmented mirror with new "fixed universal" mount) instead of 104-inch reflector originally designed. **It was classic case of running before you could walk** and everybody ended up falling over Ritchey. Although it was a visionary plan, significant fraction of French astronomers deemed Richey insane and crazy.

- French "stakeholders" of RC telescope construction ordered independent assessment of the project in 1925 which was lead by Andre Danjon (his colleague Andre Couder participated) estimated project at $350K (!). In April of 1926 project was closed and Ritchey was fired.
- Ritchey continued to work on 0.5m RC telescope design now in competition with Andrew Couder who initiated work on 0.8m RC telescope at Paris Observatory.
- In 1930, after twenty years of trying the first RC had been built, but had only produced results far inferior to those produced with much cheaper telescopes of the day.

Cited from "Catchers of the Light: The Forgotten Lives of the Men and Women Who First …"

Ritchey-Chrétien telescope story

- Ritchey returned to US and eventually received contract to build a 40-inch RC from USNO. Telescope was build in 1934 in the area of City of Washington but due to significant light contamination never produced spectacular results.
- Ritchey died in 1945 on his ranch at Azusa, Los Angeles CA.
- In 1955 the 40inch RCT was moved to Flagstaff, AZ from Washington where it started to produce spectacular results and it is still in operation today.
- RC optical design today is used in the construction of the world's most famous telescopes.



The 40inch RCT United States Naval Observatory Flagstaff Station

Examples of large Ritchey–Chrétien telescopes
The 2.4 m Hubble Space Telescope
The four 8.2 m telescopes comprising the Very Large Telescope in Chile
The two 10.0 m telescopes of the Keck Observatory
The 8.2 m Subaru telescope at Mauna Kea Observatory
The two 8.0 m telescopes comprising the Gemini Observatory
The 10.4 m Gran Telescopio Canarias at Roque de los Muchachos Observatory

10m Keck R-C segmented telescopes atop Mauna Kea

History has sided with Ritchey

Cited from "Catchers of the Light: The Forgotten Lives of the Men and Women Who First …"

R-C telescope history lessons

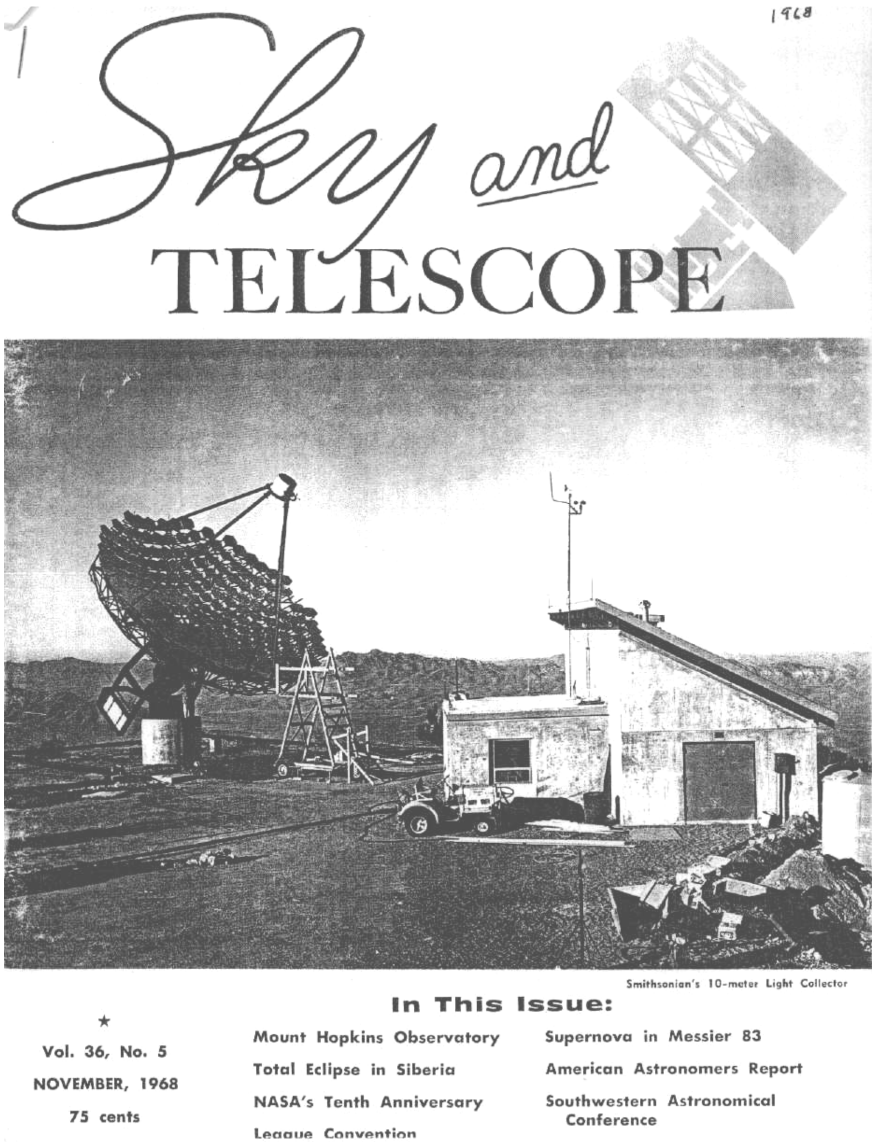
There are at least three lessons to learn from the RC telescope development history:

