Alson E. Hatheway Inc.

Ivory and Ebony Optomechanical Modeling Tools

Solutions and Opportunities

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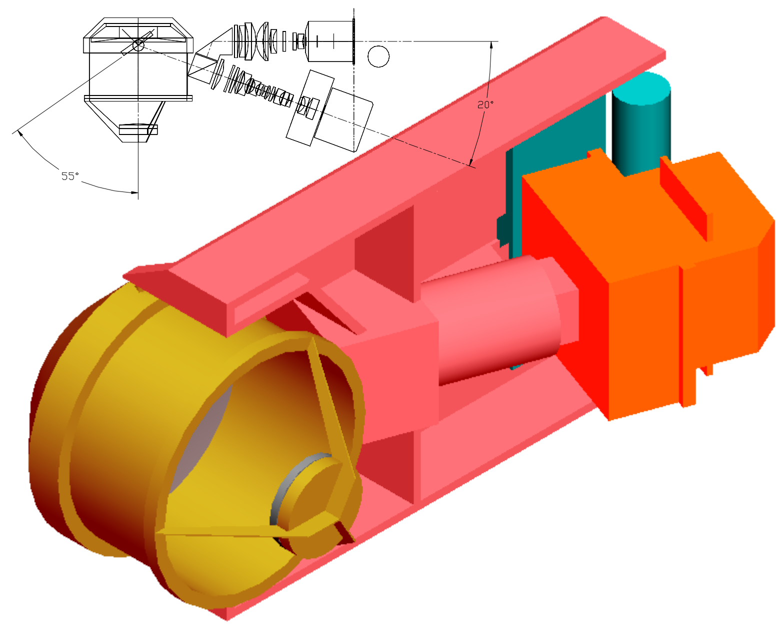
www.aehinc.com



Alson E. Hatheway

B. S. Mechanical Engineering	U. C., Berkeley
Registered Professional Engineer	California
Industrial Experience:	Boeing, Ford, Xerox, Hughes, Gould

Formed AEH in 1979

Honors and Awards:

- Life Member of ASME
- Fellow of SPIE
- Fellow of OSSC
- Senior Member of AIAA
- *Who's Who in Science and Engineering*
- *Who's Who in America*
- *Who's Who in the World*
- Four Patents (one pending)

Service to Industry:

- Board of Directors of SPIE
- President of OSSC
- Chairman of AIAA
- Chair: SPIE's Optomechanical/Instrument Technical Group
- Vice Chair: ANSI-ASME B46, Nanometer Metrology
- Faculty: University of La Verne
- Tutorial Instructor
- Authored forty publications
- Edited eight conference proceedings

Engineered Solutions **AEH.**

Optomechanical Engineering Projects

LAD	1968
AN/ALQ-123 ***EW Cover***	1971
AIRS	1974
HALO	1976
ADOPT	1976
E Target	1980
Thermal Weapon Sight	1984
Lucky Strike	1984
Optical Pressure Transducer	1984
Airborne LIDAR	1984
Talon Gold	1985
LBE	1985
R/AF-18 HUD	1986
F/O Acoustic Sensor	1986
Star Lab	1988
LEAP/Gremlin	1988
UVPI ***AWST Cover***	1989
Lambda'	1989

IRIS litho lens	1990
2145 litho lens	1990
RAFT	1992
SBIRS Low	1995
SBIRS High	1996
F/O encoder	1998
Microscope Projector	1999
CA/295	2001
FAME	2002
IFTIS Window and Pod	2003
Optical Correlator	2003
ATP Laser	2003
DART	2004
HAS	2004
RAFT III	2005
Optical Vibrometer	2005
ASTIMIDS (FLIR)	2006
ASTIMIDS (MSI)	2006
Seeker Head	2006

Optomechanical Modeling Tools for *Unified* Analysis

***Flow* the requirements down from the optical physics to the engineering implementation.**

***Exploit* the "small displacement" domains in optics, structural mechanics, heat transfer and servo-controls.**

***Formulate* mechanical challenges in mechanical design tools: *Unify* the disciplines.**

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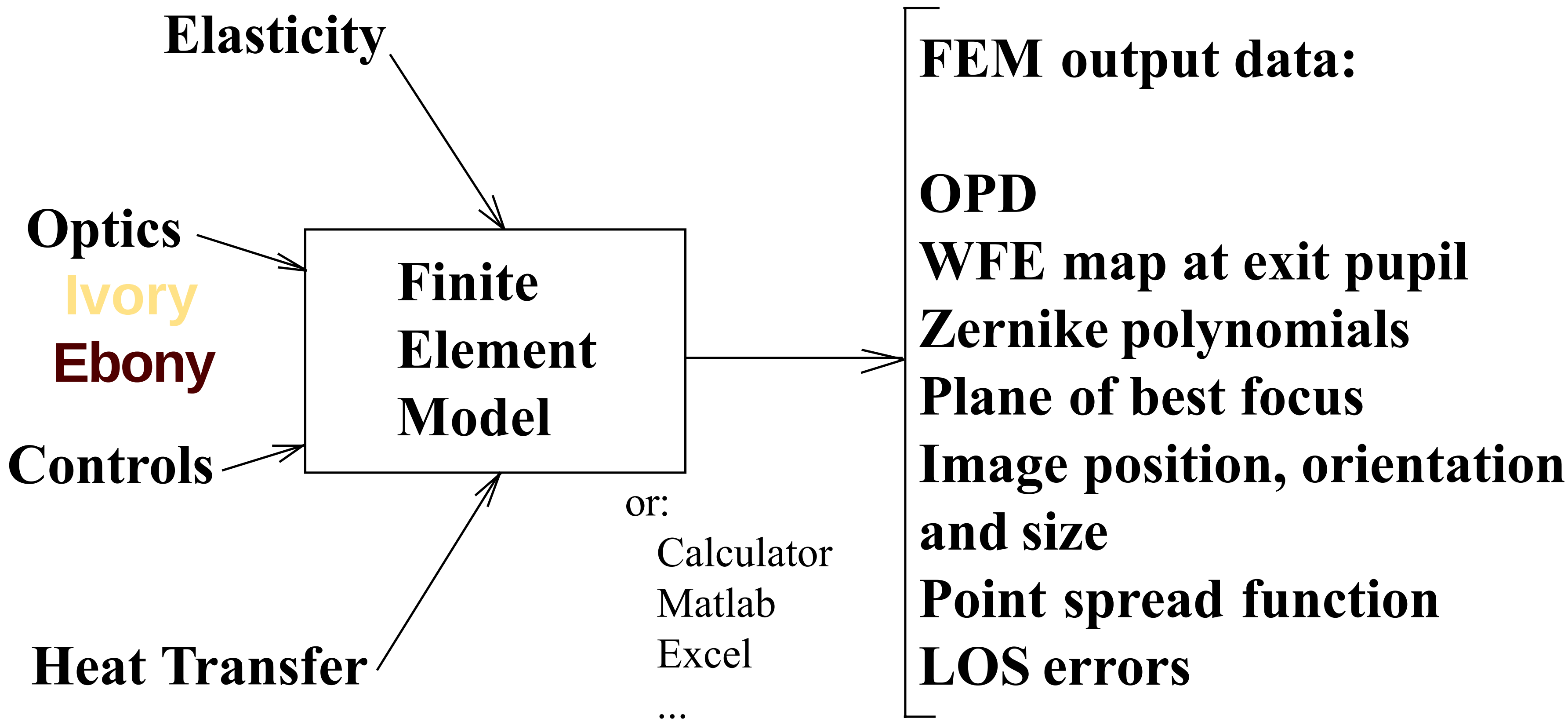
Unified Modeling



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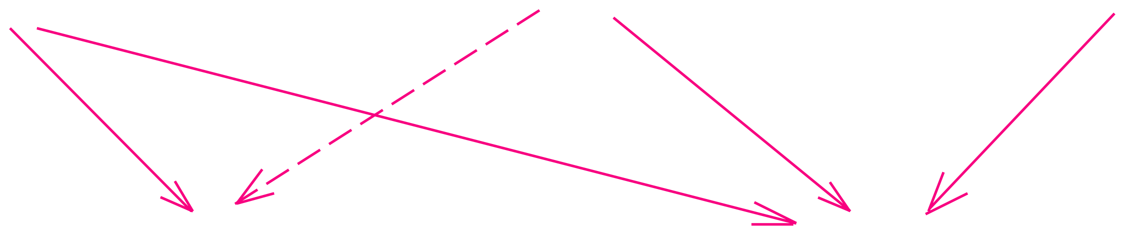
Optomechanical Modeling Tools - Ivory^{tm} and Ebony^{tm}

Gaussian Image

Optical Aberrations

"Mechanical Aberrations"



Ivory

Gaussian Images

Line-of-Sight
Tolerancing
Alignment
Thermal Sensitivity
Pressure Sensitivity

Ebony

Optical Ray Tracing

WFE
Geometric Blur
Point Spread Function
Plane of Best Focus
Zernike Coefficients

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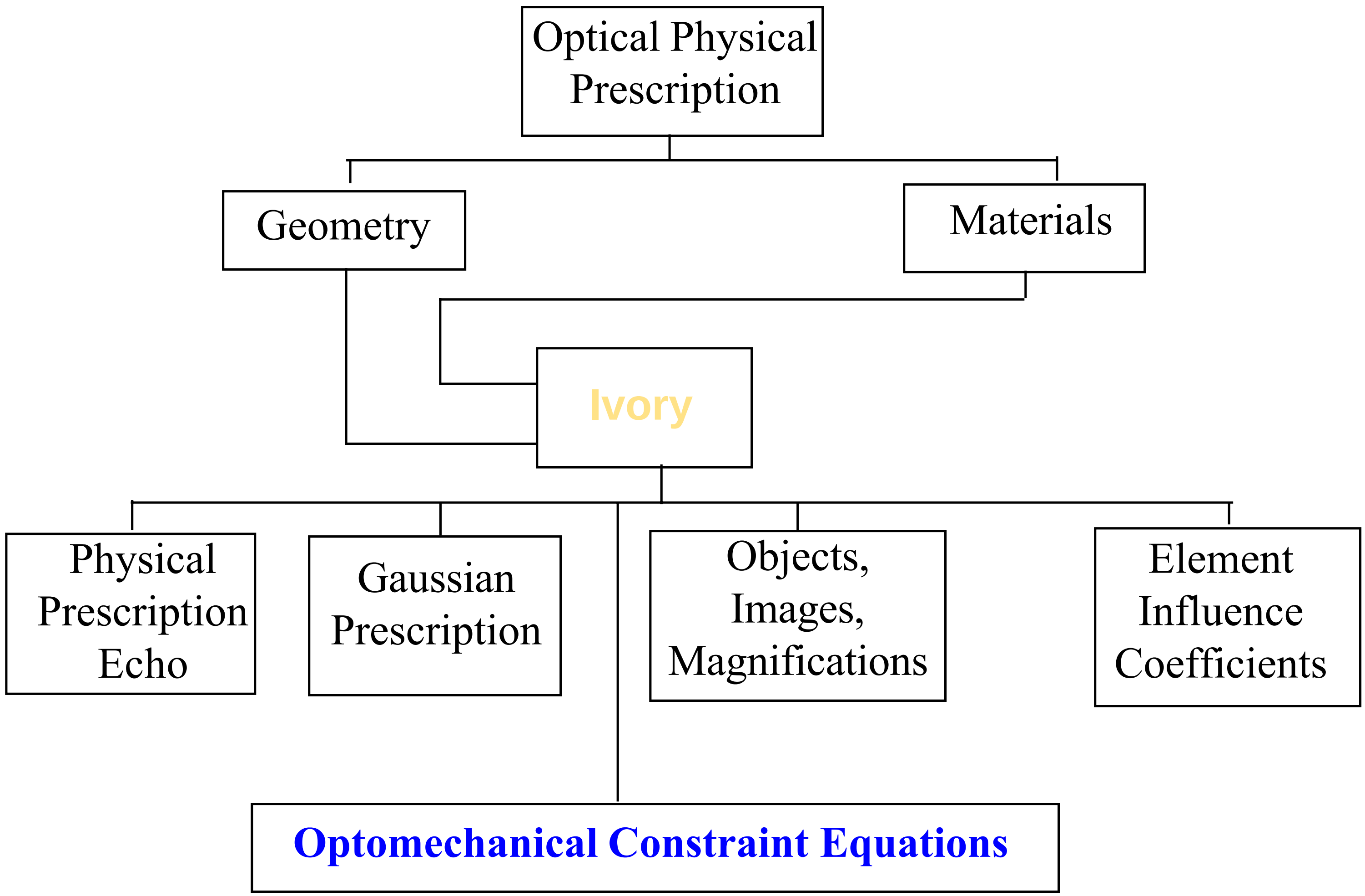
Ivory Controls the Gaussian Images through MATLAB, Excel and NASTRAN

