Off-Axis Reflective Optics for EO/IR Camera Onboard CubeSat: Linear Astigmatism Free - Three Mirror System (LAF-TMS)

2024 CubeSat Developers Workshop

2024 April 23-25, CalPoly, San Luis Obispo, CA

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Inyoung Hwang, Kyung-Su Na (Agency for Defense Development, Korea)

Background

Soojong Pak (CV)

EO
(**E**lectro-**O**ptics)

IR
(**I**nfra**R**ed)

Educations

1990 Feb	B.S. Astronomy, Seoul National University, Korea
1997 Aug	PhD. Astronomy, Univ of Texas at Austin, US

Job Experiences

1997 Aug – 1998 May	Postdoc, Max-Planck-Institut für extraterrestrische Physik, Germany (Infrared Spectrograph, SINFONI)
1998 Sep – 2002 Dec	Assistant Prof., Astronomy, Seoul National University
2001 Aug – 2002 Aug	Visiting Associate Professor, ISAS/JAXA, Japan (Space Infrared Telescope, AKARI)
2002 Dec – 2006 Feb	Senior Researcher, Korea Astronomy and Space Science Institute (Space Infrared Telescope, SPICA)
2006 Mar – Now	Professor, Astronomy and Space Science, Kyung Hee University

(Astronomical Optical and Infrared Instrumentation and Observation)

Electromagnetic Wave (EO/IR Bands)

Band	Full Name	λ [μm]	Sensor	Optics
EO	Visible	0.4 – 0.7	Si	
NIR	Near-infrared	0.7 – 1.1	Si	
SWIR	Short-Wavelength Infrared	1.1 – 3	InGaAs, HgCdTe (MCT)	
MWIR	Mid-Wavelength Infrared	3 – 5	MCT, InSb (Cooled Photoconductor)	Si, Ge, ZnSe, ZnS F/D < 5
LWIR	Long-Wavelength Infrared	8 – 14	(Uncooled Microbolometer)	Chalcogenide, Ge F/D < 1.2

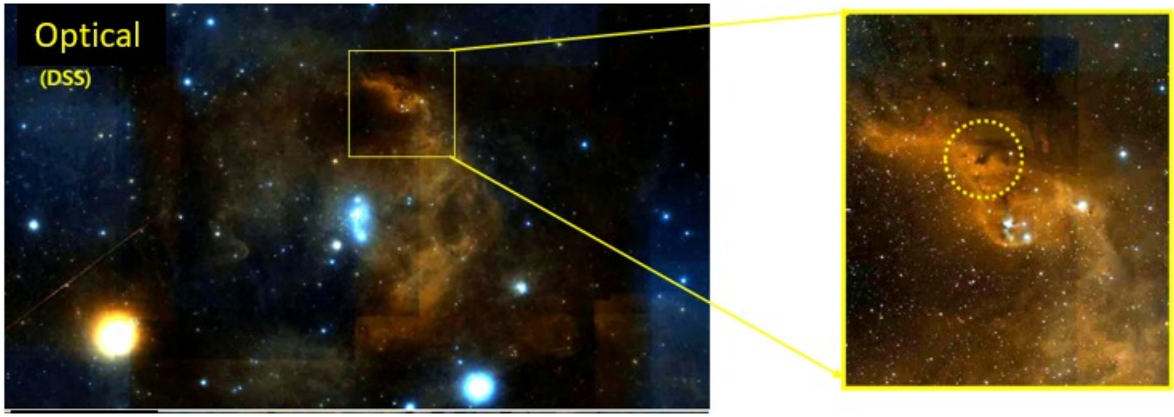
reflected radiation

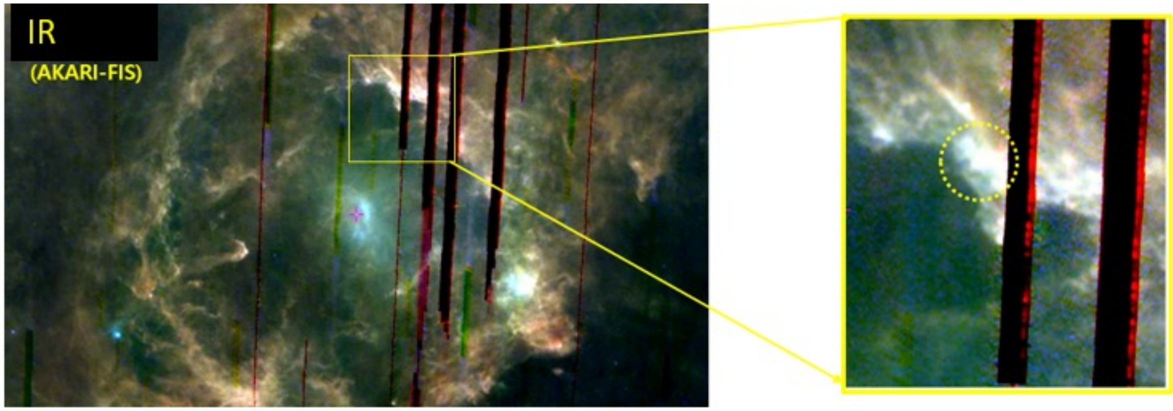
thermal radiation

Driggers et al. (2022, Introduction to Infrared and Electro-Optical Systems) classifies that ***EO*** systems are those that respond to wavelengths within the 0.4 to 3-mm region, where the light collected by an EO sensor was reflected by objects in the scene. The ***MWIR and LWIR*** band imagers are called forward-looking infrared (FLIR) systems or imaging infrared (IIR) sensors.

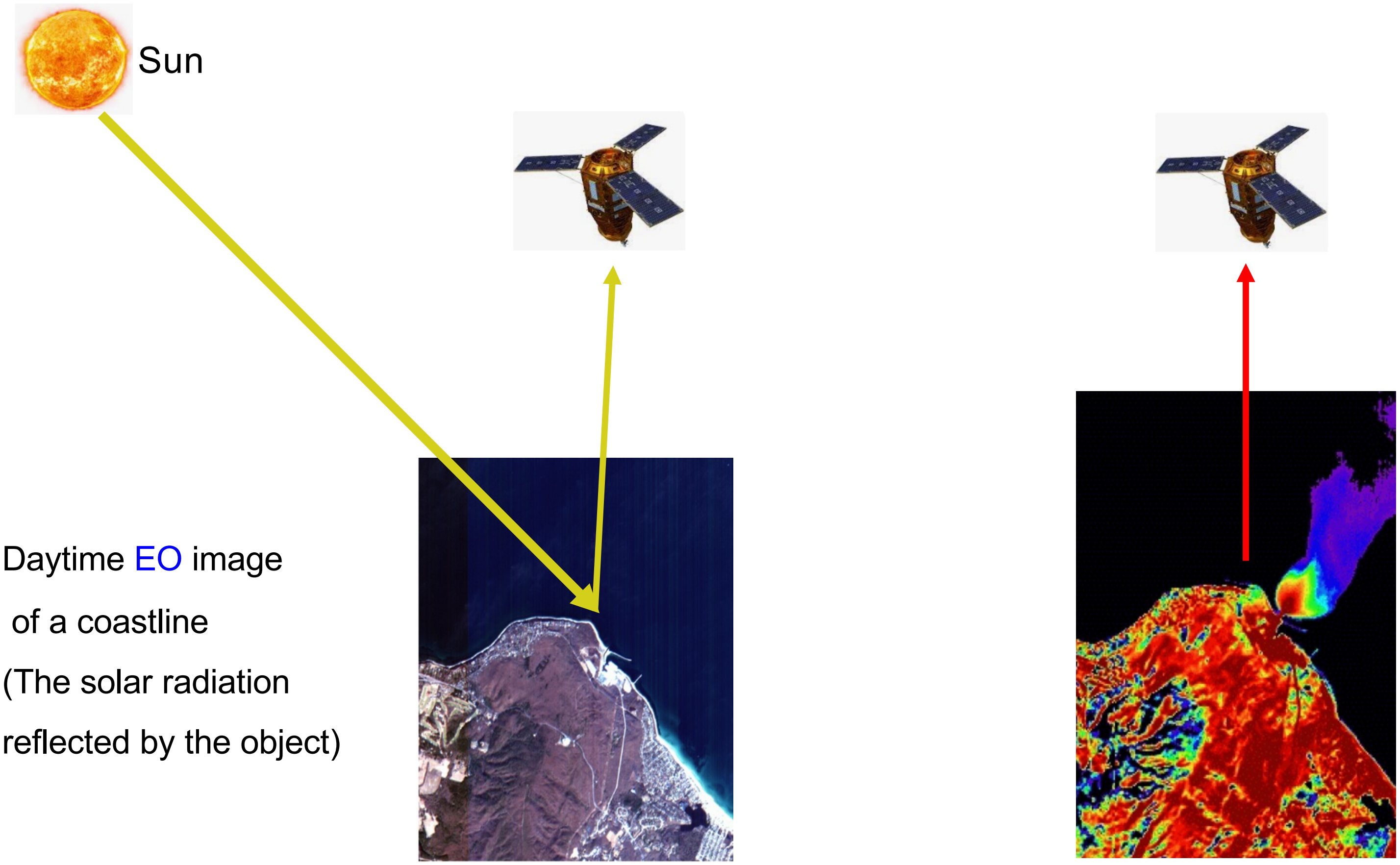
Optical & IR Astronomy

Star Forming Molecular Cloud (λ Ori)