- **Lesson 1:** "Principle of Unripe Time" detrimentally affected the development of the Ritchey-Chretien design primarily due to the resistance of peers who didn't wish to change and/or could not accept a promise of superior performance of RCTs and could not be motivated to take the risks. SC-MST design for CTA is well motivated by simulations and we are grateful to NSF and all contributing funding agencies for taking the risk.
- **Lesson 2:** "Do not run before you could walk." MRI pSCT is considerably ambitious project, which attempts to demonstrate its advantages for SC-MST. However, pSCT team is not developing this project in "vacuum" we are eager to collaborate with and learn a great deal of experience from MST, ASTRI and GCT teams to make the pSCT a success story.
- **Lesson 3:** Adequate funding is essential for the success of the projects pioneering the field.

FLWO

Whipple 10m is the first multi-mirror telescope

(arguably)



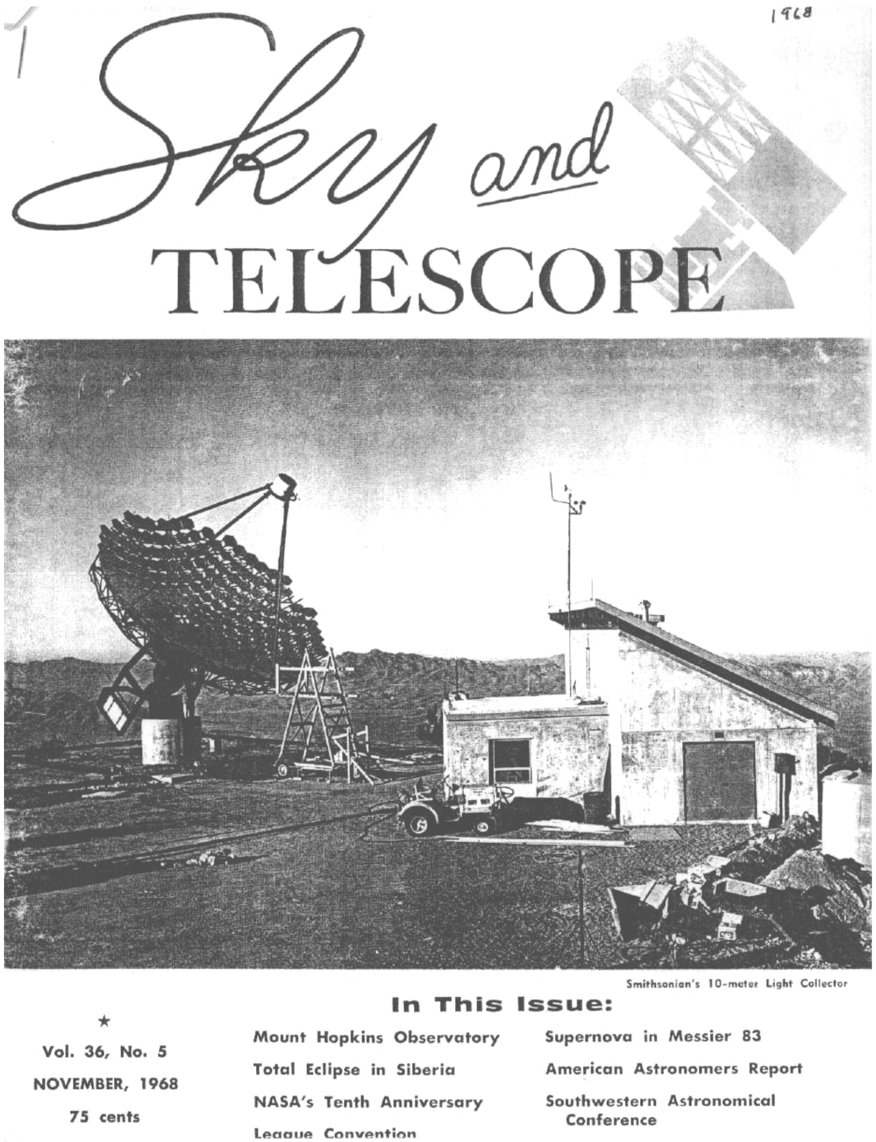
Unsuccessful attempts:

- William Parsons in late 1800s (two pieces);
- G.W. Richie "crazy" ideas in early 1920s;
- After World War II, G. Horn-d'Arturo assembled a 1.8m Zenith Telescope at the University of Bologna with mirror composed of 61 8inch segments. *(I wonder if this has anything to do with the choice of Bologna as CTA HQ?...);*
- Turku University Observatory in Finland, hosted fixed mount telescope which had 6 12.6inch mirrors mounted on a single rigid cell;

First successful attempt of moving telescope:

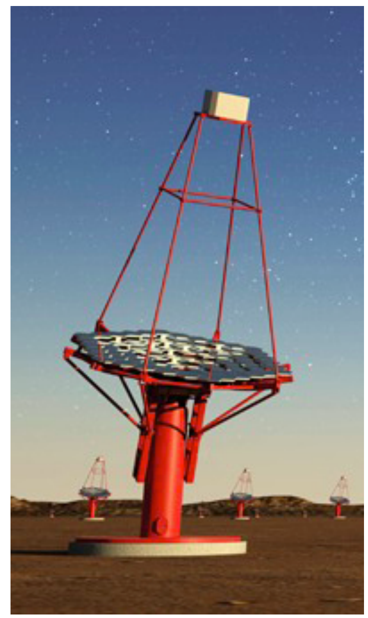
A giant …., 10m Whipple telescope, was erected on Mount Hopkins in November of 1968.

Whipple 10m is the first multi-mirror telescope
(arguably)



"Since 1968 not much has changed - 10m DC telescopes still rule the gamma-ray sky!"