Ivory



Influence coefficients between all optical elements and the image at the detector.

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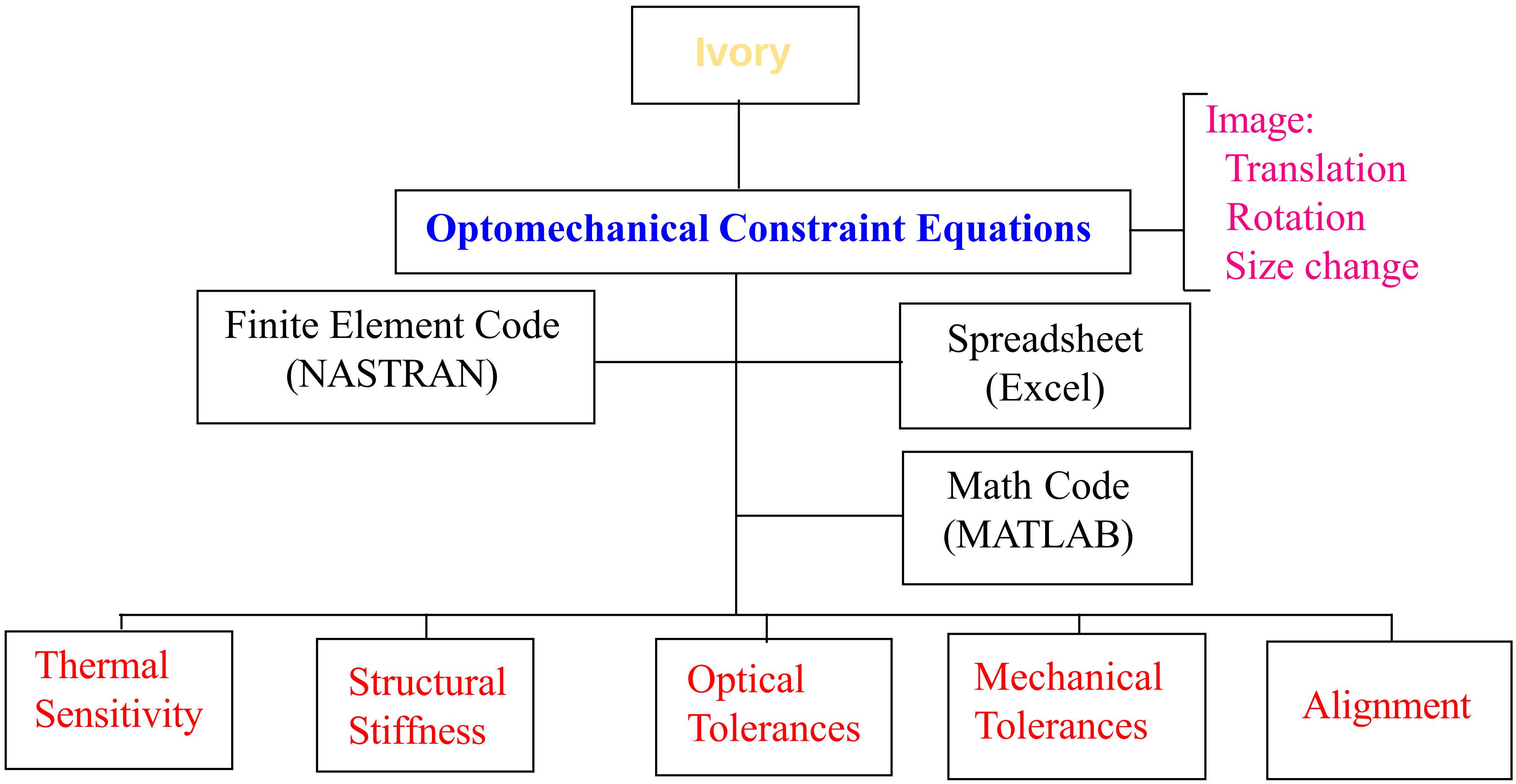
Ivory Applications



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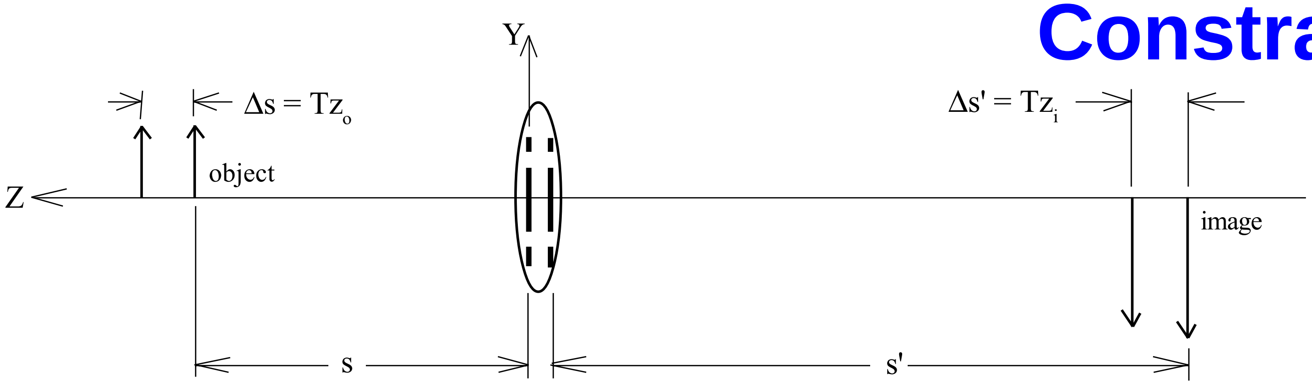
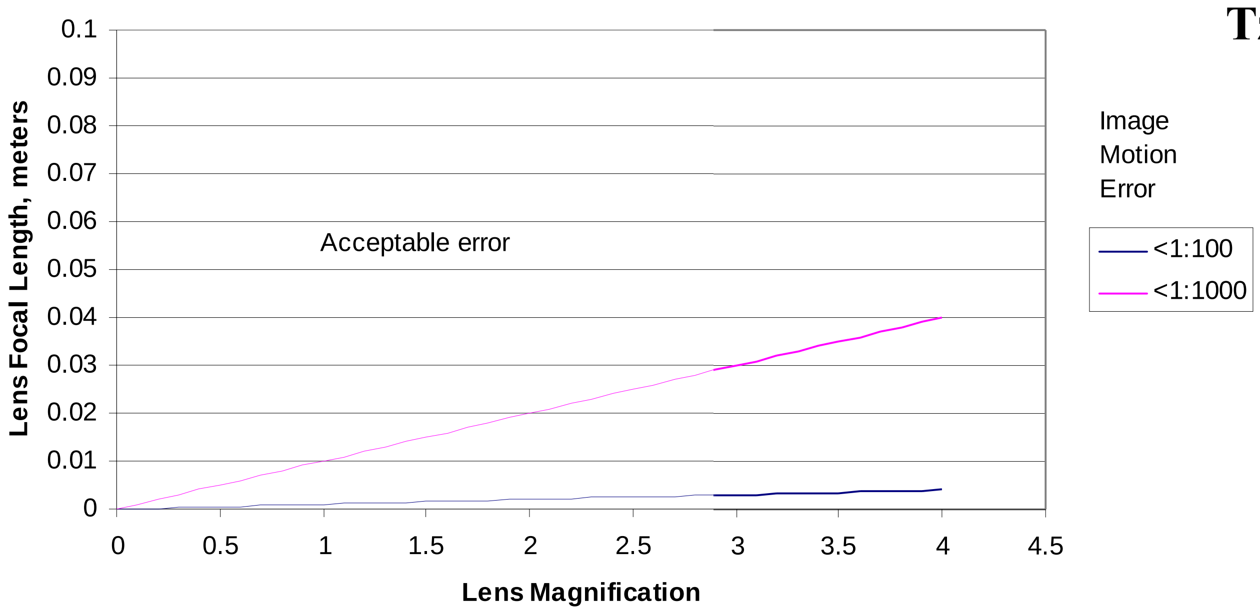
Accuracy of the Optomechanical Constraint Equations



Gauss' equation:
1/s - 1/s' = 1/f

The influence function:
$$Tz_i/Tz_o = M^2/(1 - MTz_o/f)$$

Object Motion = 0.01 millimeters



Error/Image Motion= $-MTz_o/f$

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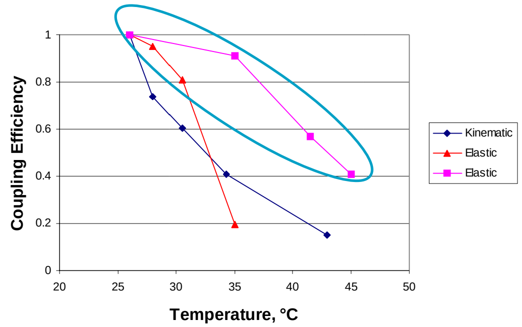
Ivory - Fiber Optic Encoder

How much is due to mirror mount?
How good can it get?