Space-based EO/IR Remote Sensing (Surveillance Reconnaissance)

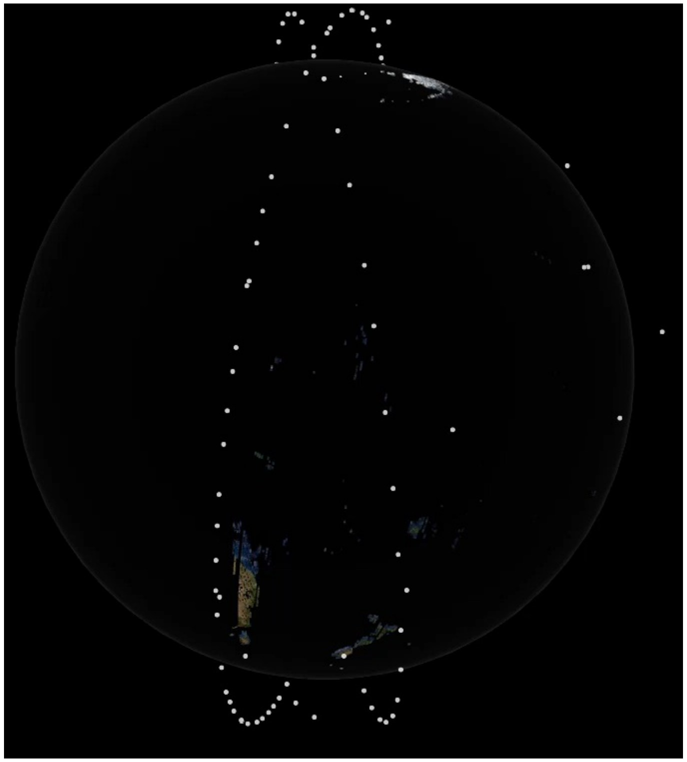


Daytime EO image
of a coastline
(The solar radiation
reflected by the object)

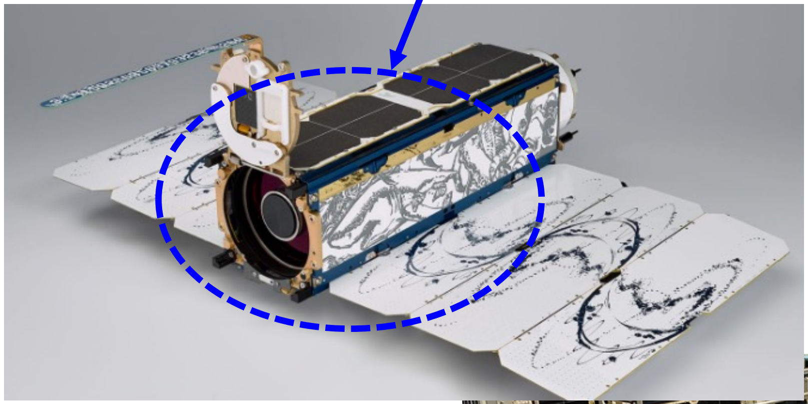
Nighttime IR image
of a coastline
(The radiation directly
from the object)

EO Camera on CubeSat

- Planet Labs launched 452 CubeSats (3U).

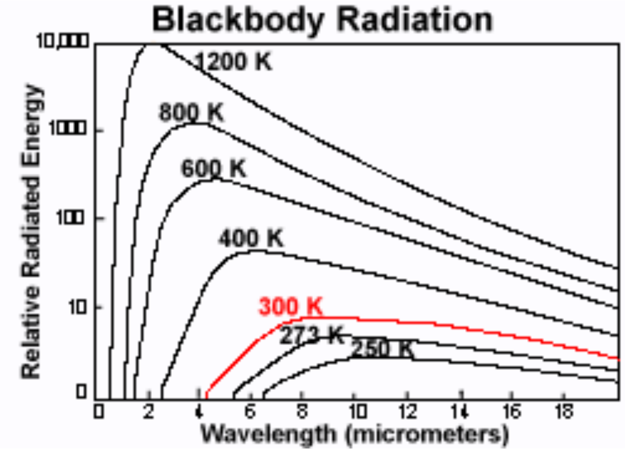


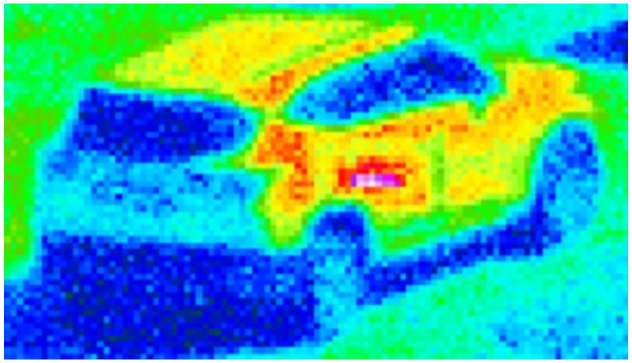
Catadioptric system (???)
(ON-Axis Reflective &
Refractive Corrector)



IR Technology

IR Radiation (Planck Function)





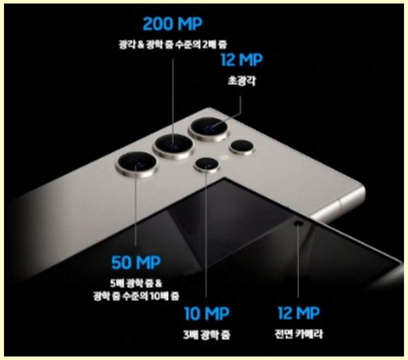
$$I_\lambda(T) = \varepsilon \frac{2hc^2}{\lambda^5} \frac{1}{\exp(hc/k\lambda T) - 1}$$

***IR** Radiation is a function of **emissivity (ε)** and **temperature (T)**.*

IR Camera = IR Sensor + **IR Optics**

IR Sensor

Samsung Galaxy S24 Smart Phone



IR Optics

IR Telescope

Requirements of **IR** Telescope

- Optical Resolution $\approx 1.22 \frac{\lambda}{D} h$

  Small Spatial Resolution @ D ↑ and λ ↓

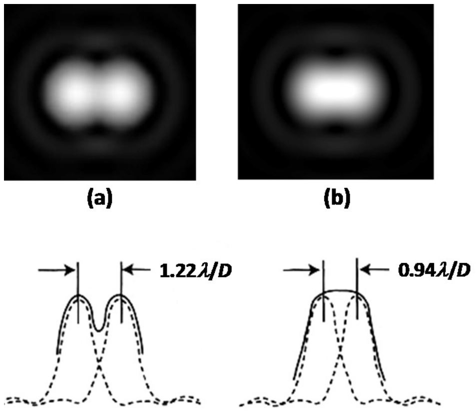
  *==> IR needs **large D** optics.*

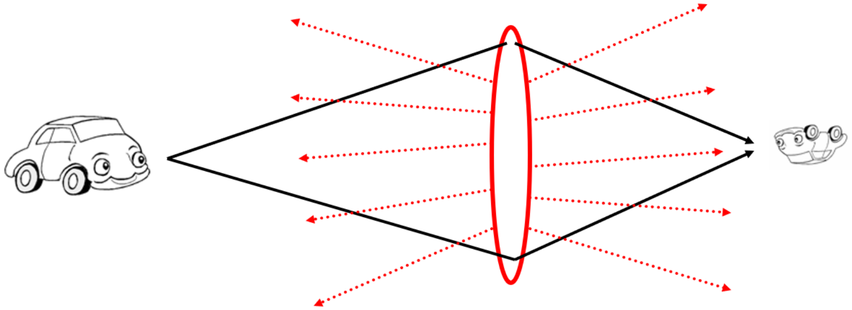
- Radiometry

  IR emission from optics increases the noise.

  *==> IR needs **small F/D** ratio optics,*

  e.g., fast optics.

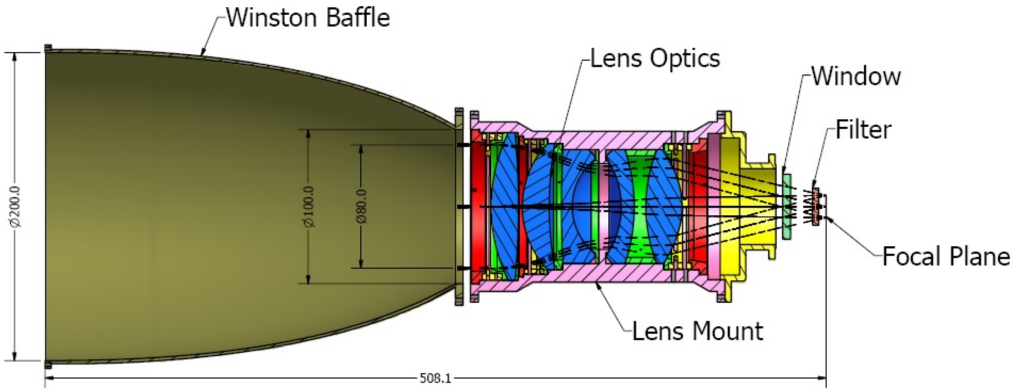




Refractive IR Telescope

Example of MIRIS/STSAT-3

- Developed by Korea Astronomy and Space Science Institute
- Lunched in 2013 Nov
- Astronomical Survey at 1.1 – 1.6 um.