by the same local Artist at TrevorFest



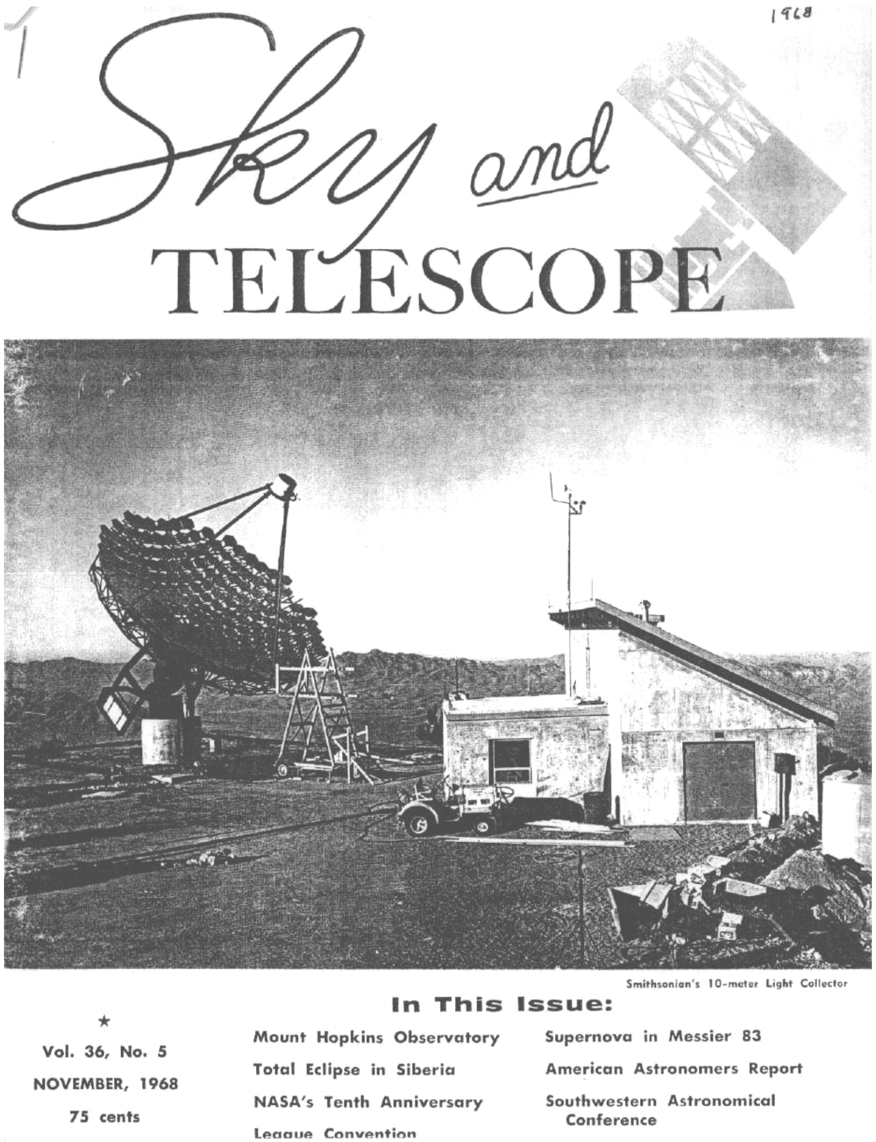
DC-MST for CTA

First successful attempt of moving telescope:

A giant …., 10m Whipple telescope, was erected on Mount Hopkins in November of 1968.

Whipple 10m is the first multi-mirror telescope

(arguably)


Sky and TELESCOPE

Smithsonian's 10-meter Light Collector

In This Issue:

Vol. 36, No. 5
NOVEMBER, 1968
75 cents

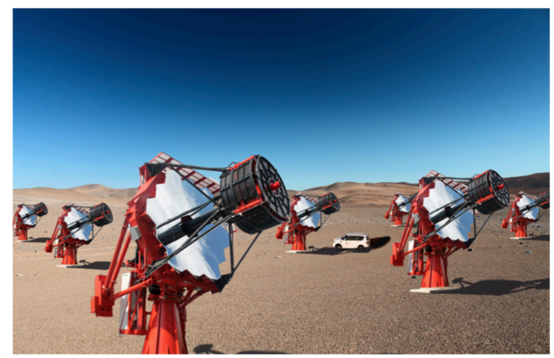
Mount Hopkins Observatory
Total Eclipse in Siberia
NASA's Tenth Anniversary
League Convention

Supernova in Messier 83
American Astronomers Report
Southwestern Astronomical Conference

"Since 1968 not much has changed - 10m DC telescopes still rule the gamma-ray sky!"

