Synthesis of Initial Plane-Symmetric Optical Systems using Parabasal Theory

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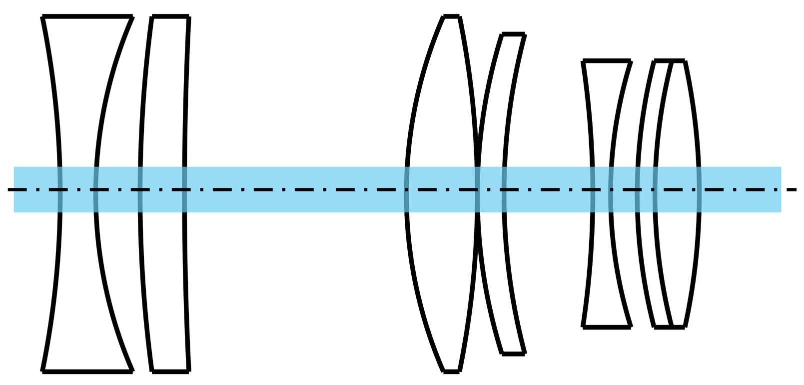
Motivation - From Paraxial (PA) to Parabasal (PB)

Paraxial Theory

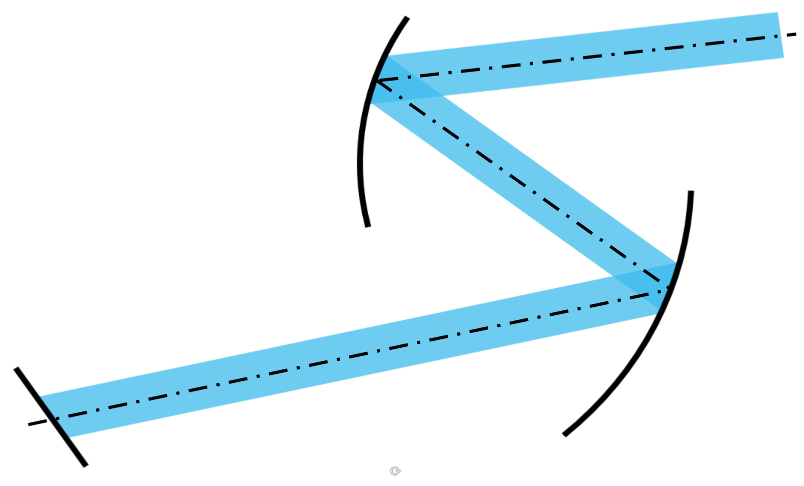


- differential region around the reference → **optical axis**
- valid for rotational symmetric systems only
- single Gaussian image plane

increasing complexity of system geometry

rotational symmetric system geometries | **double-plane symmetric** system geometries | **plane symmetric** sytem geometries | **symmetry free** system geometries

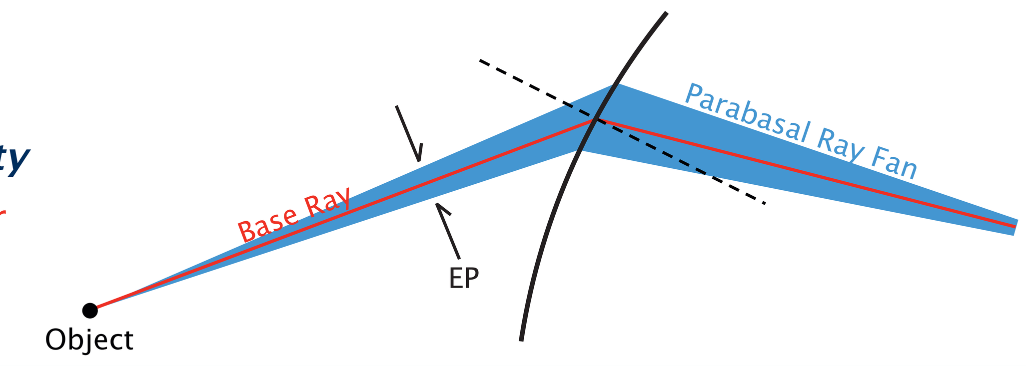
Parabasal Theory



- differential region around the reference → **base ray (center object-EP)**
- valid for generalized systems
- meridional and sagittal image plane (astigmatism)