Instrument

Summary

The following table summarizes the specification of MIRIS.

Item	Parameter	Specification	Remark
Telescope	Aperture	80 mm	
	F-number	F/2	
	Focal length	160 mm	
	Field of View	3.67°×3.67°	
Detector	Teledyne PICNIC (HgCdTe)		
	Detector array	256 × 256	
	Pixel size	40 μm	
	Pixel scale	51.6″	
Filters	Broadband	1.1 & 1.6 μm	Δλ/λ ≳ 0.5
	Narrowband	PAAL & PAAC	
Orbit	Low Earth, Sun-synchronous orbit		
	Altitude	about 620 km	
	Inclination	97.8°	
	MLTAN [1]	22.3 o'clock	

[1] Mean local time of ascending node

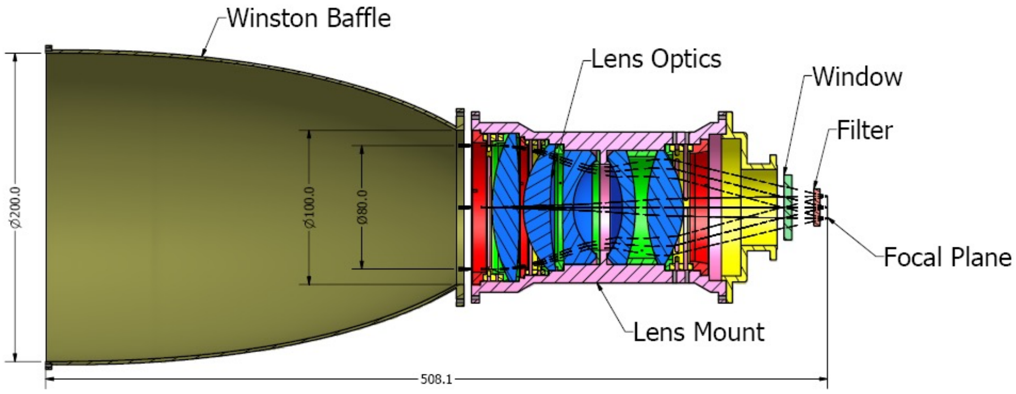
Refractive IR Telescope

Pros

- Good ***optical Performances***
- Confirmed ***fabrication methods*** for lens

Cons

- Limited ***lens materials* @ > 5** μm
- Heavy weight
- Complex ***opto-mechanical*** structures



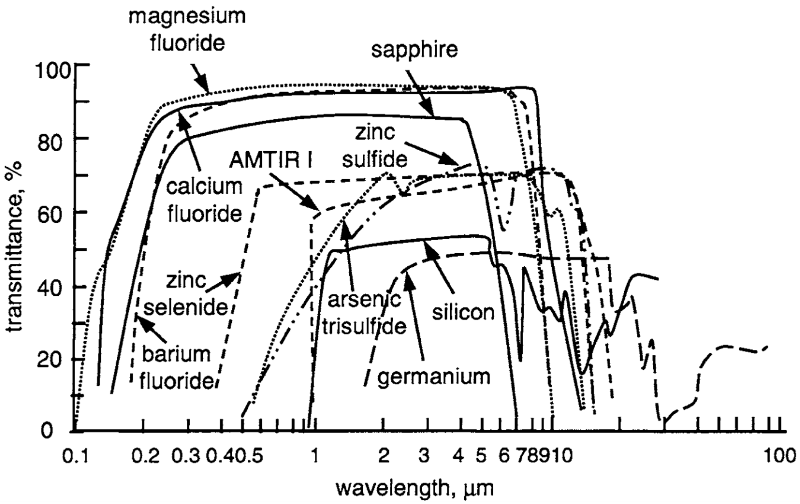


Figure 12.13 in Robert E. Fisher et al. (2008, Optical System Design)

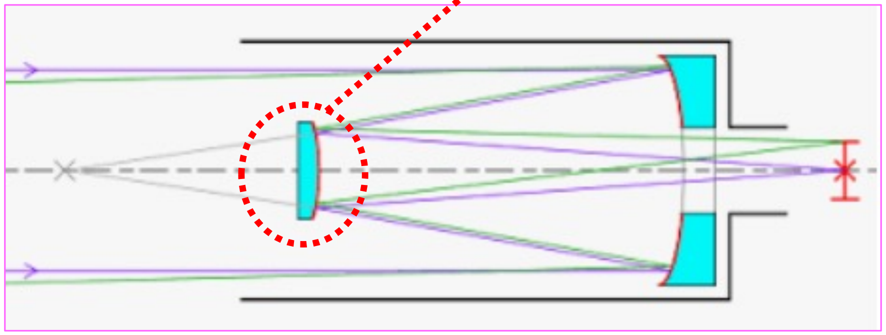
On-Axis Reflective Telescope

Cons

- ***Central Obstruction*** by secondary mirrors
  - ✓ Limited FoV: Smaller F/D ratio needs larger secondary mirrors.
  - ✓ Diffraction by the secondary mirror degrades the optical resolution (MTF).

Pros

- Confirmed ***fabrication methods*** for mirrors.
- Easy optics ***alignment***



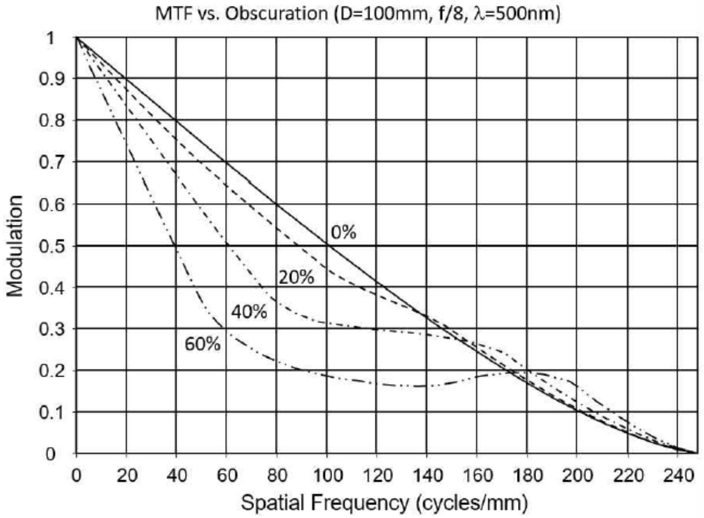
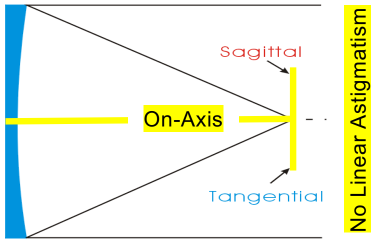


Fig. 4 in Pak, Chang, and Lee (2023, Journal of Korean Space Association for National Defense)