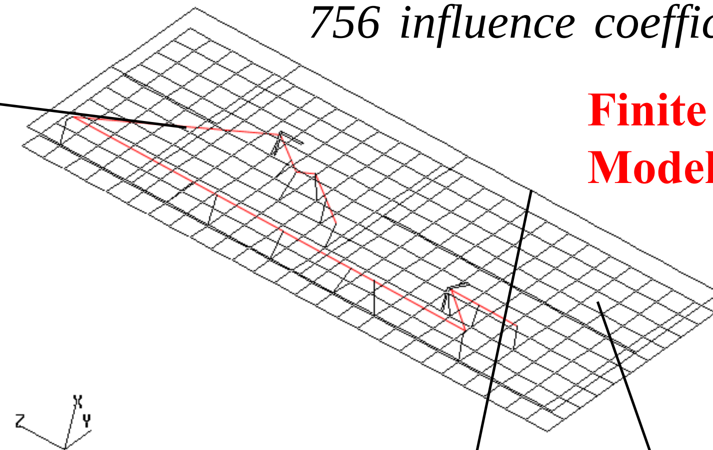
108 Optomechanical Degrees of Freedom:

- 48 translations
- 48 rotations
- 6 focal lengths
- 4 principal thicknesses
- 2 grating spacings

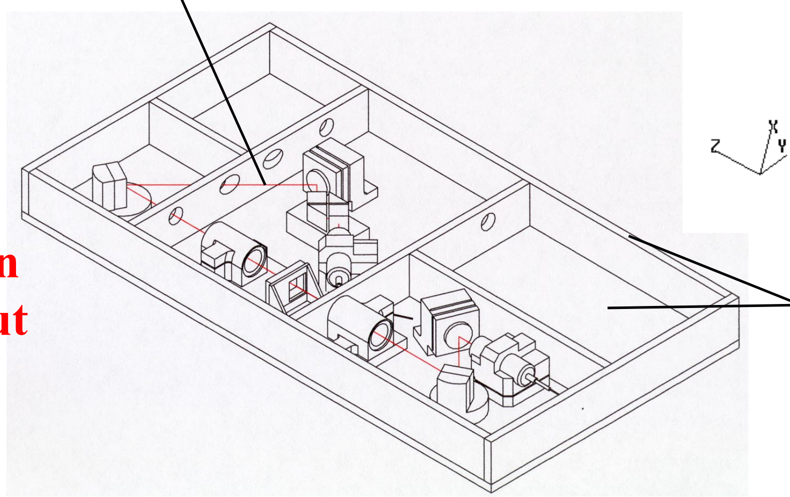
756 influence coefficients

Axial Chief Ray

Finite Element Model



Design Layout



Optical Bench

Stiffening Rails

Calculates the motions of P_1 for each of the 16 optical elements.

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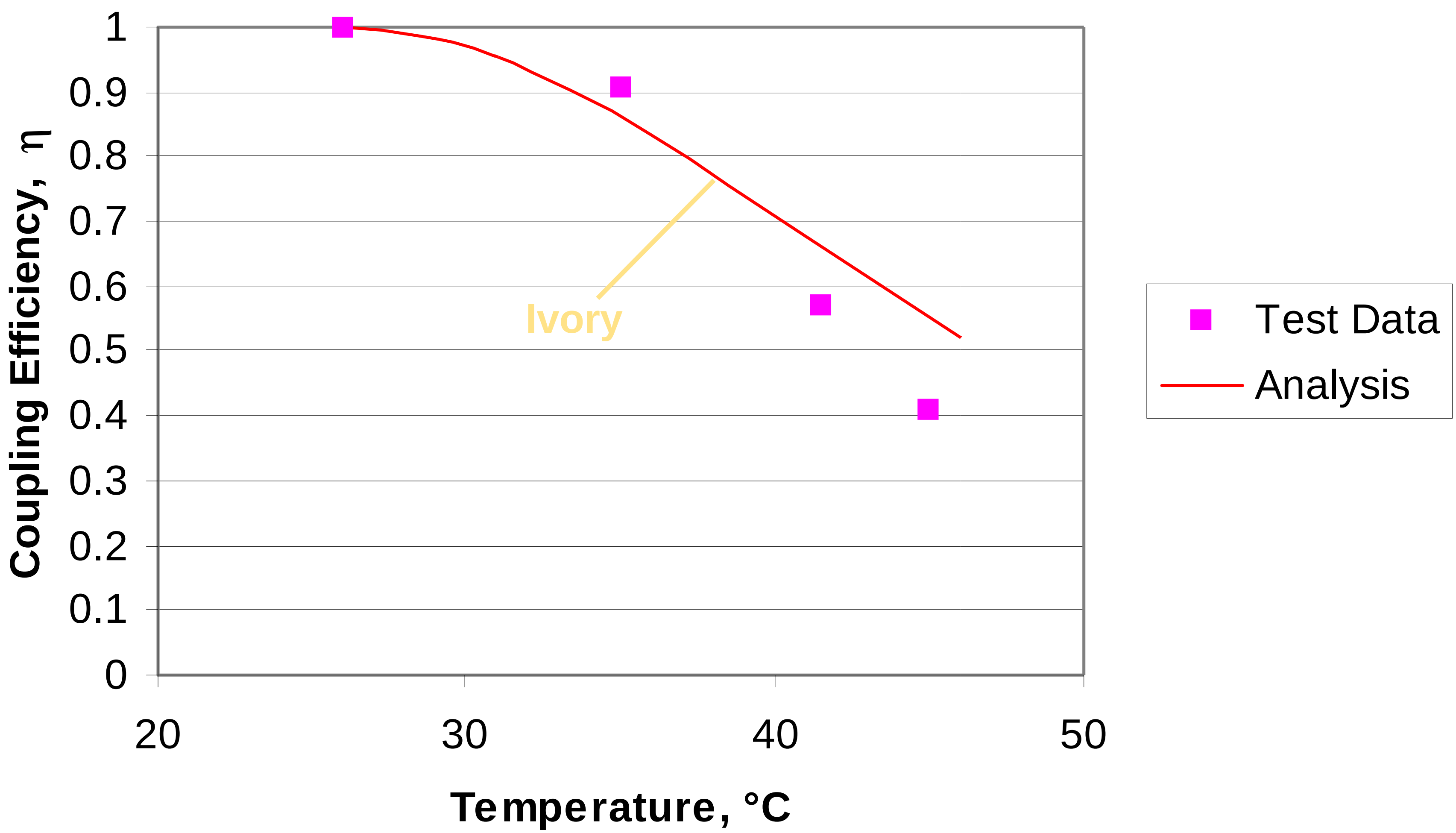
Ivory - Thermo-elasto-optical Analysis of Encoder



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Ivory Segregates the Contributors

Increasing the Coupling Efficiency, η

Contributors:	Net Errors	Mirror Mounts	Lens Thermal	Aluminum Bench
Registration Variables:				
Tx	**0.003443**	0.003443		
Ty	**0.000312**	1.51E-6		
Tz	**0.035492**		-0.00518	0.040696
Rx	**2.72E-11**			
Ry	**4.97E-12**			
Rz	**-2.7E-16**			
ΔM/M	**0.00594**		0.000225	0.005715
η as analyzed	**.522**			
η with CRES mounts		**0.846**		
η with CRES bench				**0.985**

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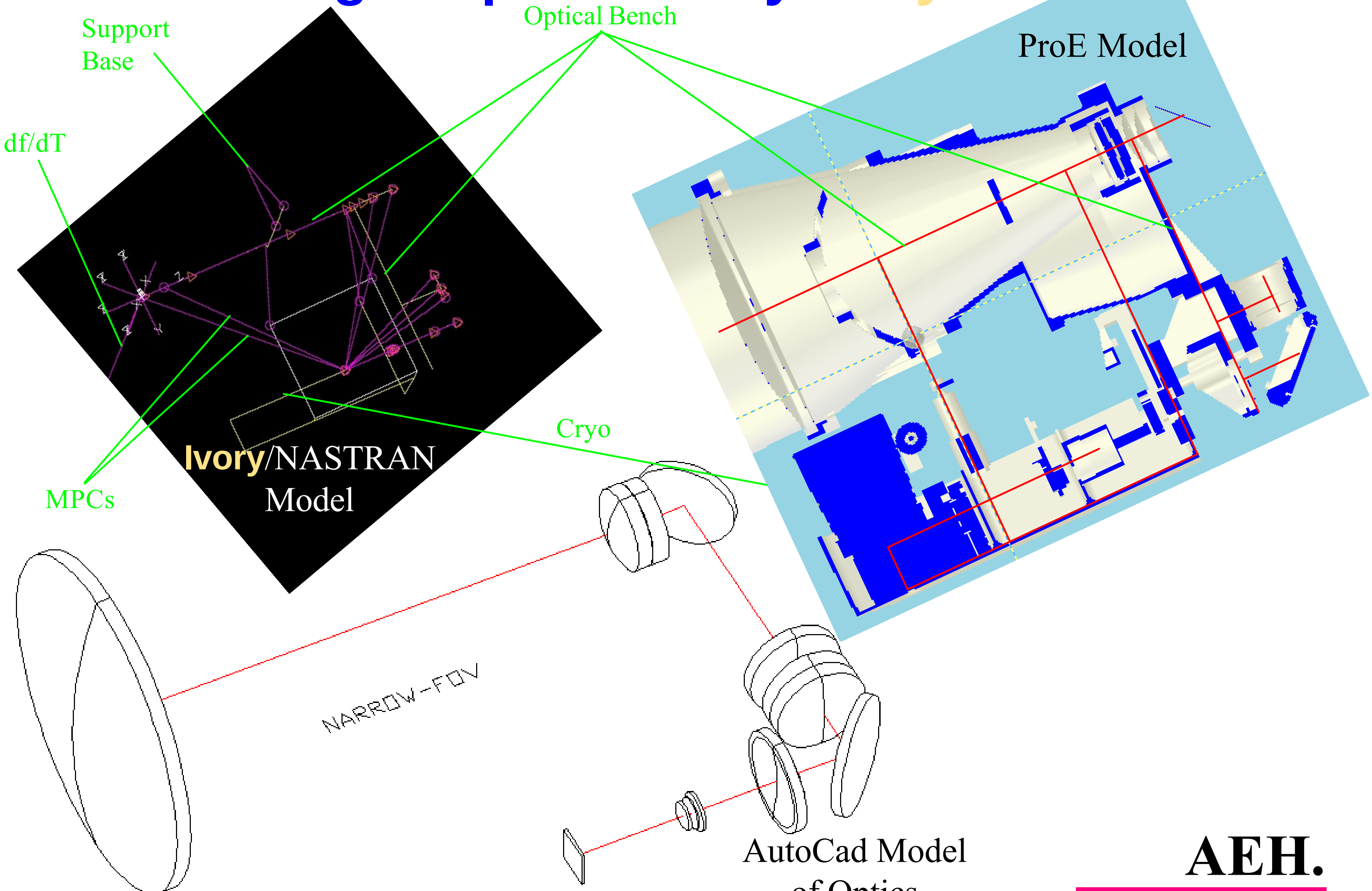
Infrared Imager Optimized by Ivory



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Infrared Imager - in Ivory/NASTRAN