by the same local Artist at TrevorFest

SC-MST and DC-MST for CTA

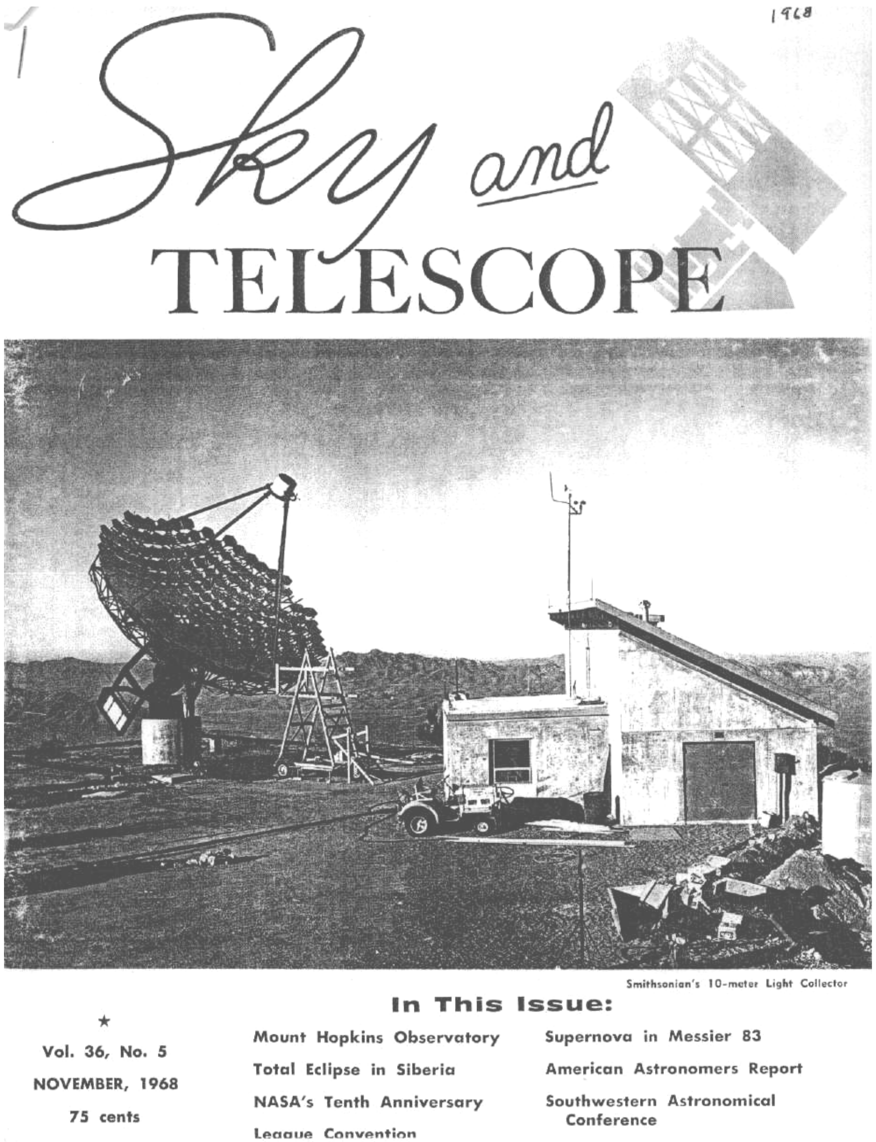


First successful attempt of moving telescope:

A giant …., 10m Whipple telescope, was erected on Mount Hopkins in November of 1968.

Whipple 10m is the first multi-mirror telescope

(arguably)



They called it

"Non-coherent multiple-mirror light-backet"