OFF-Axis Reflective Telescope



Pros

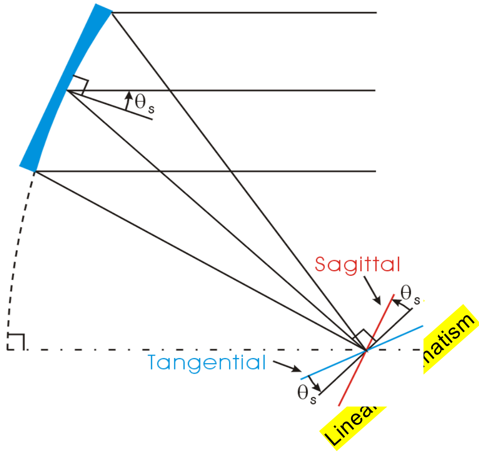
- ***NO abstraction***

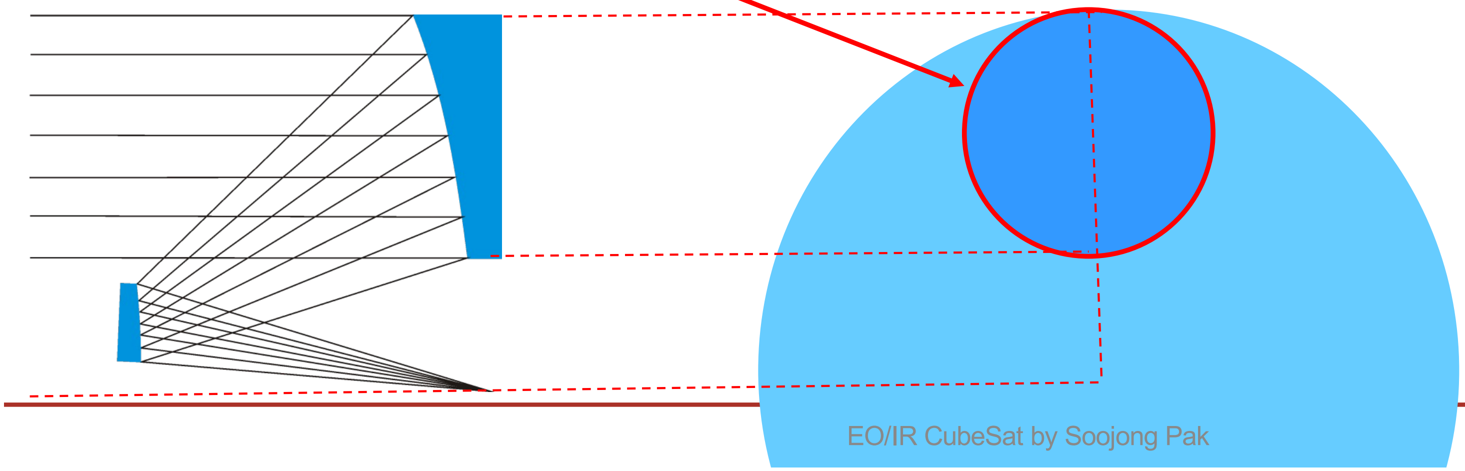
  of secondary mirror
- Confirmed

  fabrication methods for mirrors

Cons

- High ***linear astigmatism***





Innovative Off-Axis Reflective Telescope with ***Linear Astigmatism Free (LAF)*** Condition

Innovative Off-Axis Reflective Design (*a.k.a. Chang Theory*)

- Dr. Seunghyuk Chang found analytic solutions with which the linear astigmatism is eliminated, using ***the optical path length method*** by Karl Schwarzschild in 1905.

- References
  - **S. Chang 2003, PhD Thesis, University of Southern California**
    "Geometrical theory of aberrations for Classical Offset Reflector Antennas and Telescopes“
  - S. Chang and A. Prata, Jr. 2005, Journal of the Optical Society of America A 22, 2454-2464
    "Geometrical theory of aberrations near the axis in classical off-axis reflecting telescopes“
  - S. Chang, J. H. Lee, S. P. Kim, H. Kim, W. J. Kim, I. Song, and Y. Park, 2006, Applied Optics 45, 484-488
    "Linear astigmatism of confocal off-axis reflective imaging systems and its elimination“
  - S. Chang, 2015, J. Opt. Soc. Am. A 32, 852-859
    “Linear astigmatism of confocal off-axis reflective imaging systems with N-conic mirrors and its elimination“

Coaxial Off-Axis vs. **Confocal** Off-Axis (Chang Theory)

Previous Theory: Coaxial Off-Axis

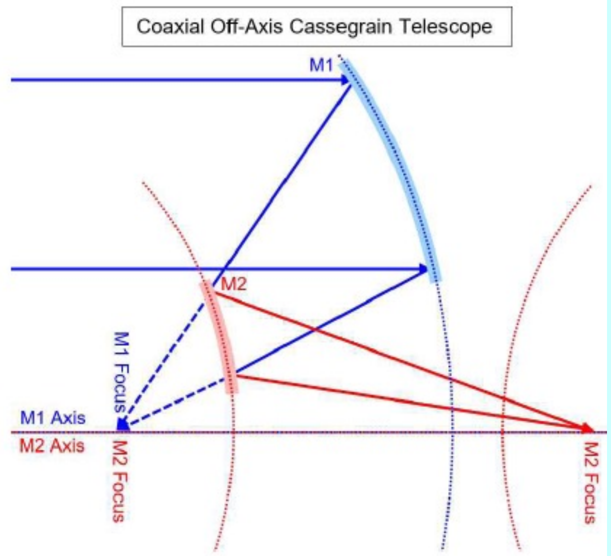


그림 5. 동축 비축 카세그레인 망원경의 광학 구조
(Fig 5. Schematic optical layout of coaxial off-axis Cassegrain telescope)

Chang's Theory: Confocal Off-Axis

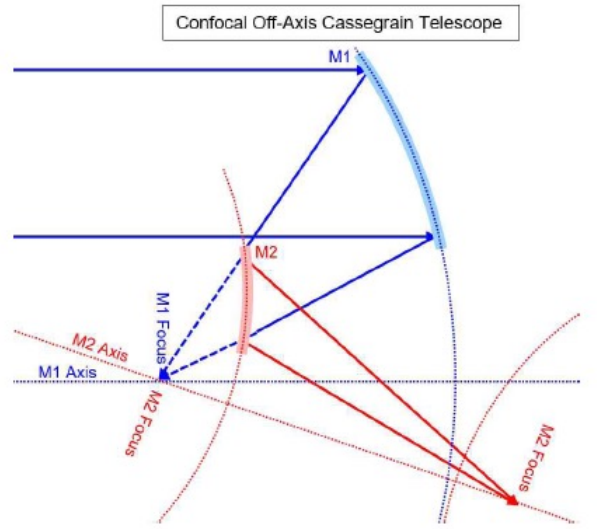
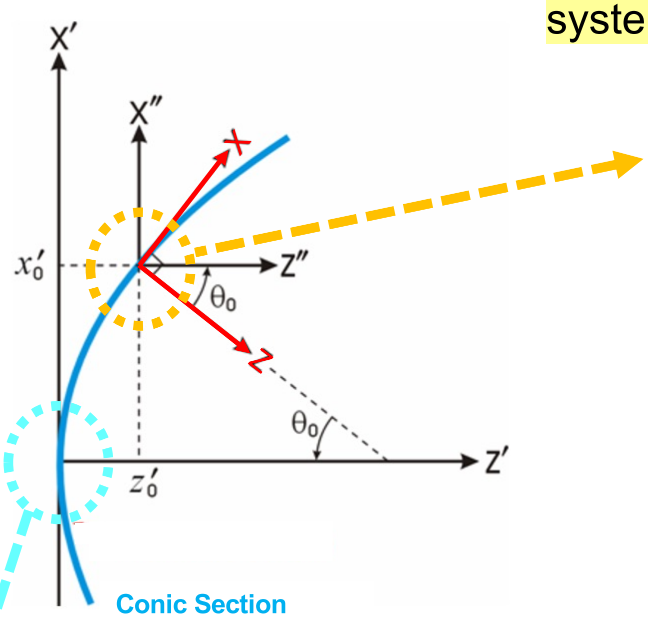


그림 9. 동초점 비축 카세그레인 망원경의 광학 구조
(Fig 9. Schematic optical layout of confocal off-axis Cassegrain telescope)

Vertex Equation in Geometrical Optics



- **Vertex equation in the Localized** coordinate system at (x_0', z_0')

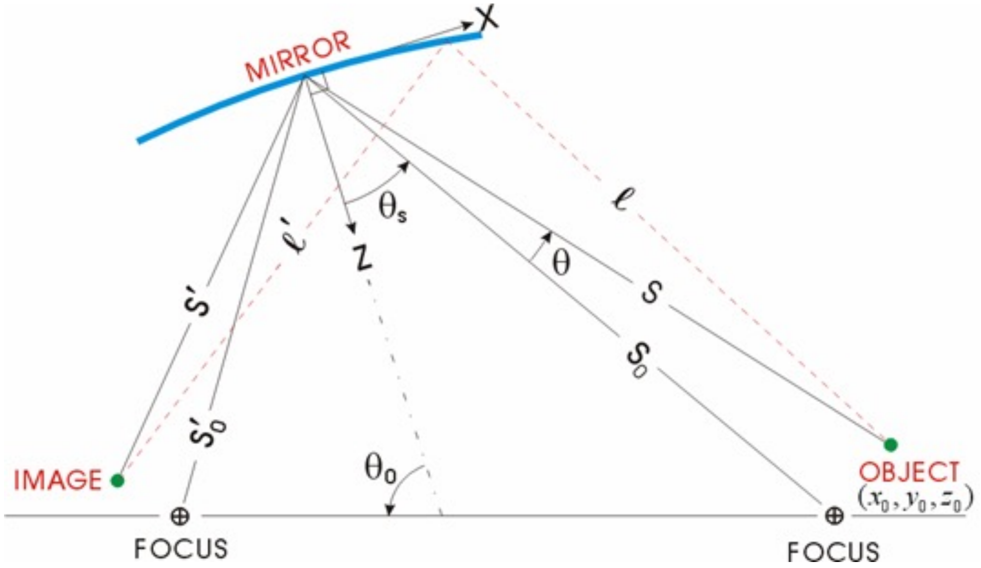
$$(1-K\cos^2\theta_0)z^2 - \left(xK\sin 2\theta_0 + \frac{2R}{\sqrt{1-K\sin^2\theta_0}}) \right) z + (1-K\sin^2\theta_0)x^2 + y^2 = 0$$

- Vertex equation of conic sections of revolution :

$$\rho'^2 - 2Rz' + (1-K)z'^2 = 0$$

Optical Path Length (OPL)

- The OPL is constant in a perfect focusing mirror.
- The variance of the OPL yields aberrations



$$OPL = \ell + \ell' = s + s' + \underbrace{A_1 x^2 + A_1' y^2}_{\text{Astigmatism}} + \underbrace{A_2 x^3 + A_2' xy^2}_{\text{Coma}} + O(4)$$