Ivory's NASTRAN Optomechanical Model

```
BEGIN BULK $NFMPC6.BDF

$ UNITS: P,I,S,F,BTU
$ ALLOW 200
GRIDS,MATERIALS,ELEMENTS,PROPERTIES

PARAM,AUTOSPC,YES
PARAM,GRDPNT,0

$ NARROW FIELD DISPLACEMENTS WITHOUT
DF EFFECTS.

CORD2R,1,,0.,0.,0.,0.,0.,1.,
,1.,0.,1.
CORD2R,2,,0.,0.,0.,0.,-1.,1.,
,1.,0.,0.
CORD2R,3,,0.,0.,0.,0.,1.,0.,
,-1.,0.,0.
CORD2R,4,,0.,0.,0.,0.,1.,1.,
,-1.,0.,0.
CORD2R,5,,0.,0.,0.,0.,0.,-1.,
,1.,0.,0.

$ IMAGE DEGREES OF FREEDOM

GRID,1000,1,0.,0.,0.
GRID,1001,1,0.,0.,0.,,23456

$ IMAGE MOTIONS

MPC,1000,1000,1,-1.,1,1,-2.2803,
,,1,5,.5131,2,1,-.519,
,,2,5,3.2867,3,1,1.6241,
,,3,5,.5168,4,5,-2.4535,
,,5,1,-1.3823,5,5,.033,
,,6,1,2.1148,6,5,-.2064,
,,7,1,-1.3475,7,5,-.0995,
,,8,5,-3.3475,9,1,1.5604,
,,9,5,-.1395,10,5,-.0159,
,,11,5,-.015,12,5,-.015,
,,13,1,-1.

MPC,1000,1000,2,-1.,1,2,-2.2803,
,,1,4,-.5131,2,2,-.519,
,,2,4,-3.2867,3,2,1.6241,
,,3,4,-.1568,4,3,-1.6621,
,,4,4,3.4698,5,2,1.3823,
,,5,4,.033,6,2,-2.1148,
,,6,4,-.2064,7,2,1.3475,
,,7,4,-.0995,8,3,.7925,
,,8,4,-4.7341,9,2,1.5604,
,,9,4,.1395,10,4,-.0159,
,,11,4,-.015,12,4,-.0159,
,,13,2,-1.

MPC,1000,1000,3,-1.,1,3,5.2,
,,2,3,2.6366,3,3,-6.4552,
,,4,3,-1.9535,5,3,-1.3385,
,,6,3,3.5971,7,3,-3.326,
,,8,3,-.4441,9,3,.686,
,,13,3,-1.,2016,1,-5.2,
,,2026,1,-.2694,2036,1,-2.6376,
,,2056,1,-1.9106,2066,1,-4.4724,
,,2076,1,-1.8158,2096,1,-2.4347,
,,2106,1,-1.,2116,1,-1.,
,,2126,1,-1.

MPC,1000,1000,4,-1.,1,4,-2.2803,
,,2,4,-.519,3,4,1.6241,
,,4,4,2.3506,5,4,1.3823,
,,6,4,-2.1148,7,4,1.3475,
,,8,4,1.1207,9,4,1.5604,
,,13,4,-1.

MPC,1000,1000,5,-1.,1,5,-2.2803,
,,2,5,-.519,3,5,1.6241,
,,4,5,1.6621,5,5,-1.3823,
,,6,5,2.1148,7,5,-1.3475,
,,8,5,-.7925,9,5,1.5604,
,,13,5,-1.

MPC,1000,1000,6,-1.,4,5,-1.4142,
,,8,5,-1.4142,13,6,-1.

$ IMAGE CHANGE OF SIZE

MPC,1001,1001,1,-1.,1,3,-3.4684,
,,2,3,-1.7933,3,3,4.63,
,,4,3,.8934,5,3,.7571,
,,6,3,-1.4961,7,3,1.0557,
,,8,3,.4456,9,3,.3151,
,,2016,1,3.5849,2026,1,.1861,
,,2036,1,2.1797,2056,1,-.094,
,,2066,1,.2389,2076,1,.2104,
,,2096,1,.8775

$ ELEMENT FIRST-PRINCIPAL
POINTS.

GRID,1,1,0.,0.,0.,1
GRID,2,1,0.,0.,-0.75776,1
GRID,3,1,0.,0.,-7.67038,1
GRID,4,1,0.,0.,-8.28937,2
GRID,5,1,0.,-2.90525,-8.28937,3
GRID,6,1,0.,-3.34409,-8.28937,3
GRID,7,1,0.,-3.65594,-8.28937,3
GRID,8,1,0.,-4.47000,-8.28937,4
GRID,9,1,0.,-4.47000,-7.56189,5
GRID,10,1,0.,-4.47000,-6.21920,5
GRID,11,1,0.,-4.47000,-6.15878,5
GRID,12,1,0.,-4.47000,-6.05920,5
GRID,13,1,0.,-4.47000,-4.60087,5

$ FOCUS CHANGE PROPERTIES

$ L1, ZNS
GRID,2011,1,.4,,,1,23456
=,*1,=,-7.2194,==
=,*1,=,-21.3561,==
=,*1,=,1.,==

$ L2, SI
GRID,2021,1,.216,,,1,23456
=,*1,=,-.9748,==
=,*1,=,-.8313,==
=,*1,=,1.,==

$ L3, GE
GRID,2031,1,.18,,,1,23456
=,*1,=,-5.9592,==
=,*1,=,-2.4372,==
=,*1,=,1.,==

$ #4, A MIRROR

$ L5, SI
GRID,2051,1,.225,,,1,23456
=,*2,=,2.9452,==
=,*1,=,1.,==

$ L6, GE
GRID,2061,1,.144,,,1,23456
=,*1,=,2.3166,==
=,*2,=,1.,==

$ L7, SI
GRID,2071,1,.243,,,1,23456
=,*1,=,4.0274,==
=,*1,=,1.9867,==
=,*1,=,1.,==

$ #8, A MIRROR

$ L9, SI
GRID,2091,1,.19,,,1,23456
=,*1,=,-1.9446,==
=,*1,=,-3.2981,==
=,*1,=,1.,==

$ #10, SAPP WINDOW
GRID,2101,1,.04,,,1,23456
=,*3,=,1.,==

$ #11, GE WINDOW
GRID,2111,1,.02,,,1,23456
=,*3,=,1.,==

$ #12, SAPP WINDOW
GRID 2121,1,.04,,,1,23456
=,*3,=,1.,==

$ FIXED ENDS
GRID,2015,1,0.,0.,0.,1,123456
=11,*10,==

SPC1,1,123456,2045,2085

$ LENS DESIGN VARIABLES

$ SI CTE
MAT1,2,19.+6,,.15,.0874,1.4444-6,70.,.05

$ SI DNDT
MAT1,21,19.+6,,.15,.0874,8.6111-
5,70.,.05

$ GE CTE
MAT1,3,14.9+6,,.15,.102,3.1944-6,70.,.05

$ GE DNDT
MAT1,31,14.9+6,,.15,.102,8.3333-
5,70.,.05

$ SAPP CTE
MAT1,4,52.+6,,.163,.144,3.7222-6,70.,.05

$ SAPP DNDT
MAT1,41,52.+6,,.163,.144,5.5556-
6,70.,.05

$ ZNS CTE
MAT1,5,10.9+6,,.27,.148,3.6111-6,70.,.05

$ ZNS DNDT
MAT1,51,10.9+6,,.27,.148,2.5000-
5,70.,.05

$ ELEMENT BARS
PBAR,2,2,1.,1.,1.,1.,0.
=3,*1,*1,==

PBAR,21,21,1.,1.,1.,1.,0,
=3,*10,*10,==

CBAR,2011,5,2015,2011,0.,0.,1.1
=,2012,=,=,2012,==
=,2013,=,=,2013,==
=,2014,51,=,2014,==
=,2021,2,2025,2021,==
=,2022,=,=,2022,==
=,2023,=,=,2023,==
=,2024,21,=,2024,==
=,2031,3,2035,2031,==
=,2032,=,=,2032,==
=,2033,=,=,2033,==
=,2034,31,=,2034,==
=,2051,2,2055,2051,==
=,2052,=,=,2052,==
=,2053,=,=,2053,==
=,2054,21,=,2054,==
=,2061,3,2065,2061,==
=,2062,=,=,2062,==
=,2063,=,=,2063,==
=,2064,31,=,2064,==
=,2071,2,2075,2071,==
=,2072,=,=,2072,==
=,2073,=,=,2073,==
=,2074,21,=,2074,==
=,2091,2,2095,2091,==
=,2092,=,=,2092,==
=,2093,=,=,2093,==
=,2094,21,=,2094,==
=,2101,4,2105,2101,==
=,2104,41,=,2104,==
=,2111,3,2115,2111,==
=,2114,31,=,2114,==
=,2121,4,2125,2121,==
=,2124,41,=,2124,==

$ FOCAL LENGTH CHANGES

GRID,2016,1,0.,0.,0.,1
=11,*10,==

SPC1,1,123456,2046,2086

$ ENDDATA

MPC,1002,2016,1,-1.,2011,1,-.3323,
,,2012,1,-1.7878,2013,1,.196,
,,2014,1,-6.917

MPC,1002,2026,1,-1.,2021,1,-2650.,
,,2022,1,-3780.,2023,1,3700.,
,,2024,1,-83.64

MPC,1002,2036,1,-1.,2031,1,-.3149,
,,2032,1,-.1809,2033,1,1.0017,
,,2034,1,.4653

$ #4, A MIRROR

MPC,1002,2056,1,-1.,2053,1,.4126,
,,2054,1,-.5014

MPC,1002,2066,1,-1.,2062,1,-.331,
,,2064,1,.2539

MPC,1002,2076,1,-1.,2071,1,-.4773,
,,2072,1,-.3038,2073,1,1.4252,
,,2074,1,-.6295

$ #8, A MIRROR

MPC,1002,2096,1,-1.,2091,1,-.846,
,,2092,1,-2.1095,2093,1,.6559,
,,2094,1,-.7531

MPC,1002,2106,1,-1.,2101,1,.3964,
,,2104,1,.0146

MPC,1002,2116,1,-1.,2111,1,.7513,
,,2114,1,1.24-3

MPC,1002,2126,1,-1.,2121,1,.3964,
,,2124,1,.0146
```

```
$ ELASTIC STRUCTURAL MODEL
$ OPTICAL BENCH
$ BEGIN EVERYTHING ABOVE 200

GRID,151,1,-2.,0,-4.1,1
=,*1,1,4.,==

$ FIRST VERTICES IDENTIFIED

GRID,101,1,0.,0.,-.08938,1       $
V1
=,*1,=,=,=,-1.6396,1             $
WF1
=,*1,=,=,=,-4.1,1                $
BENCH
=,*1,=,=,=,-4.8894,1             $
MF1, MF2 & MF3 USE WF2 & WF3
(SHIFTED SLIGHTLY)
=,*1,=,=,=,-6.7436,1             $
WF2
=,*1,=,=,=,-6.9776,1             $
WF3
=,*1,=,=,=,-7.0,1                $
BASEPLATE

GRID,108,1,0.,0.,-7.2676,1       $
V2
GRID,109,1,0.,0.,-7.5916,1       $
V3
GRID,110,1,0.,0.,-8.2894,1       $
V4
=,*1,=,=,-1.5,-7.0,==
=,*1,=,=,-3.3441,==

GRID,113,1,0.,-2.8395,-8.2894,1 $
V5
GRID,114,1,0.,-3.3441,-8.2894,1 $
V6
GRID,115,1,0.,-3.5267,-8.2894,1 $
V7
GRID,116,1,0.,-4.4700,-8.2894,1 $
V8
GRID,117,1,0.,-4.4700,-7.4894,1 $
V9
=,*1,=,=,=,-7.0,==               $
BASEPLATE
=,*1,=,=,-5.5,-7.0,==            $
CRYO SUPPORT
=,*1,=,=,-5.5,-3.5,==            $
CRYO SUPPORT
=,*1,=,=,-5.5,-.8,==             $
CRYO SUPPORT
=,*1,=,=,-4.4700,==              $
CRYO ENGINE

GRID,123,1,0.,-4.4700,-6.2313,1 $
V10
GRID,124,1,0.,-4.4700,-6.1613,1 $
V11
GRID,125,1,0.,-4.4700,-6.0713,1 $
V12
GRID,126,1,0.,-4.4700,-4.6009,1 $
V13

$ 6061-T6 ALUMINUM

$ Tube: 3.0 OD x 0.1 wall thickness

MAT1,200,10.+6,,.3,.098,13.-
6,70.,.05
PBEAM,201,200,1.,1.,1.,,1.
=,*1,==
=23,*1,==
PBEAM,251,200,1.,1.,1.,,1.

$ STRUCTURE

CBEAM,101,201,101,102,.1,.1,.1
=,*1,202,102,103,==
=,*1,203,103,104,==
=,*1,204,104,105,==
=,*1,205,105,106,==
=,*1,206,106,107,==
=,*1,207,107,108,==
=,*1,208,108,109,==
=,*1,209,109,110,==
=,*1,210,107,111,==
=,*1,211,111,112,==
=,*1,212,112,118,==
=,*1,213,112,114,==
=,*1,214,114,113,==
=,*1,215,114,115,==
=,*1,216,116,117,==
=,*1,217,117,118,==
=,*1,218,118,119,==
=,*1,219,119,120,==
=,*1,220,120,121,==
=,*1,221,121,122,==
=,*1,222,122,126,==
=,*1,223,126,125,==
=,*1,224,125,124,==
=,*1,225,124,123,==

$ OPTICAL BENCH SUPPORT

CBEAM,151,251,151,103,.1,.1,.1
=,152,251,152,103,.1,.1,.1

RBAR,201,1,101,,123456      $ P1/V1
=,*1,*1,108,==              $ P2/V2
=,*1,*1,*1,==               $ P3/V3
=,*1,*1,*1,==               $ P4/V4
=,*1,*1,113,==              $ P5/V5
=,*1,*1,*1,==               $ P6/V6
=3,*1,*1,*1,==              $ P7/
V7,P8/V8,P9/V9
RBAR,210,10,123,,123456     $ P10/V10
=,*1,*1,*1,==               $ P11/V11
=2,*1,*1,*1,==              $ P12/
V12,P13/V13

ENDDATA
```