Behind the back they called it

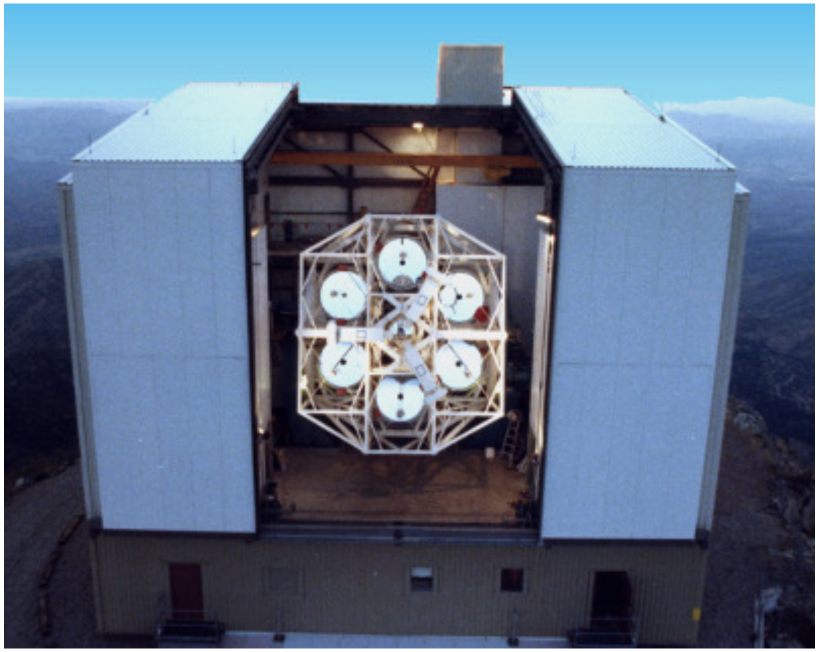
"Big dumb light-backet"

In Unusual Telescopes, P.L. Manly

248 segments, f/0.73, PSF- 2.5 inch

First successful attempt of moving telescope:
A giant light collector was erected on Mount Hopkins in November of 1968.

True First Multi-mirror Telescope



MMT on Mt. Hopkins was completed in 1978
6 separate 72 inch f/2.7 mirrors (176 in telescope equivalent). F=194 in

MMT was used mostly for:

- Spectroscopy and Photometry in Infrared;
- For speckle interferometry of space satellites;
- During the daytime as a sub-millimeter wavelength radio telescope!

Fred Lawrence Whipple Observatory
Multi Mirror Telescope (MMT)

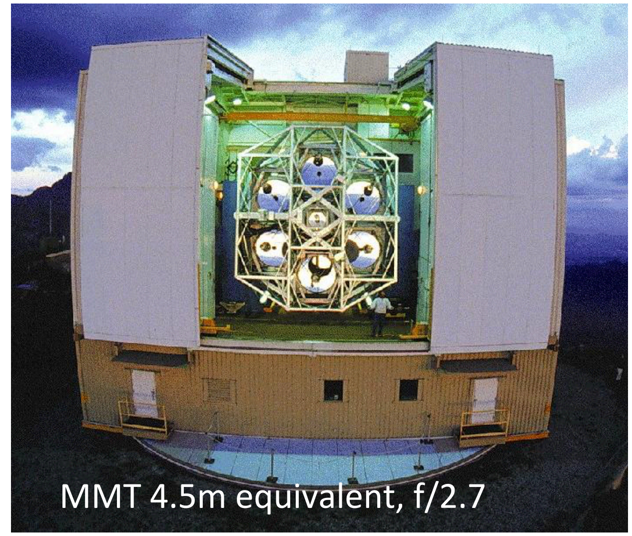
Rigorous design of alt-az mount and OSS was done in 1970s to assure that it is possible to correct gravitational load utilizing Serrurier truss, when motion of OSS elements happens but nearly compensate each other. Computer controlled active optics was employed to adjust each mirror for coherency. Special dome was constructed to control thermal loads

Re-alignment was required every few minutes or if the telescope slewed to a different part of the sky.