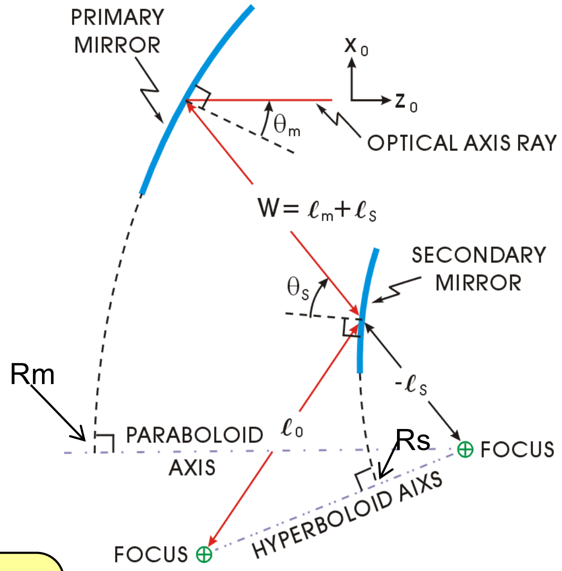
Aberrations of Two-Mirror Off-Axis Telescope

Coma $ATC = \theta \frac{3x_0^2}{4f^2}$

The 3rd order Coma is identical to the On-Axis telescope.

Astigmatism

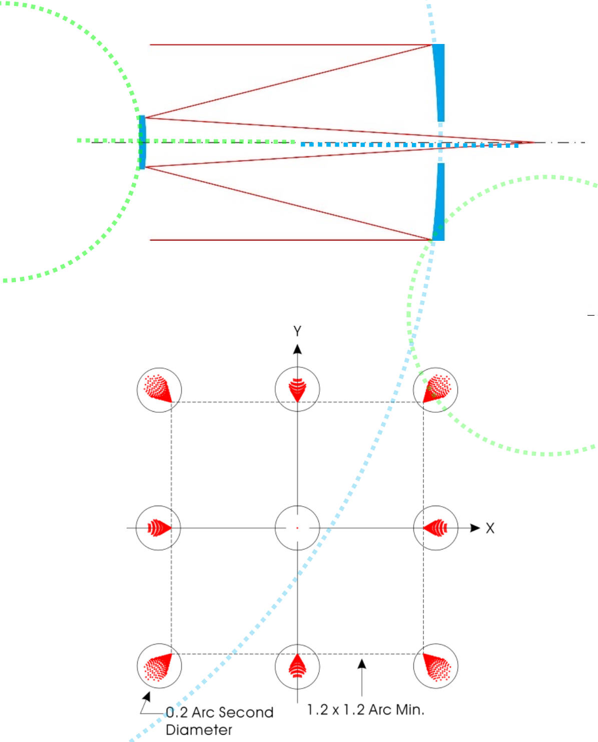
$$\frac{\Delta s'}{f} = \underbrace{2\theta\left(\frac{\ell_m}{\ell_s}\frac{\sin 2\theta_m}{R_m} - \frac{\sin 2\theta_s}{R_s}\right)\ell_0}_{\text{Linear Astigmatism}} - \underbrace{\frac{\theta^2}{\ell_0}\left[W - f\left(1+\tan\theta_m \tan\theta_s\right)\right]}_{\text{3rd Order Astigmatism}}$$



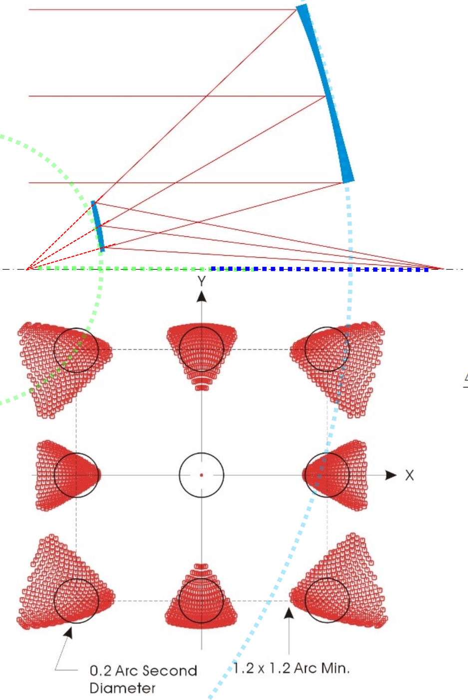
Linear Astigmatism is eliminated at $\frac{\ell_m}{R_m}\sin 2\theta_m = \frac{\ell_s}{R_s}\sin 2\theta_s$

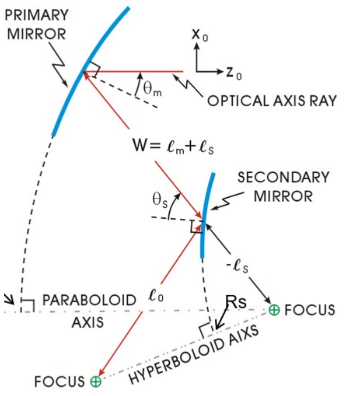
Example: F/8 Classical Cassegrain

축대칭
On-Axis



동축 비축
Coaxial Off-Axis

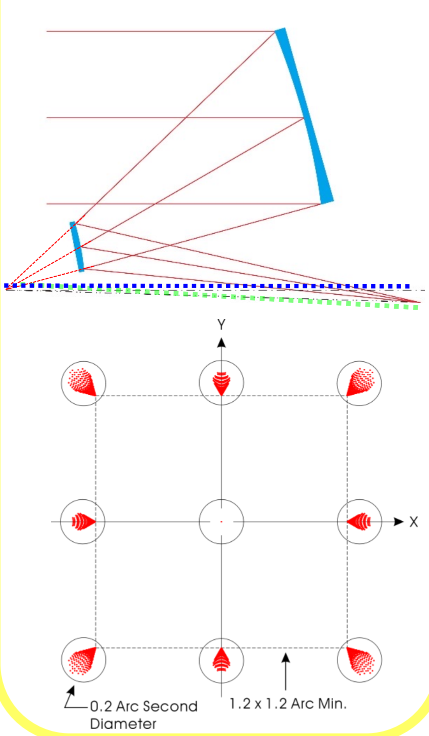




$$\frac{\Delta s'}{f} = \underbrace{2\theta\left(\frac{\ell_m}{\ell_s}\frac{\sin 2\theta_m}{R_m} - \frac{\sin 2\theta_s}{R_s}\right)\ell_0}_{\text{Linear Astigmatism}} - \underbrace{\frac{\theta^2}{\ell_0}\left[W - f\left(1 + \tan\theta_m \tan\theta_s\right)\right]}_{\text{3rd Order Astigmatism}}$$

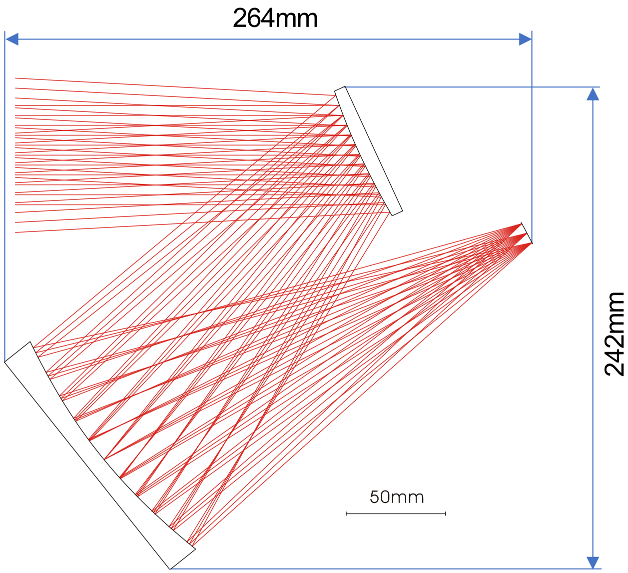
$\frac{\ell_m}{R_m}\sin 2\theta_m = \frac{\ell_s}{R_s}\sin 2\theta_s$ 의 조건에서 선형비점수차가 제거된다.