System Reference and Area of Validity

- base ray: object center → pupil center
- rays that make small angels with the base ray are called parabasal rays



Derivation of 1st order imaging properties for tilted systems

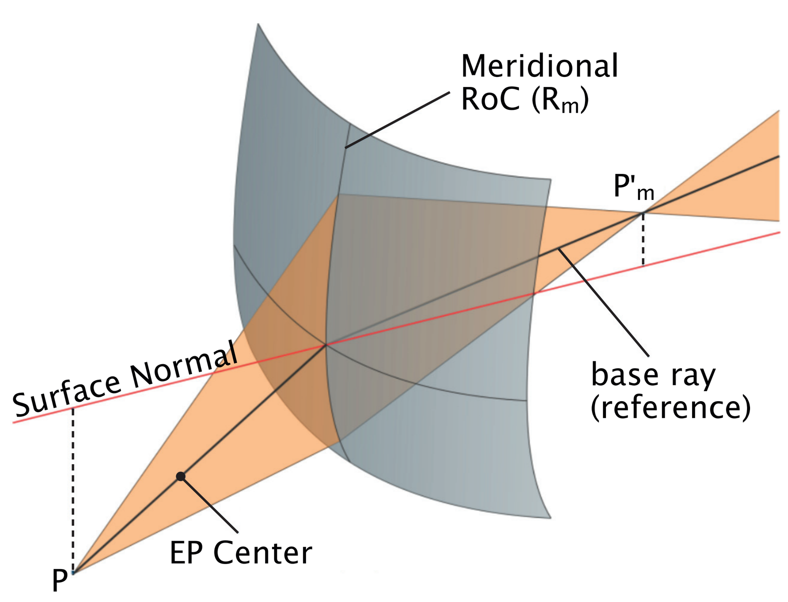
Derivation of Parabasal Imaging Framework

Characteristics in Differential Regime around the Base Ray

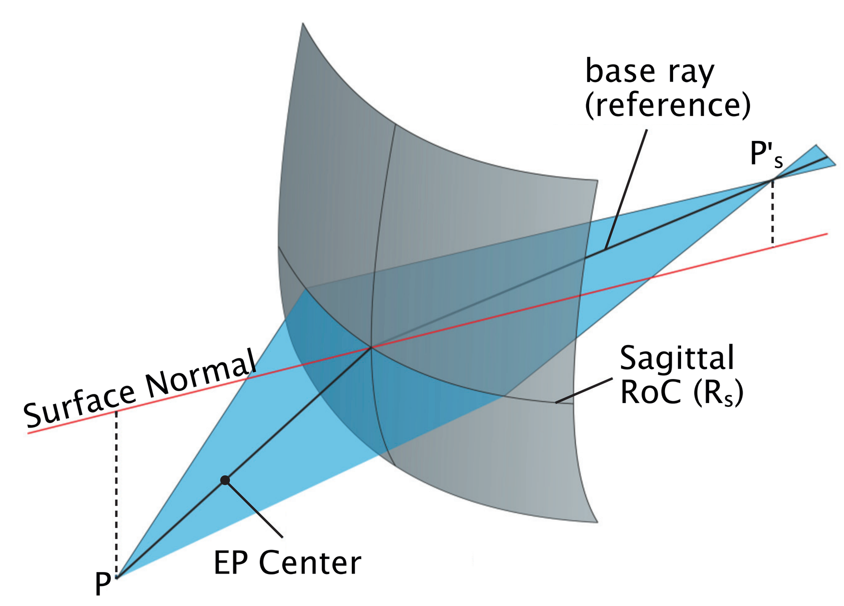
- any surface in the vicinity of a specific point is appropriately described by two curvatures

→ object / entrance pupils are imaged into meridional & sagittal image points / exit pupils

Meridional Imaging



Sagittal Imaging



Concept for Parabasal Imaging Framework Derivation

- infinitesimal object point shift → determination of image point shift using Coddingtons eq.