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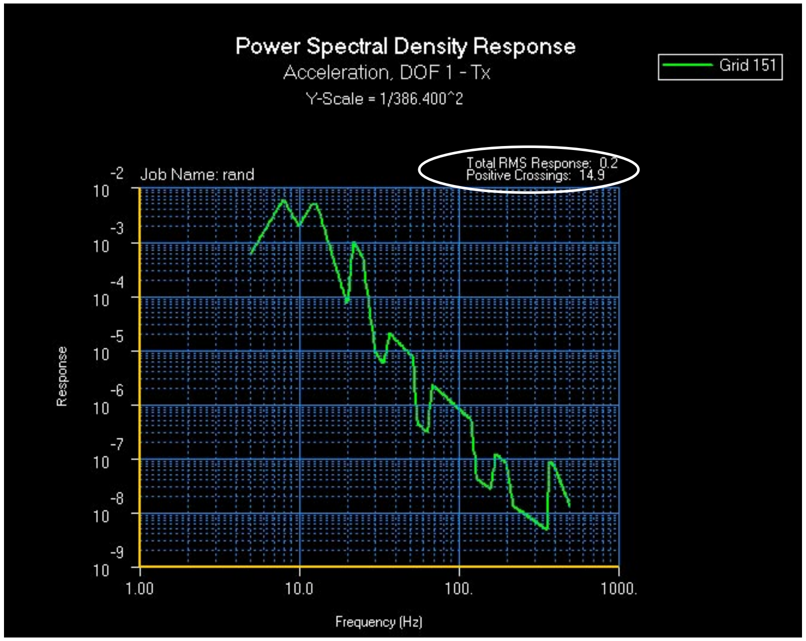
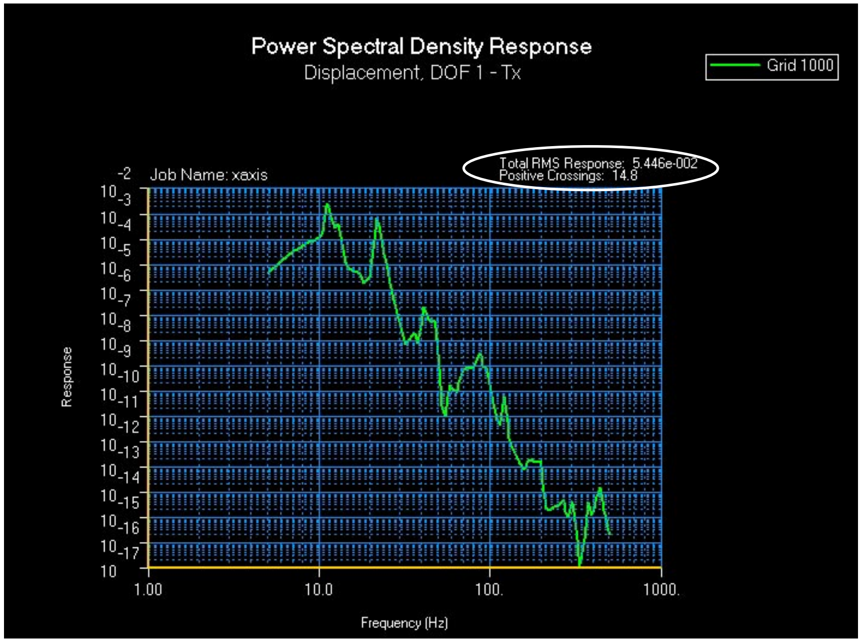
Infrared Imager - in Ivory/NASTRAN

Excitation PSD



Initial
Tx image response PSD



Other response quantities:

Ty
Tz
Rx
Ry
Rz
ΔM/M

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Infrared Imager Margins of Safety

NASTRAN modeling:

Model Comparison	Mass Lb	CG, in. (ProE coordinate system) X	Y	Z	
ProE	4.97	-2.53	-2.3	0.98	
NASTRAN	4.74	-2.47	-2.84	0.52	(Balasted by increasing the density of the Albemet)

NASTRAN modeling parameters:

Fundamental resonance:	425	Hz
Structural damping:	0.05	
Pass-band:	5 to 500	Hz
Structural material:	Albemet	

NASTRAN results.

Vibration Excitation Axis: X, Y, Z

Registration Variables:	RMS response of image at the detector: X	Y	Z
Tx	5.31E-06	1.50E-07	8.27E-07
Ty	2.43E-08	1.51E-06	2.37E-06
Tz	9.53E-07	2.11E-06	1.25E-06
Rx	1.05E-07	7.34E-09	3.75E-08
Ry	7.41E-07	5.65E-08	2.97E-07
Rz	5.56E-07	3.13E-08	1.65E-07
DM/M	1.15E-08	1.34E-06	3.66E-07

Units: inches, radians

7 microradians equivalent RMS image motion:	**Margins of Safety: X**	**Y**	**Z**
0.000138	**25.0**	**915.8**	**165.8**
0.000138	**5668.2**	**90.6**	**57.3**

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Infrared Imager Thermal Sensitivity- Ivory/NASTRAN

Construction Material	Focus Shift (in/F)	Change in Size (-)	Mass (lb)
Aluminum	.00320	-.00215	7.88
CRES	.00300	-.00203	10.44
Titanium	.00283	-.00192	8.71
AlBeMet	.00295	-.00199	7.58
Nothing	.00281	-.00182	-

A positive focus shift puts the image in front of the detector.
A positive change is size makes the image*absolutely* larger.

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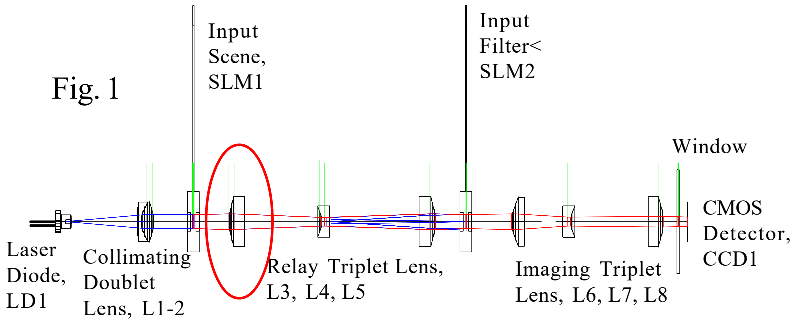
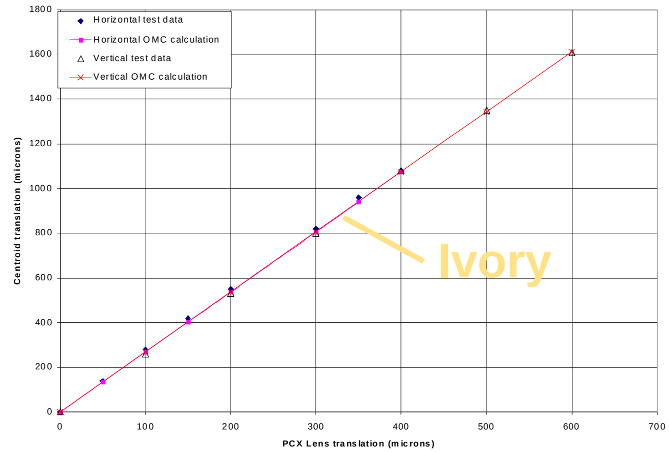
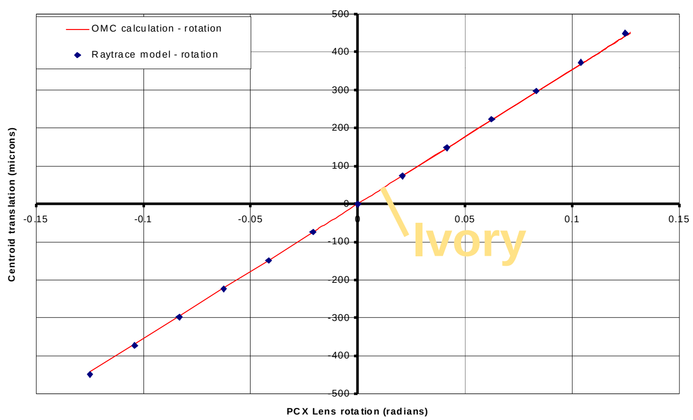
Image Correlator in Ivory