동초점 비축
Confocal Off-Axis)



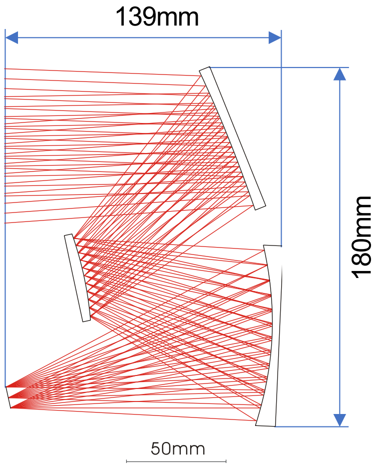
LAF 2-Mirror vs. 3-Mirror System

D50mm F/2 Wide Field Space Telescope

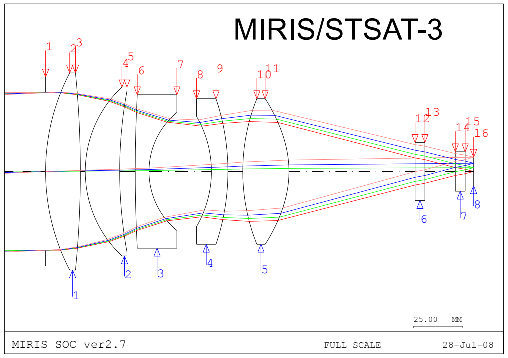


Linear Astigmatism Free 2-Mirror Design
(Schwarzschild-Chang Type)

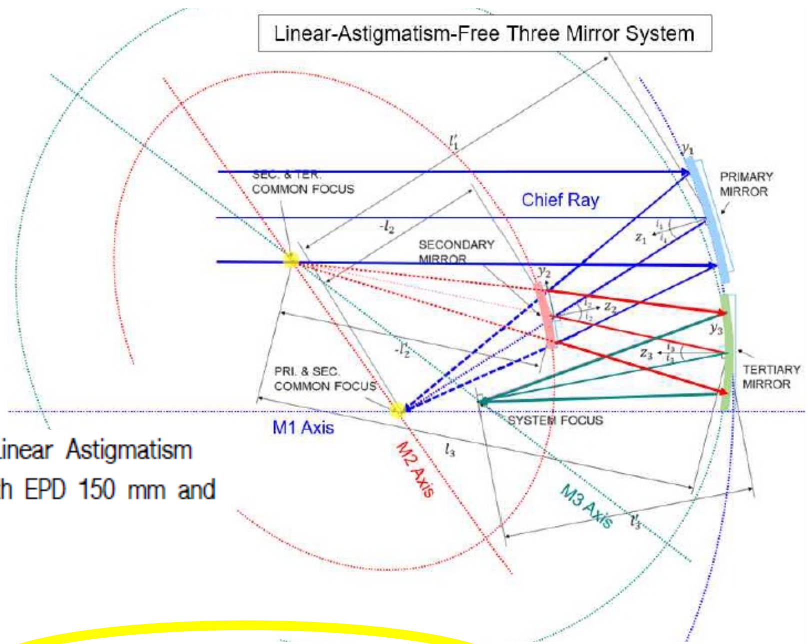
Kim, Pak, Chang et al., 2010



LAF-TMS:
Linear Astigmatism Free
Three Mirror System



Three Mirror Anastigmat (TMA) vs LAF-TMS

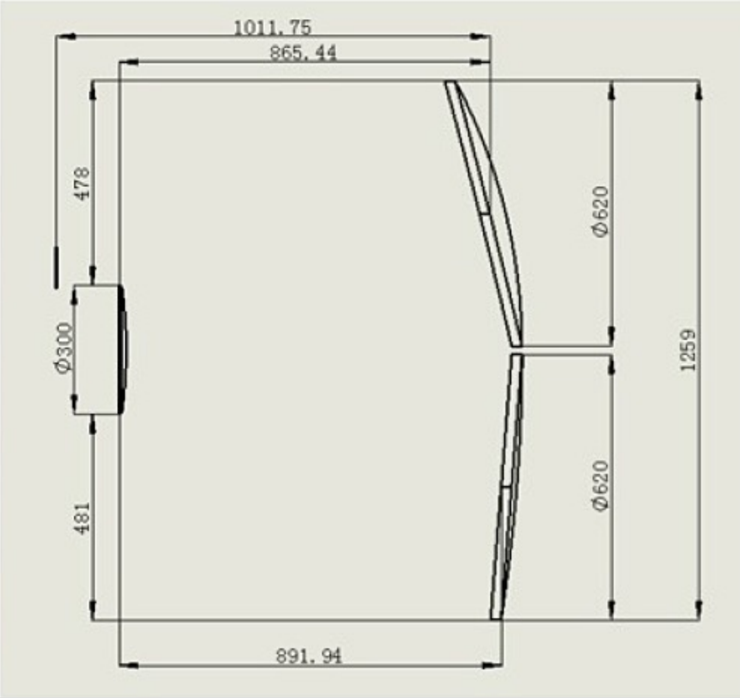


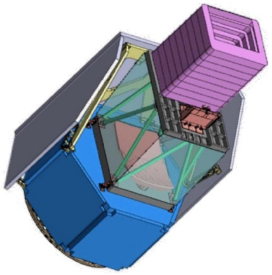
(Fig 15. Schematic optical layout of Linear Astigmatism Free-Three Mirror System LAF-TMS with EPD 150 mm and f-number 3.3)

	TMA (Coaxial Off-Axis)	LAF-TMS (Confocal Off-Axis)
Design Process	(1) Start from Paul-Becker type (On-axis) (2) Select the off-axis part from the PB (3) Optimize the mirror, etc. numerically Focused on **third-order aberrations** (Spherical, Coma, Third-order astigmatism)	(1) Find Linear Astigmatism Free Condition (2) Optimize the mirrors numerically Focused on **other third-order aberrations**
Linear Astigmatism	Can be reduced by optimization (**Not zero**)	**Elliminated**

Example: LAF-TMS vs. TMA (Messier, D400mm F/2)

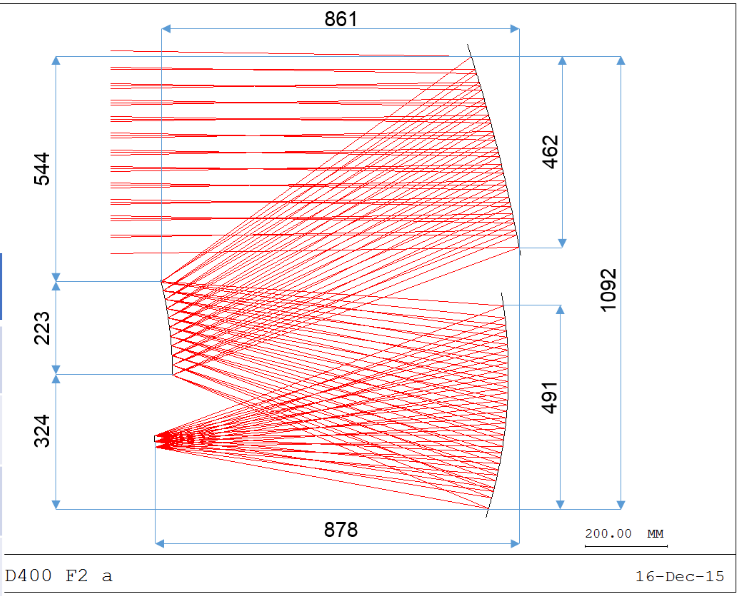
TMA (Three Mirror Anastigmat)
Coaxial Off-Axis





	TMA	LAF	LAF/TMA
M1	620	491	0.79
M2	300	223	0.74
M3	620	461	0.74
mass ratio			0.4

LAF-TMS
Linear Astigmatism Free
Three Mirror System
Confocal Off-Axis

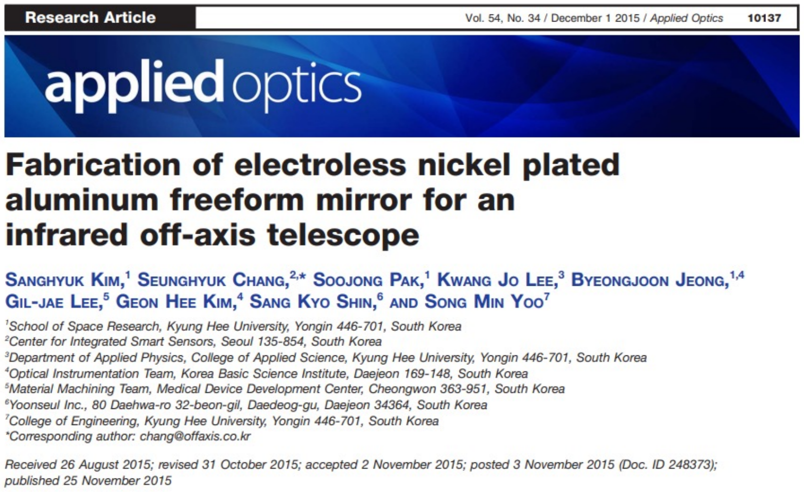


* Hugot, Wang, Valls-Gabaud et al., 2014, SPIE 9143, 9143X (https://doi.org/10.1117/12.2057461)

Applications of
Linear Astigmatism Free (LAF) Space Telescopes

(1) Fabrication of Aluminum Freeform Mirror

- XY Polynomial Mirrors: Quadratic surface composed of polynomials expanded into monomials of $x^m y^n$ with degree m, n $(m + n \leq 10)$, where C_j is the monomial coefficient. $z = \sum_{j=2}^{66} C_j \, x^m y^n$, where $j = \frac{(m+n)^2+m+3n}{2} + 1$



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applied optics

Fabrication of electroless nickel plated aluminum freeform mirror for an infrared off-axis telescope