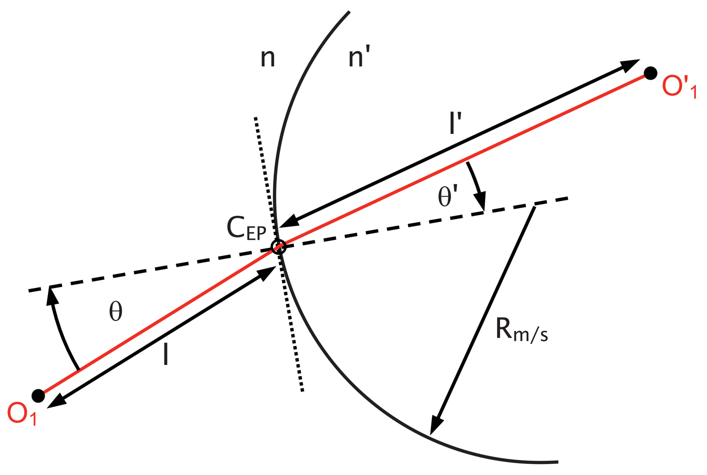
Coddingtons Equations

meridional

$$F_m(l_m,l'_m,\theta_m,\theta'_m) = \frac{n'\cos^2\theta'_m}{l'_m} - \frac{n\cos^2\theta_m}{l_m} - \frac{n'\cos\theta'_m - n\cos\theta_m}{R_m} = 0$$

sagittal

$$F_s(l_s,l'_s,\theta_s,\theta'_s) = \frac{n'}{l'_s} - \frac{n}{l_s} - \frac{n'\cos\theta'_s - n\cos\theta_s}{R_s} = 0$$

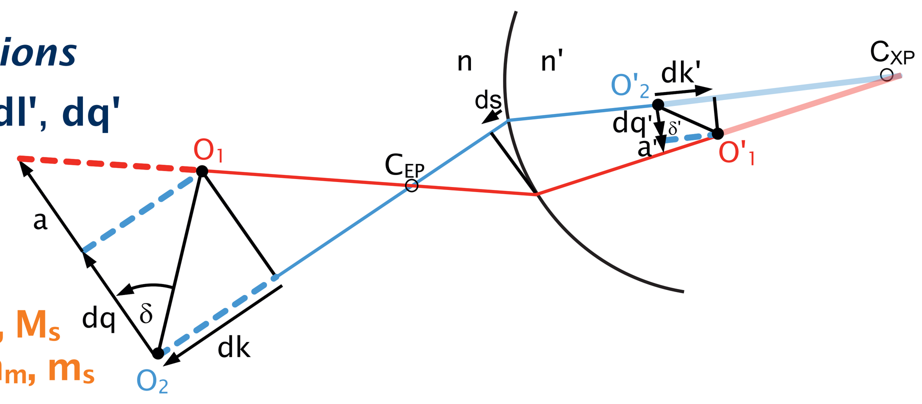


⇨ **meridional & sagittal image & pupil center position**

Differential Geometry and Geometric Relations

O_1 to O_2 by **dl**, **dq** → **dθ**, **dθ'** → O'_1 to O'_2 by **dl'**, **dq'**
with total derivatives $\mathbf{dF_m}$, $\mathbf{dF_s}$ → δ'_m, δ'_s

⇨ **meridional & sagittal image plane tilt**



obj. shift along base ray, i.e. **dq** = **dq'** = 0 → M_m, M_s
obj. shift perp. to base ray, i.e. **dθ** = **dθ'** = 0 → m_m, m_s