Cited from "Unusual Telescopes" by Peter L. Manly

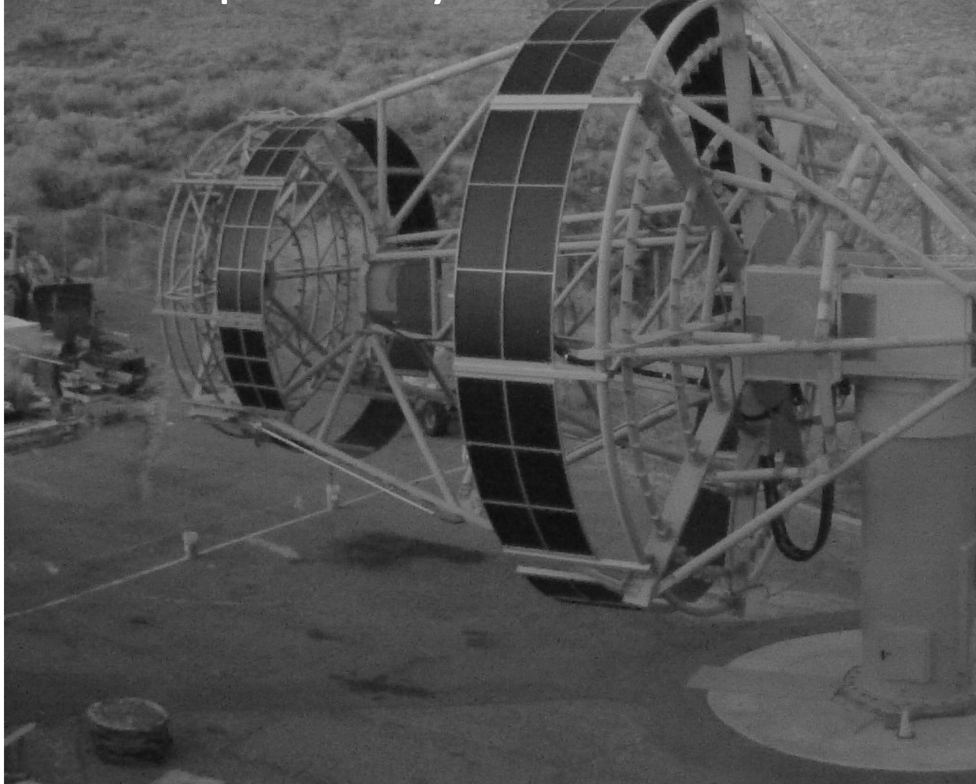
FLWO, the "cradle" of multi-mirror telescopes

Evolution from " light-bucket" to telescope



Will be used for:

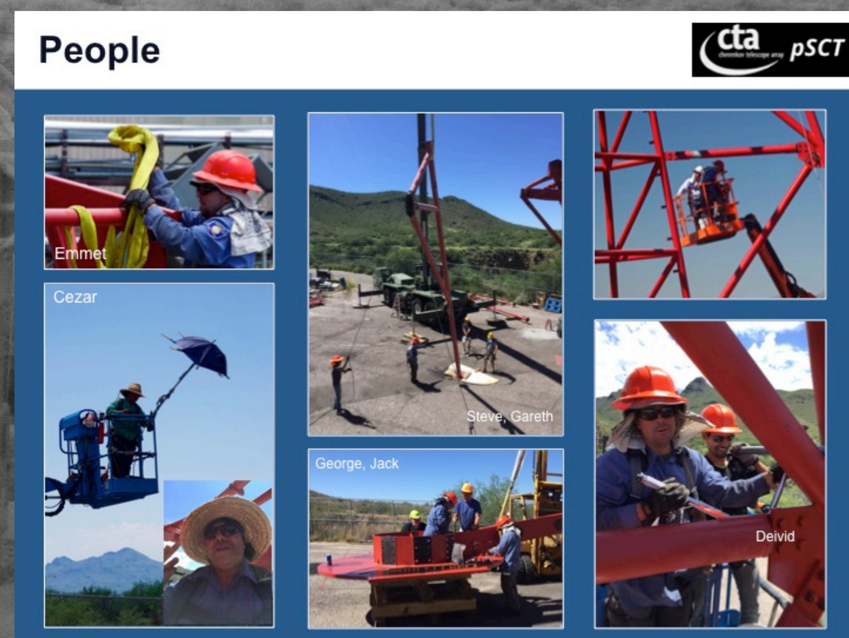
- **Mostly for gamma-ray Observatory;**
- **Intensity Interferometry;**
- **SETI;**
- **Solar Concentration;**
- **Possibly mm/sub-mm radio telescope in the day time.**



Acknowledgement:

Many Thanks to everybody who

- Took the risk and approved this project
- Funded MRI
- And helped to design pSCT and bring the project to the state where we are today
- Particularly I wanted to thank FLWO personnel for great contribution during the period of civil engineering work and telescope assembly.



http://cta-psct.physics.ucla.edu

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To Be Continued…

Action…