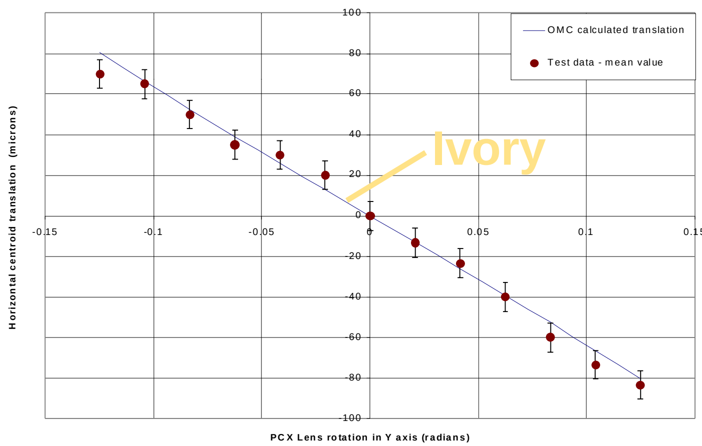
X & Y Translations



X & Y Rotations



Combined Translations & Rotations



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Ivory, Optimal Folding

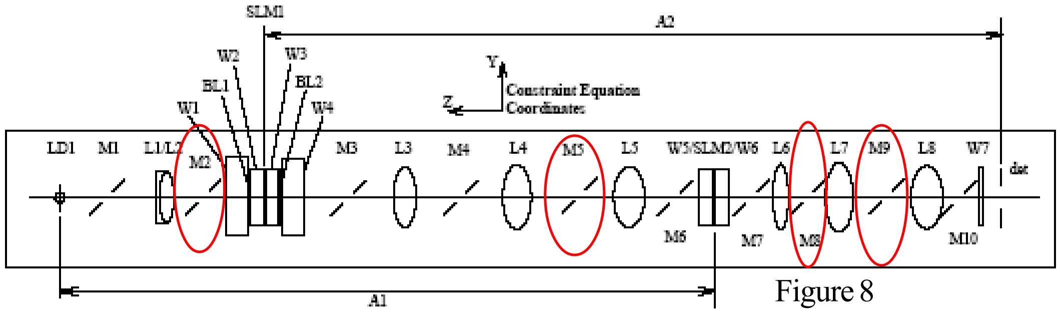
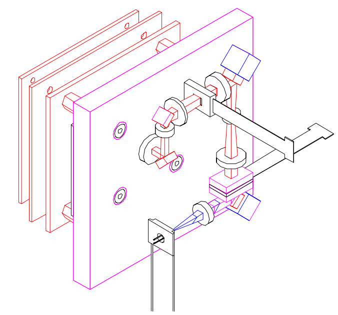


Figure 8



Mirror	A1 image coefficients Ty_i/Rx_m	Tx_i/Ry_m	Tz_i/Tz_m	A2 image coefficients Ty_i/Rx_m	Tx_i/Ry_m	Tz_i/Tz_m
M1	62.0	-87.7	-26.2			
M2	**-125.0**	**-176.7**	**-0.00024**			
M3	125.2	-177.1	-0.00024	5.35	-7.57	-0.593
M4	-74.8	-105.8	-10.1	-17.1	-24.1	-0.318
M5	**26.6**	**-37.6**	**-0.829**	**51.8**	**-73.3**	**-3.41**
M6	-5.90	-8.35	-1.41	-81.6	-115.4	-0.0116
M7				80.3	-113.6	-0.0116
M8				**-56.0**	**-79.2**	**-8.31**
M9				**21.8**	**-30.9**	**-0.951**
M10				-3.93	-5.56	-1.41

Influence coefficients from Ivory's OCE

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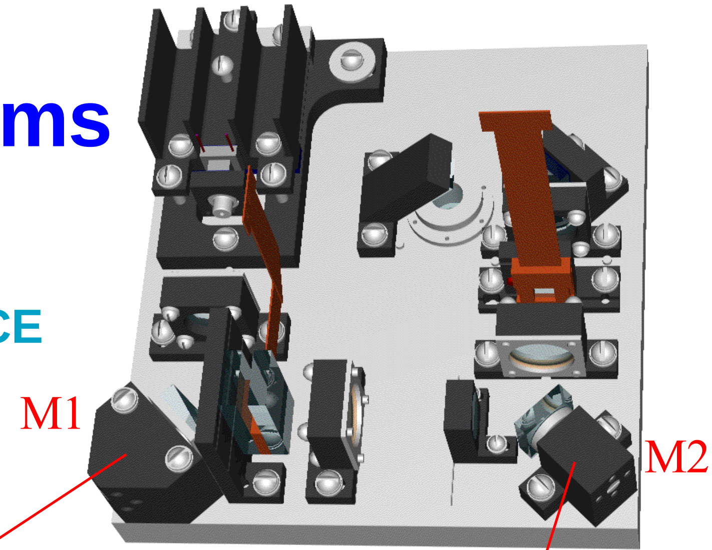
Ivory, Alignment Mechanisms



Influence coefficients from Ivory's OCE

Registration of the A1 image:

Tx					**125.0**						-26.6	
Ty			0.0184	**-176.8**					1.083	-37.6		
Tz			-.00024						-0.829			
Rx				0.026						-1.53		
Ry					0.018						1.083	
Rz					1.414						**1.414**	
ΔM/M			0.000208						-0.031			
Registration	Tx	Ty	Tz	Rx	Ry	Rz	Tx	Ty	Tz	Rx	Ry	Rz
Variables	M1 Motions						M2 Motions					

	M1 (Rx	M1 Ry)	M2 (Rx	M2 Ry)
Required:	**(Rx**	**Ry)**	**(Rx**	**Ry)**
Stroke, mr (±)	**8.5**	**11.1**		**42.**
Resolution, μr (±)	**8.5**	**12.**		**589.**
Achieved:				
Stroke, mr (±)	**17.**	**17.**	**52.**	**52.**
Resolution, μr(±)	**0.26**	**0.26**	**556.**	**556.**

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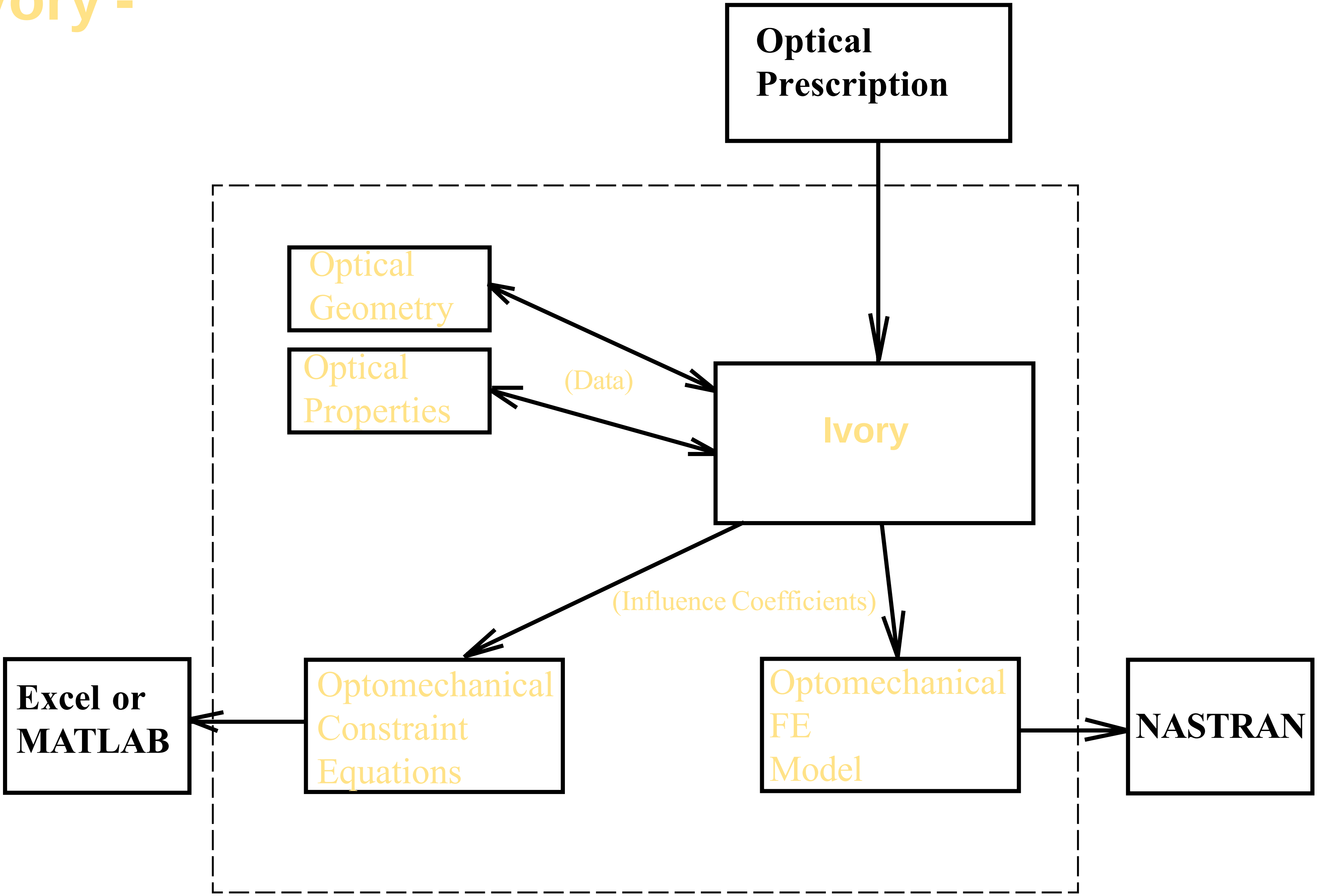
Ivory, Athermalization

The coefficient of thermal expansion, CTE, and the temperature coefficient of refractive index, TCRI, were input to the optomechanical constraint equations to determine the thermal sensitivities of focus and magnification for both the A1 and A2 optical paths.

Bench Material:	**Aluminum**	**CRES**	**Titanium**	**Invar**
for A1				
Tz/ΔT (mm/C°)	-0.023	-0.013	-0.012	-0.0053
ΔM/MΔT (/C°)	0.00030	0.00032	0.00033	0.00034
for A2				
Tz/ΔT (mm/C°)	-0.0041	-0.0039	-0.0039	-0.0038
ΔM/MΔT (/C°)	0.00036	0.00036	0.00036	0.00036

The stability with a CRES bench was seen as adequate over the anticipated service environments.