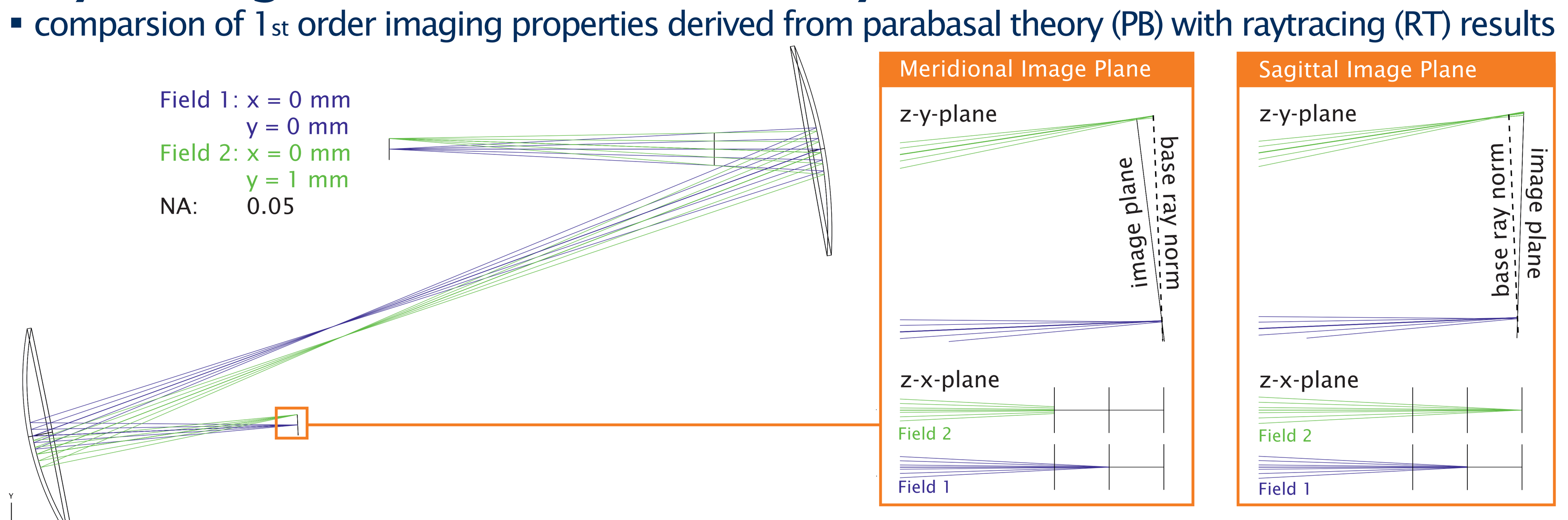
⇨ **meridional & sagittal axial ($M_{m/s}$) & lateral ($m_{m/s}$) magnification**