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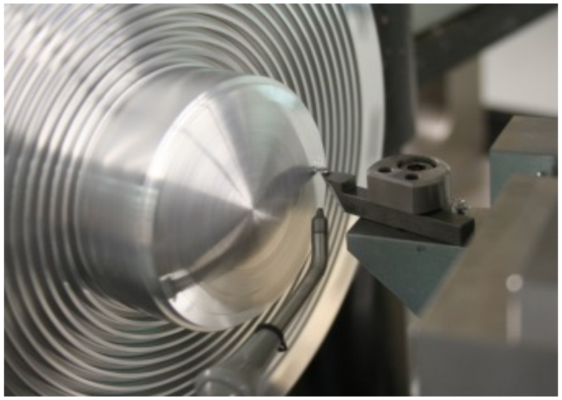
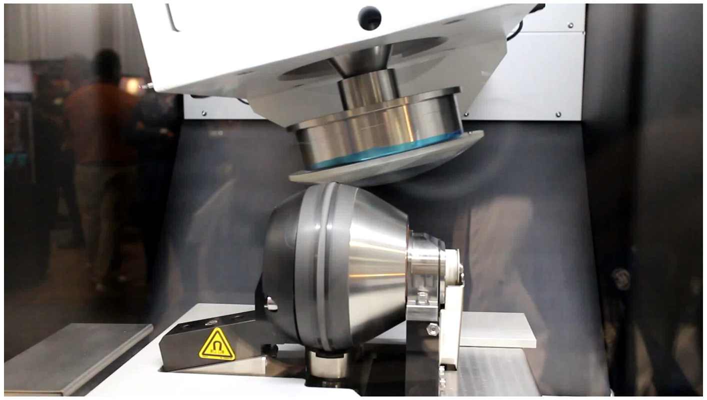
Single **P**oint **D**iamond **T**urning



Magneto **R**heological **F**inishing



(2) Protomodel for Space IR Telescope

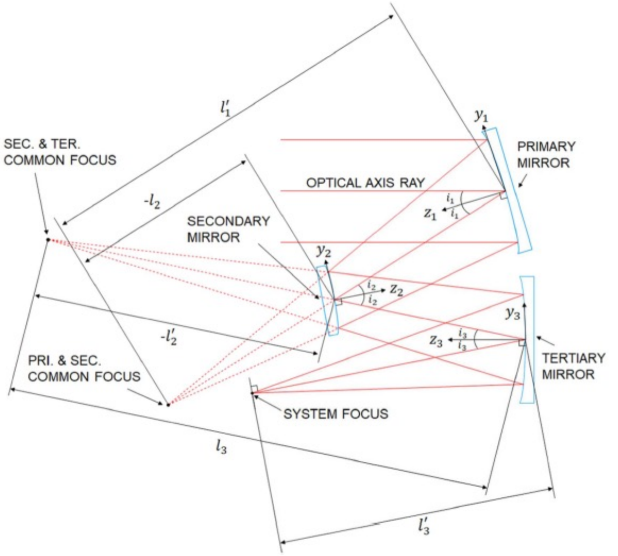
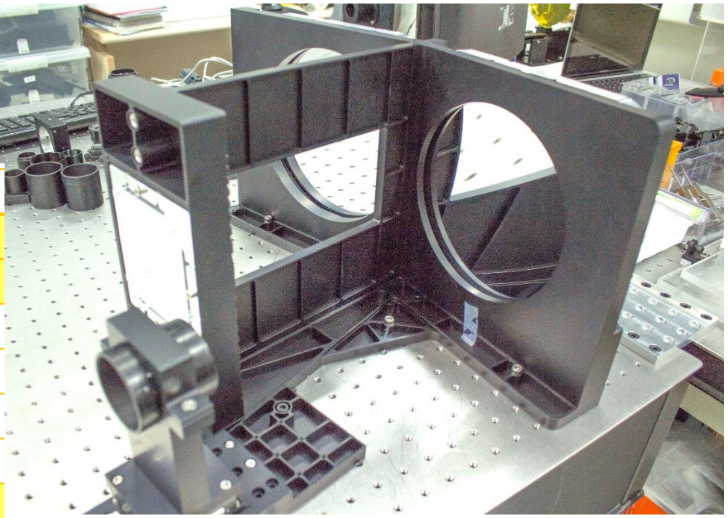
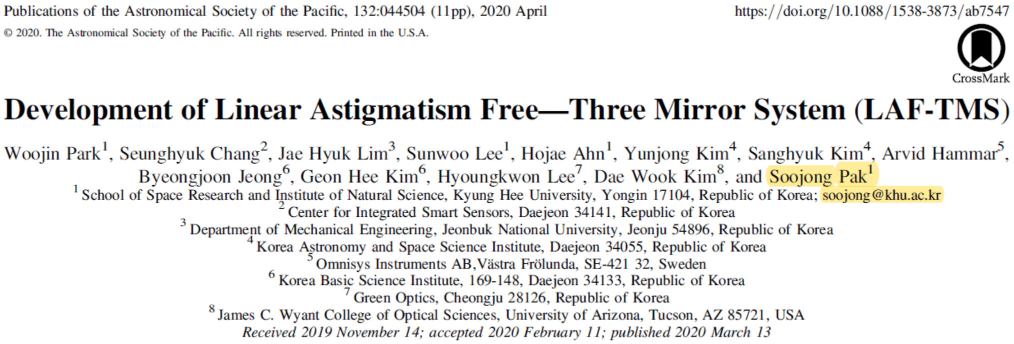


Figure 1. The optical layout of LAF-TMS. Optical path is drawn in red solid lines.
(A color version of this figure is available in the online journal.)

Parameter	Value
EPD	**150 mm**
EFL	**500 mm**
Pixel size	6 um
Pixel FOV	2.5 ″
Array Format	8K x 6K
Array Size	49 x 37 mm
FOV	**5.5° x 4.1°**





Publications of the Astronomical Society of the Pacific, 132:044504 (11pp), 2020 April
https://doi.org/10.1088/1538-3873/ab7547

CrossMark

Development of Linear Astigmatism Free—Three Mirror System (LAF-TMS)

Woojin Park[1], Seunghyuk Chang[2], Jae Hyuk Lim[3], Sunwoo Lee[1], Hojae Ahn[1], Yunjong Kim[4], Sanghyuk Kim[4], Arvid Hammar[5],
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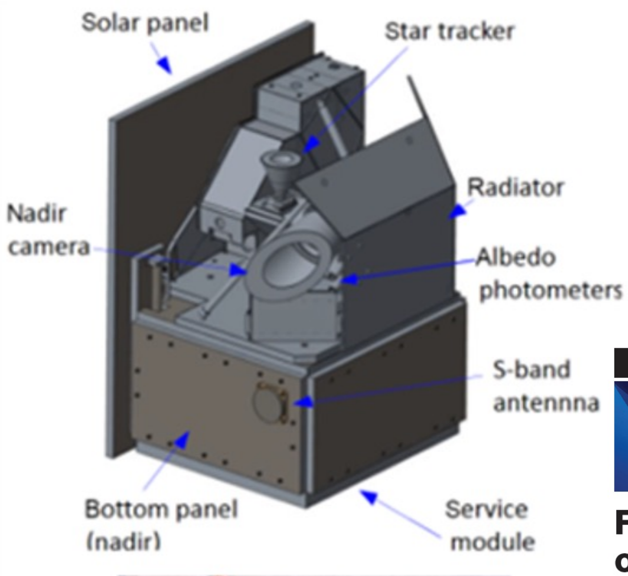
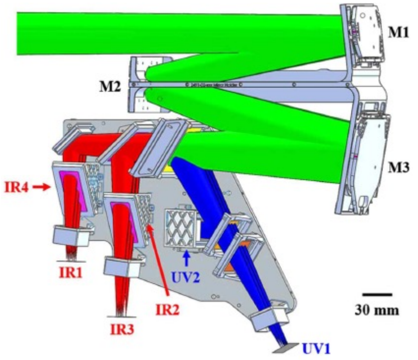
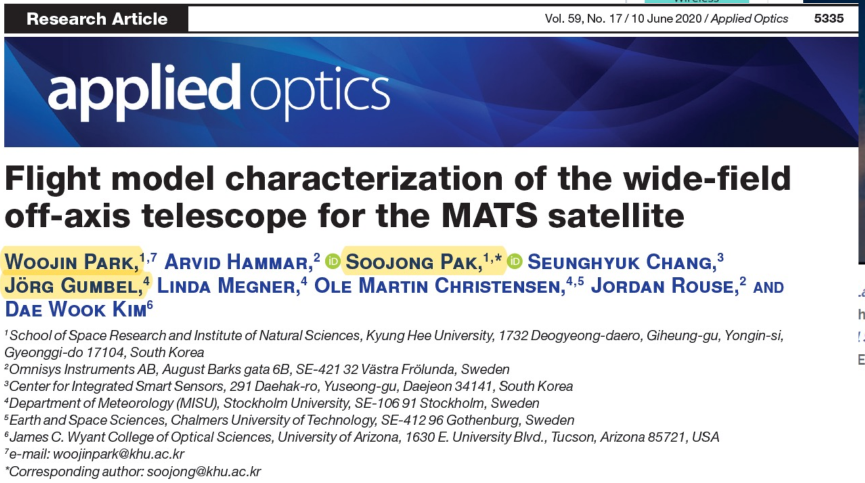
(3) Swedish Science Satellite MATS

(Mesospheric Airglow/Aerosol Tomography and Spectroscopy)

- Lunched on Nov 4, 2022.