Ivory -



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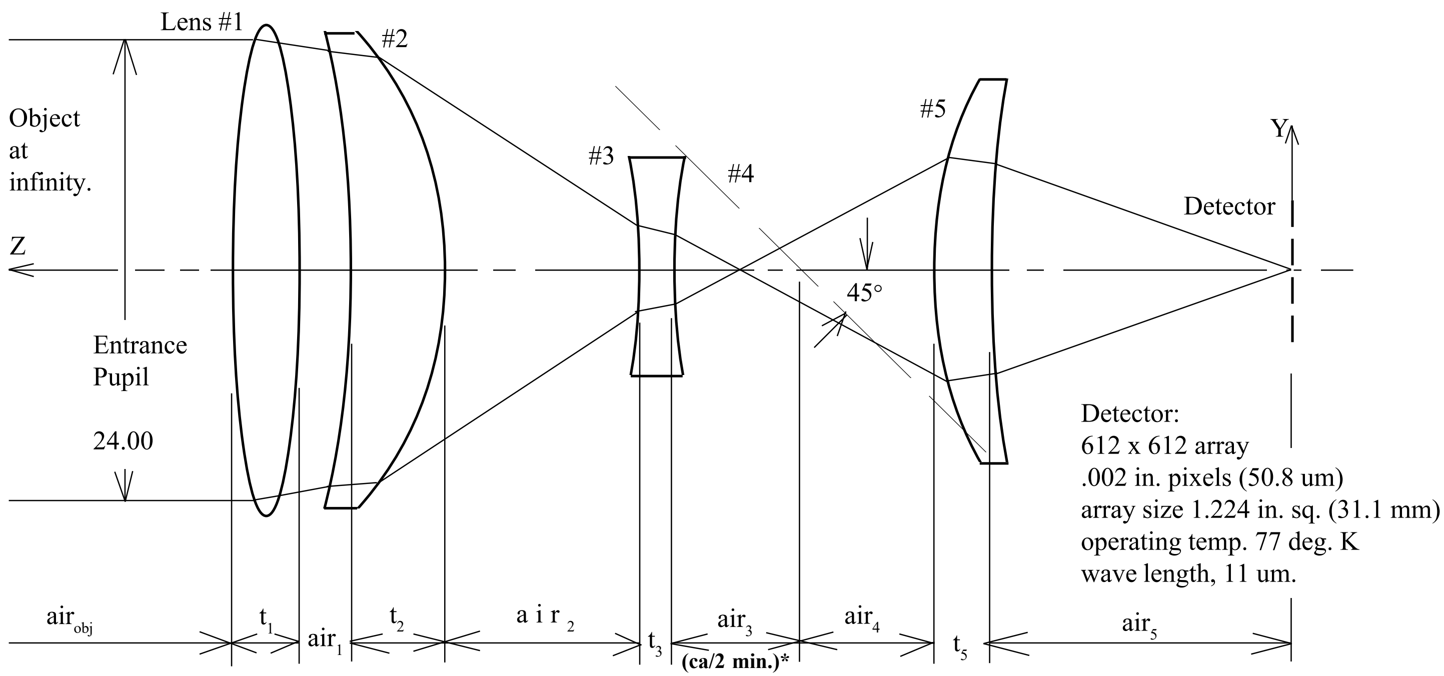
A Folded Receiver



Surface	Lens	Radius	Index	Thickness	Angle of Inc.	Angle of Rot.
1	obj.	inf.	1.0000	inf.		
2	1	-300.	4.0026	2.0000		
3	1	300.	1.0000	5.3566		
4	2	110.	4.0026	3.4500		
5	2	55.	1.0000	17.7750		
6	3	310.	4.0026	2.0000		
7	3	-215.	1.0000	*3.5		
8	4	inf.	1.0000	8.4417	-45	33
9	5	-11.	4.0026	1.5000		
10	5	-22	1.0000	20.4727 (best focus)		
11	det.	inf.	1.0000	-		

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Ivory Input Files

firrec.dat

Surf	Elem	Radius	Index	Thickness	Type	f1	f2	f3	f4
1	obj	inf	AIR	inf	obj				
2	1	-300.	GE	2.0000	LENS				
3	1	300.	AIR	5.3566	LENS				
4	2	110.	GE	3.4500	LENS				
5	2	55.	AIR	17.7750	LENS				
6	3	310.	GE	2.0000	LENS				
7	3	-215.	AIR	3.5000	LENS				
8	4	inf	AIR	8.4417	MIRR	-45	33		
9	5	-11.	GE	1.5000	LENS				
10	5	-22.	AIR	20.4727	LENS				
11	det	inf	AIR	0.0	det				

firrec.ind

MATERIAL	INDEX
AIR	1.0000
GE	4.0026

Double-click on Ivory.exe.
Type the project name "firrec" and press Enter.
Double-click on the file "firrec.out."

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Ivory Output File: “firrec.out”

Header

```
Output from -
                IVORY Optomechancial Modeling Tools
                                        (Version Cord7D)
                                                        Copyright 2006, Alson E. Hatheway Inc.

This Product has been licensed to Alson E. Hatheway for one user(s).

PROJECT NAME: 'FIRREC'       TIME AND DATE: 18:29:50 07-26-2006
```

Physical Prescription

PHYSICAL PRESCRIPTION ECHO

Surf	Elem	Radius	Index	Thickness	Type	f1	f2	f3	f4
1	obj	inf	1.0000	inf	obj				
2	1	-300.	4.0026	2.0000	LENS				
3	1	300.	1.0000	5.3566	LENS				
4	2	110.	4.0026	3.4500	LENS				
5	2	55.	1.0000	17.7750	LENS				
6	3	310.	4.0026	2.0000	LENS				
7	3	-215.	1.0000	3.5000	LENS				
8	4	inf	1.0000	8.4417	MIRR	-45	33		
9	5	-11.	4.0026	1.5000	LENS				
10	5	-22.	1.0000	20.4727	LENS				
11	det	inf	1.0000	0.0	det				

Gaussian Prescription

GAUSSIAN PRESCRIPTION

ELE	F	H1	H2	P	P/AIR	PHI	THETA	TYPE
obj	0	0	0	0	inf	0	0	obj
1	50.08193	-.2504639	.2504639	1.499072	7.25347	0	0	LENS
2	34.98851	-1.646407	-.8232033	2.626797	17.246	0	0	LENS
3	-42.16034	-.2942056	.2040458	1.501749	3.704046	0	0	LENS
4	inf	0	0	0	8.101722	-45	33	MIRR
5	6.647026	.3399783	.6799567	1.160022	21.15266	0	0	LENS
det	0	0	0	0	0	0	0	det

Objects, Images and Magnifications

OBJECTS, IMAGES AND MAGNIFICATIONS

ELE	F	S	S'	M	PHI	THETA	TYPE
obj	inf	0	0	+1.0000	0	0	obj
1	50.08193	inf	-50.0819	0	0	0	LENS
2	34.98851	-42.8285	-19.2568	+0.4496	0	0	LENS
3	-42.16034	-2.0108	-2.1115	+1.0501	0	0	LENS
4	inf	+1.5926	+1.5926	+1.0000	-45	33	MIRR
5	6.647026	+9.6943	-21.1463	-2.1813	0	0	LENS
det	inf	+6.38D-03	+6.38D-03	+1.0	0	0	det

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Ivory Output File: “firrec.out”

Element Influence Coefficient Arrays

ELEMENT INFLUENCE COEFFICIENT ARRAYS

+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+1.00000	+0.00000	+0.00000	+0.00000	-1.49907	+0.00000	+0.00000
+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+1.00000	+0.00000	+1.49907	+0.00000	+0.00000	+0.00000
+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+1.00000	+0.00000	+0.00000	+0.00000	-1.00000
+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+1.00000	+0.00000	+0.00000	+0.00000
+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+1.00000	+0.00000	+0.00000
+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+1.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000
+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.01997
+1.00000	+0.06277	-0.08326	+0.08326	-16.66907	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000
TX	TY	TZ	RX	RY	RZ	TX	TY	TZ	RX	RY	RZ	DF/P
OBJECT : : : : :						ELEMENT						

+0.44963	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.55037	+0.00000	+0.00000	+0.00000	-2.62680	+0.00000	+0.00000
+0.00000	+0.44963	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.55037	+0.00000	+2.62680	+0.00000	+0.00000	+0.00000
+0.00000	+0.00000	+0.20216	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.79784	+0.00000	+0.00000	+0.00000	-0.30291
+0.00000	+0.00000	+0.00000	+0.44963	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.55037	+0.00000	+0.00000	+0.00000
+0.00000	+0.00000	+0.00000	+0.00000	+0.44963	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.55037	+0.00000	+0.00000
+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+1.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000
+0.00000	+0.00000	+0.01285	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	-0.01285	+0.00000	+0.00000	+0.00000	+0.01573
+2.00000	-0.45577	-0.28949	+1.24372	-11.78357	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000
TX	TY	TZ	RX	RY	RZ	TX	TY	TZ	RX	RY	RZ	DF/P
OBJECT : : : : :						ELEMENT						

+1.05008	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	-0.05008	+0.00000	+0.00000	+0.00000	-1.50175	+0.00000	+0.00000
+0.00000	+1.05008	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	-0.05008	+0.00000	+1.50175	+0.00000	+0.00000	+0.00000
+0.00000	+0.00000	+1.10267	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	-0.10267	+0.00000	+0.00000	+0.00000	-0.00251
+0.00000	+0.00000	+0.00000	+1.05008	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	-0.05008	+0.00000	+0.00000	+0.00000
+0.00000	+0.00000	+0.00000	+0.00000	+1.05008	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	-0.05008	+0.00000	+0.00000
+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+1.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000
+0.00000	+0.00000	-0.02491	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.02491	+0.00000	+0.00000	+0.00000	+0.00119
+3.00000	+0.06007	-0.05592	+0.11602	+14.05127	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000
TX	TY	TZ	RX	RY	RZ	TX	TY	TZ	RX	RY	RZ	DF/P
OBJECT : : : : :						ELEMENT						

-0.83867	-0.54464	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+2.25222	+0.00000	+0.00000
-0.54464	+0.83867	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+1.41421	+3.18512	+0.00000	+0.00000	+0.00000
+0.00000	+0.00000	+1.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	-1.41421	+0.00000	+0.00000	+0.00000	+0.00000
+0.00000	+0.00000	+0.00000	+0.83867	+0.54464	+0.00000	+0.00000	+0.00000	+0.00000	-2.00000	+0.00000	+0.00000	+0.00000
+0.00000	+0.00000	+0.00000	+0.54464	-0.83867	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+1.41421	+0.00000	+0.00000
+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	-1.00000	+0.00000	+0.00000	+0.00000	+0.00000	+1.41421	+0.00000	+0.00000
+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000
+4.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000
TX	TY	TZ	RX	RY	RZ	TX	TY	TZ	RX	RY	RZ	DF/P
OBJECT : : : : :						ELEMENT						

-2.18131	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+3.18131	+0.00000	+0.00000	+0.00000	-1.16002	+0.00000	+0.00000
+0.00000	-2.18131	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+3.18131	+0.00000	+1.16002	+0.00000	+0.00000	+0.00000
+0.00000	+0.00000	+4.75813	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	-3.75813	+0.00000	+0.00000	+0.00000	-10.12076
+0.00000	+0.00000	+0.00000	-2.18131	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+3.18131	+0.00000	+0.00000	+0.00000
+0.00000	+0.00000	+0.00000	+0.00000	-2.18131	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+3.18131	+0.00000	+0.00000
+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+1.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000
+0.00000	+0.00000	-0.32816	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.32816	+0.00000	+0.00000	+0.00000	+0.47861
+5.00000	-0.41124	-1.15247	+0.24606	-2.26508	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000
TX	TY	TZ	RX	RY	RZ	TX	TY	TZ	RX	RY	RZ	DF/P
OBJECT : : : : :						ELEMENT						