1st order imaging properties as optimization objective functions

Real Raytracing Simulation & Final Optimization

Raytracing Simulation of Initial System

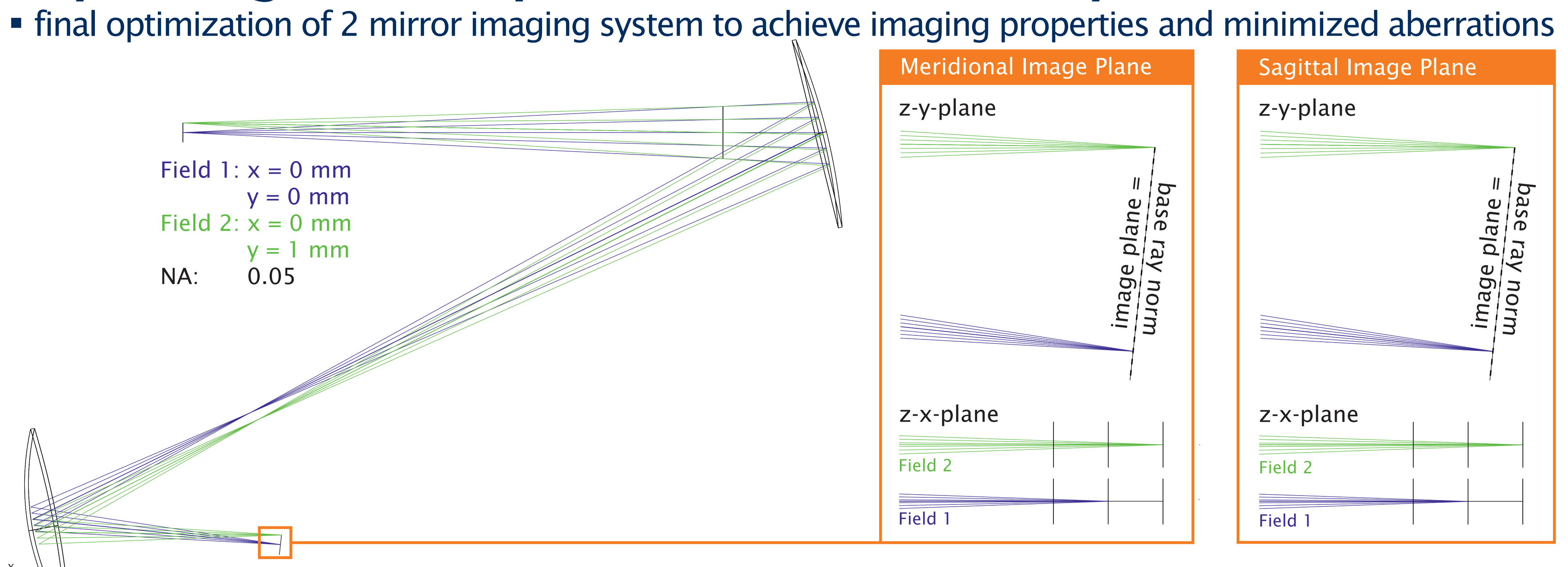
- comparsion of 1st order imaging properties derived from parabasal theory (PB) with raytracing (RT) results



	/mm				/deg			/mm							/deg	
	l_{2m}	l_{2s}	m_m	m_s	δ	δ'_m	δ'_s	l_1	$l_{1\text{-}2}$	l_{EP}	R_{1m}	R_{1s}	R_{2m}	R_{2s}	ε_1	ε_2
PB	-25.0	-25.0	1.0	1.0	0	-0.3	-0.3	-46.6	79.0	-10.0	-45.0	-43.7	-27.7	-26.9	10.0	-8.8
RT	-25.0	-25.0	0.98	0.98	0	-4.69	4.16									

Raytracing based Optimization of Initial System

- final optimization of 2 mirror imaging system to achieve imaging properties and minimized aberrations