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applied optics

Flight model characterization of the wide-field off-axis telescope for the MATS satellite

Woojin Park,[1,7] **Arvid Hammar,**[2] **Soojong Pak,**[1,*] **Seunghyuk Chang,**[3] **Jörg Gumbel,**[4] **Linda Megner,**[4] **Ole Martin Christensen,**[4,5] **Jordan Rouse,**[2] **and Dae Wook Kim**[6]

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satnews

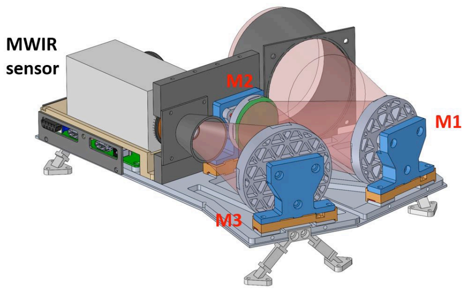
Rocket Lab launches the Swedish MATS satellite from New Zealand aboard an Electron rocket

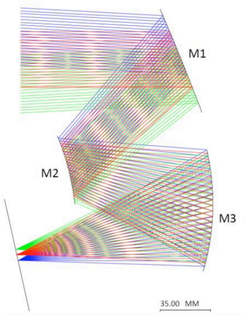
NOVEMBER 4, 2022

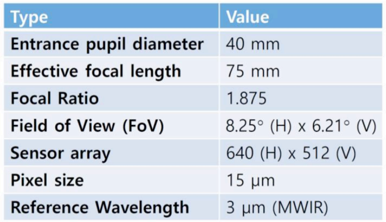
ab USA Inc. has successfully launched its 32nd *Electron* mission to he firm's 152nd satellite to orbit, a science payload for the *Swedish* *Space Agency*. The MATS satellite was deployed to its 585 km. circular Electron following lift-off at 17:27 UTC.

(4) IR Spectroscopic Imaging System for UAV

- IR Telescope Optics for MWIR/LWIR dual sensor hyperspectral Camera onboard unmanned aerial vehicle (UAV).
- Material: Aluminum 6061-T6
- Weight 3 kg
- Part of Unmanned Vehicle Core Technology Development Project funded by National Research Foundation of Korea.

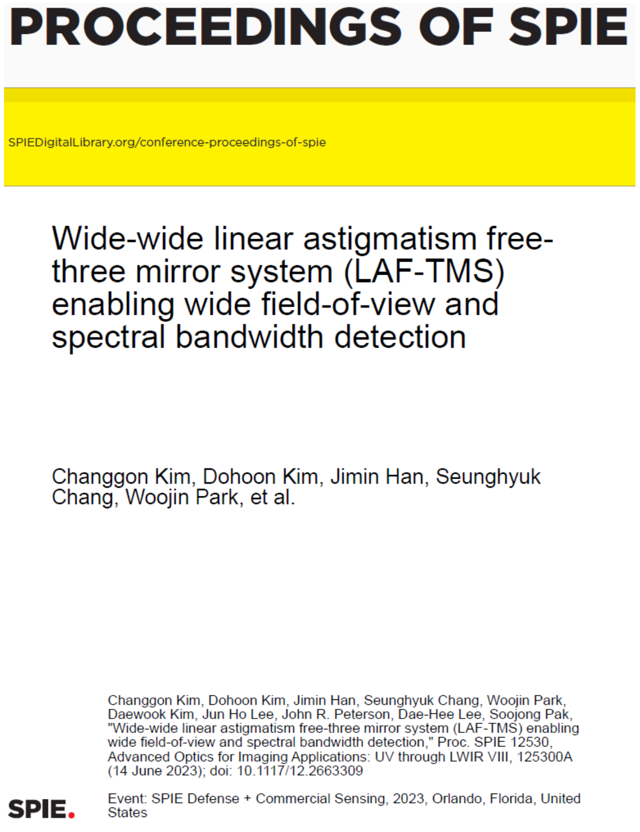






Type	Value
Entrance pupil diameter	40 mm
Effective focal length	75 mm
Focal Ratio	1.875
Field of View (FoV)	8.25° (H) x 6.21° (V)
Sensor array	640 (H) x 512 (V)
Pixel size	15 μm
Reference Wavelength	3 μm (MWIR)

The optical design satisfies the linear-astigmatism-free condition*.



PROCEEDINGS OF SPIE

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Wide-wide linear astigmatism free-three mirror system (LAF-TMS) enabling wide field-of-view and spectral bandwidth detection

Changgon Kim, Dohoon Kim, Jimin Han, Seunghyuk Chang, Woojin Park, et al.

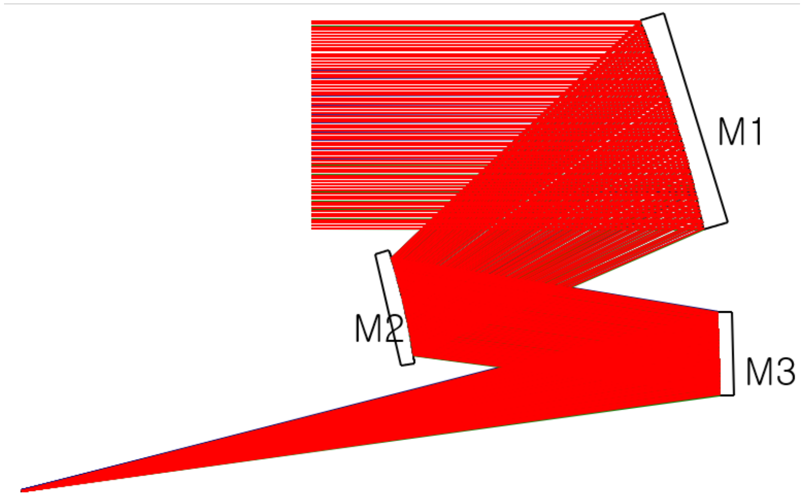
Changgon Kim, Dohoon Kim, Jimin Han, Seunghyuk Chang, Woojin Park, Daewook Kim, Jun Ho Lee, John R. Peterson, Dae-Hee Lee, Soojong Pak, "Wide-wide linear astigmatism free-three mirror system (LAF-TMS) enabling wide field-of-view and spectral bandwidth detection," Proc. SPIE 12530, Advanced Optics for Imaging Applications: UV through LWIR VIII, 125300A (14 June 2023); doi: 10.1117/12.2663309

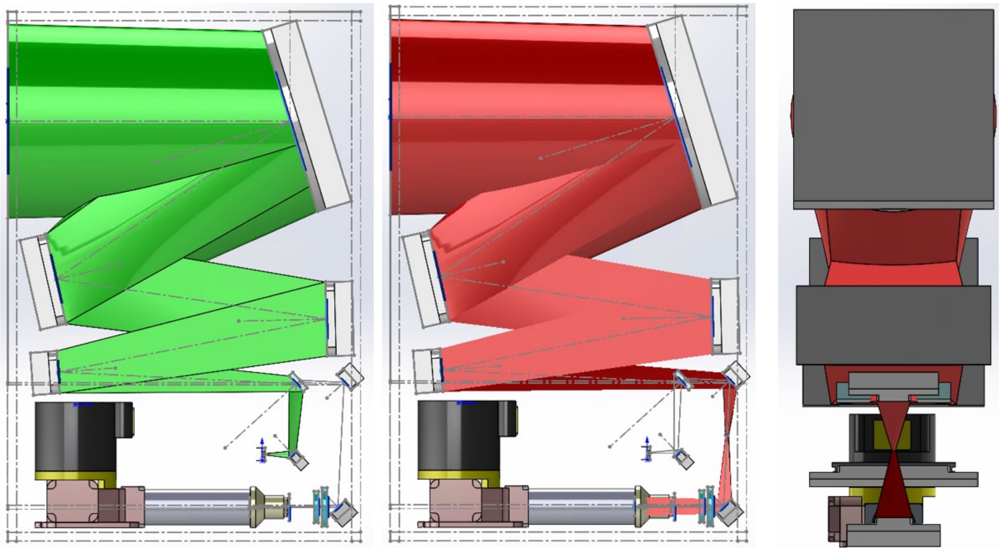
SPIE.

Event: SPIE Defense + Commercial Sensing, 2023, Orlando, Florida, United States

(5) EO/IR Onboard CubeSat (Ongoing Projects)

- EO/IR Common Aperture Optics: Remote Sensing in Dual Bands
- Inherent Athermalized Structure: All mirrors and opto-mechanical parts are made from Aluminum.





Summary

- We are leveraging astronomical infrared techniques to space IR telescopes for both astronomy and remote sensing applications.
- The optical technology for space-based IR telescopes is crucial.
- We developed noble technologies including:
  - Optical design for Linear Astigmatism Free off-axis reflective telescopes
  - Opto-mechanical design for space-based telescopes
  - Fabrication of aluminum freeform mirrors for off-axis telescopes
  - Alignment of freeform mirrors in off-axis telescopes

감사합니다.

Thank You