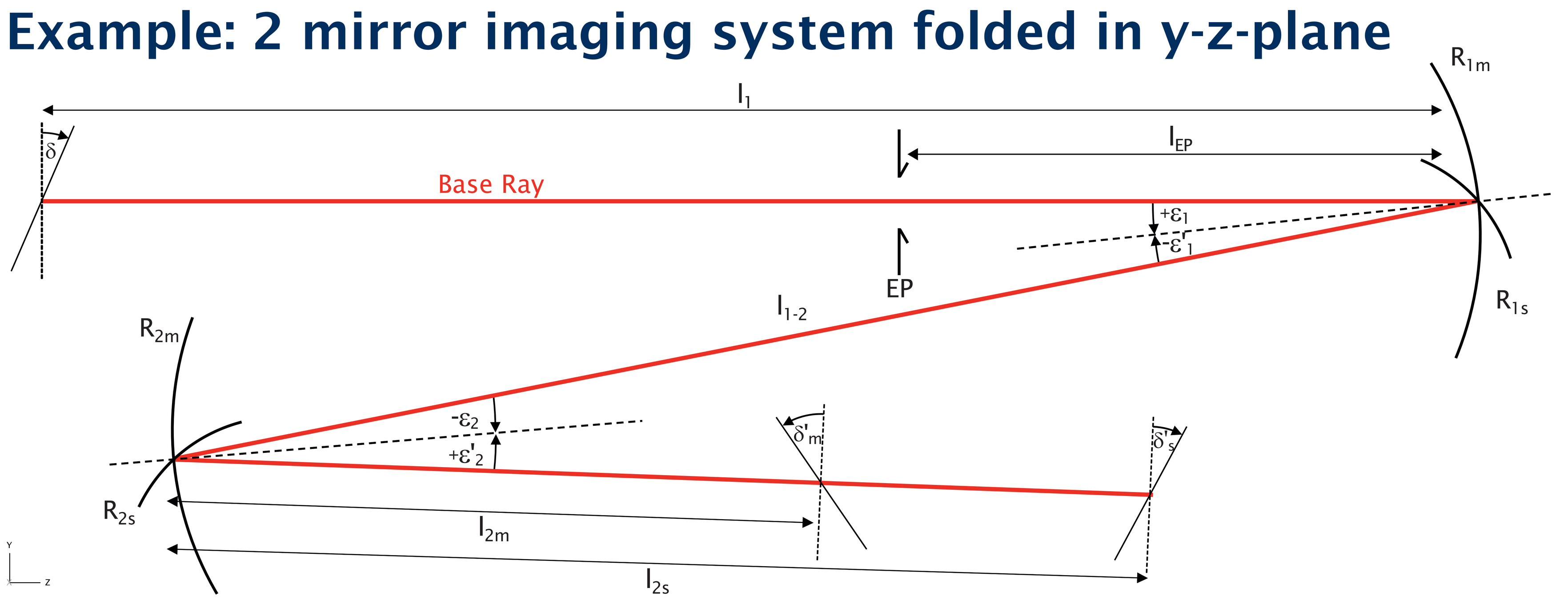


	/mm				/deg			/mm							/deg	
	l_{2m}	l_{2s}	m_m	m_s	δ	δ'_m	δ'_s	l_1	$l_{1\text{-}2}$	l_{EP}	R_{1m}	R_{1s}	R_{2m}	R_{2s}	ε_1	ε_2
RT_{opt}	-25.0	-25.0	1.0	1.0	0	0	0	-54.2	88.9	-10.0	-66.1	-65.2	-25.8	-20.6	13.4	-16.8

Imaging properties & aberration optimized tilted optical system

Efficient Synthesis of an Initial System

Example: 2 mirror imaging system folded in y-z-plane



Imaging Requirements

image distances $l_{2m} = l_{2s} = -25$ mm
lateral magnification $m_m = m_s = 1$
object plane tilt $\delta = 0°$
image plane tilt $\delta'_m = \delta'_s = 0°$

Variable System Parameters

object distance l_1
mirror distance $l_{1\text{-}2}$
EP distance l_{EP}
mirror RoCs $R_{1m/s}$, $R_{2m/s}$
mirror tilts ε_1, ε_2

Constants

$n_{1\text{-mirror1}} = n_{1\text{-mirror2}} = 1$
$n_{2\text{-mirror1}} = n_{2\text{-mirror2}} = -1$

Optimization of System Parameters based on Objective/Merit Functions derived from Coddingtons Equations

/mm				/deg			/mm							/deg	
l_{2m}	l_{2s}	m_m	m_s	δ	δ'_m	δ'_s	l_1	$l_{1\text{-}2}$	l_{EP}	R_{1m}	R_{1s}	R_{2m}	R_{2s}	ε_1	ε_2
-25.0	-25.0	1.0	1.0	0	-0.3	-0.3	-46.6	79.0	-10.0	-45.0	-43.7	-27.7	-26.9	10.0	-8.8

Automatic transfer of initial system parameters to raytracer

Conclusion

- analytical expressions for 1st order imaging properties of plane-symmetric optical systems
- analytical & optimization based determination of highly tilted, plane-symmetric initial systems
- automatic transfer of initial lens data to commercial raytracing software for final optimization

Outlook

- derivation of more accurate expression of image plane tilts
- application of imaging framework for initial freeform surface synthesis
- extension of parabasal imaging framework to optical systems without symmetry

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