+1.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	-1.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000
+0.00000	+1.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	-1.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000
+0.00000	+0.00000	+1.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	-1.00000	+0.00000	+0.00000	+0.00000	+0.00000
+0.00000	+0.00000	+0.00000	+1.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	-1.00000	+0.00000	+0.00000	+0.00000
+0.00000	+0.00000	+0.00000	+0.00000	+1.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	-1.00000	+0.00000	+0.00000
+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+1.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	-1.00000	+0.00000
+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000
+6.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000	+0.00000
TX	TY	TZ	RX	RY	RZ	TX	TY	TZ	RX	RY	RZ	DF/P
OBJECT : : : : :						ELEMENT						

Optomechanical Constraint Equations -

Prepared by Ivory for “firrec” as *firrec.out*

REGISTRATION VARIABLES

		TX	TY	TZ	RX	RY	RZ	DM/M	Df	LDes Var
Object	Tx	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Dt
	Ty	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	DR1
	Tz	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	DR2
	Rx	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Dn
	Ry	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	Rz	0.0	0.0	0.0	0.0	0.0	-1.0000	0.0	0.0	
	Df,p	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	SYSTEM-OBJECT									
Lens 1	Tx	+0.8637	+0.5609	0.0	0.0	0.0	0.0	0.0	+0.0628	Dt
	Ty	+0.5609	-0.8637	0.0	0.0	0.0	0.0	0.0	-0.0833	DR1
	Tz	0.0	0.0	+1.0607	0.0	0.0	0.0	-0.0653	+0.0833	DR2
	Rx	+0.8409	-1.2948	0.0	-0.8637	-0.5609	0.0	0.0	-16.6691	Dn
	Ry	-1.2948	-0.8409	0.0	-0.5609	+0.8637	0.0	0.0	0.0	
	Rz	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	Df,p	0.0	0.0	-1.0607	0.0	0.0	0.0	+0.0853	0.0	
	ELEMENT-1									
Lens 2	Tx	+1.0573	+0.6866	0.0	0.0	0.0	0.0	0.0	-0.4558	Dt
	Ty	+0.6866	-1.0573	0.0	0.0	0.0	0.0	0.0	-0.2895	DR1
	Tz	0.0	0.0	+4.1860	0.0	0.0	0.0	-0.3214	+1.2437	DR2
	Rx	+3.2770	-5.0461	0.0	-1.0573	-0.6866	0.0	0.0	-11.7836	Dn
	Ry	-5.0461	-3.2770	0.0	-0.6866	+1.0573	0.0	0.0	0.0	
	Rz	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	Df,p	0.0	0.0	-1.5893	0.0	0.0	0.0	+0.1329	0.0	
	ELEMENT-2									
Lens 3	Tx	-0.0916	-0.0595	0.0	0.0	0.0	0.0	0.0	+0.0601	Dt
	Ty	-0.0595	+0.0916	0.0	0.0	0.0	0.0	0.0	-0.0559	DR1
	Tz	0.0	0.0	-0.4885	0.0	0.0	0.0	+0.0586	+0.1160	DR2
	Rx	+1.7841	-2.7473	0.0	+0.0916	+0.0595	0.0	0.0	+14.0513	Dn
	Ry	-2.7473	-1.7841	0.0	+0.0595	-0.0916	0.0	0.0	0.0	
	Rz	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	Df,p	0.0	0.0	-0.0119	0.0	0.0	0.0	+2.01E-03	0.0	
	ELEMENT-3									
Mirror 1	Tx	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Dt
	Ty	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	DR1
	Tz	0.0	-3.0848	-6.7290	0.0	0.0	0.0	+0.4641	0.0	DR2
	Rx	0.0	-6.9478	0.0	+4.3626	0.0	0.0	0.0	0.0	Dn
	Ry	-4.9128	0.0	0.0	0.0	-3.0848	+1.4142	0.0	0.0	
	Rz	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	Df,p	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	ELEMENT-4									
Lens 4	Tx	+3.1813	0.0	0.0	0.0	0.0	0.0	0.0	-0.4112	Dt
	Ty	0.0	+3.1813	0.0	0.0	0.0	0.0	0.0	-1.1525	DR1
	Tz	0.0	0.0	-3.7581	0.0	0.0	0.0	+0.3282	+0.2461	DR2
	Rx	0.0	+1.1600	0.0	+3.1813	0.0	0.0	0.0	-2.2651	Dn
	Ry	-1.1600	0.0	0.0	0.0	+3.1813	0.0	0.0	0.0	
	Rz	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	Df,p	0.0	0.0	-10.1208	0.0	0.0	0.0	+0.4786	0.0	
	ELEMENT-5									
Detector	Tx	-1.0000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Dt
	Ty	0.0	-1.0000	0.0	0.0	0.0	0.0	0.0	0.0	DR1
	Tz	0.0	0.0	-1.0000	0.0	0.0	0.0	0.0	0.0	DR2
	Rx	0.0	0.0	0.0	-1.0000	0.0	0.0	0.0	0.0	Dn
	Ry	0.0	0.0	0.0	0.0	-1.0000	0.0	0.0	0.0	
	Rz	0.0	0.0	0.0	0.0	0.0	-1.0000	0.0	0.0	
	Df,p	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	DETECTOR									

Optomechanical Constraint Equations -

Prepared by Ivory

and Read into MS Excel

OPTOMECH	CONSTRAIN	EQUATIONS	(ABSOLUTE VALUES		SMALLER	THAN		ARE	PRINTED	AS	0.0)
	REGISTRAT	VARIABLES									
	TX	TY	TZ	RX	RY	RZ	DM/M	Df	LDesVar	Var	
Tx									Dt		
Ty									DR1		
Tz									DR2		
Rx									Dn		
Ry											
Rz						-1					
Df,p											
SYSTEM-OBJECT											
Tx	0.8637	0.5609						0.0628	Dt		
Ty	0.5609	-0.8637						-0.0833	DR1		
Tz			1.0607				-0.0653	0.0833	DR2		
Rx	0.8409	-1.2948		-0.8637	-0.5609			-16.6691	Dn		
Ry	-1.2948	-0.8409		-0.5609	0.8637						
Rz											
Df,p			-1.0607				0.0853				
ELEMENT-1											
Tx	1.0573	0.6866						-0.4558	Dt		
Ty	0.6866	-1.0573						-0.2895	DR1		
Tz			4.186				-0.3214	1.2437	DR2		
Rx	3.277	-5.0461		-1.0573	-0.6866			-11.7836	Dn		
Ry	-5.0461	-3.277		-0.6866	1.0573						
Rz											
Df,p			-1.5893				0.1329				
ELEMENT-2											
Tx	-0.0916	-0.0595						0.0601	Dt		
Ty	-0.0595	0.0916						-0.0559	DR1		
Tz			-0.4885				0.0586	0.116	DR2		
Rx	1.7841	-2.7473		0.0916	0.0595			14.0513	Dn		
Ry	-2.7473	-1.7841		0.0595	-0.0916						
Rz											
Df,p			-0.0119				2.01E-03				
ELEMENT-3											
Tx									Dt		
Ty									DR1		
Tz		-3.0848	-6.729				0.4641		DR2		
Rx		-6.9478		4.3626					Dn		
Ry	-4.9128				-3.0848	1.4142					
Rz											
Df,p											
ELEMENT-4											
Tx	3.1813							-0.4112	Dt		
Ty		3.1813						-1.1525	DR1		
Tz			-3.7581				0.3282	0.2461	DR2		
Rx		1.16		3.1813				-2.2651	Dn		
Ry	-1.16				3.1813						
Rz											
Df,p			-10.1208				0.4786				
ELEMENT-5											
Tx	-1								Dt		
Ty		-1							DR1		
Tz			-1						DR2		
Rx				-1					Dn		
Ry					-1						
Rz						-1					
Df,p											
DETECTOR											
Thank	you	for	using	IVORY(tm)	to	prepare	the	Optomechan	Constraint	Equations	for

AEH.

Optomechanical Solutions

Opto-mechanical Constraint Equations - Prepared by Ivory and Read into NASTRAN as Multipoint Constraints

```
NASTRAN
CEND
TITLE=irrec'S IVORY(TM) UNIFIED OPTOMECHANICAL MODEL
$ SINGLE POINT CONSTRAINT SETS MUST BE CALLED OUT IN THE CASE CONTROL DECK.
SPC=1000
$ MULTIPOINT CONSTRAINT SETS MUST BE CALLED OUT IN THE CASE CONTROL DECK.
MPC=1000
SET 1=1,2,3,4,5,1001,1002
DISP(PHASE)=1
BEGIN BULK
$ THE FOLLOWING GRID POINTS/DOFS HAVE BEEN ASSIGNED:
$ 1 THRU  4 /123456 ARE ASSIGNED TO THE CORRESPONDING OPTICAL ELEMENTS.
$   5 /123456 ARE ASSIGNED TO THE SYSTEM DETECTOR.
$ 1000/123456 ARE ASSIGNED TO THE REGISTRATION VARIABLES TX, TY, TZ, RX, RY, RZ.
$ 1001/1 IS ASSIGNED TO THE REGISTRATION VARIABLE DM/M.
$ 1002/123456 ARE ASSIGNED TO THE SYSTEM OBJECT.
MPC     1000    1000    1       -1.     1       1       -1.0299.
                1       5        1.5439.2       1       -1.2607.
                2       5        6.0168.3       1        .1092.
                3       5        3.2758.4       1        3.1813.
                4       5       -1.16.  5       1       -1.

MPC     1000    1000    2       -1.     1       2       -1.0299.
                1       4       -1.5439.2       2       -1.2607.
                2       4       -6.0168.3       2        .1092.
                3       4       -3.2758.4       2        3.1813.
                4       4        1.16.  5       2       -1.

MPC     1000    1000    3       -1.     1       3        1.0607.
                2       3        4.186. 3       3       -.4885.
                4       3       -3.7581.5       3       -1.

MPC     1000    1000    4       -1.     1       4       -1.0299.
                2       4       -1.2607.3       4        .1092.
                4       4        3.1813.5       4       -1.
```

Constraint definitions

Complex displacement output request

Element P1 GRID point definitions

Influence coefficients from OCE assigned to element GRID points and constraint set DOFs.

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Optomechanical Solutions

Opto-mechanical Constraint Equations - Prepared by Ivory and Read into NASTRAN as Multipoint Constraints

```
MPC     1000    1000    5       -1.     1       5       -1.0299.
                2       5       -1.2607.3       5        .1092.
                4       5        3.1813.5       5       -1.

MPC     1000    1000    6       -1.     1002    6        1.
                5       6       -1.

MPC     1000    1001    1       -1.     1       3       -.0653.
                2       3       -.3214. 3       3        .0586.
                4       3        .3282.

SPC     1000    1001    23456

$ DETECTOR
$ PRINCIPAL POINT
GRID    5       0       0.      0.      0.      0
$ DETECTOR COORDINATE SYSTEM
CORD2R  5       0       0.      0.      0.      0.      0.      1.
        1.      0.      0.
$ INCIDENT OPTICAL AXIS COORDINATE SYSTEM
CORD2R  10      0       0.      0.      0.      0.      0.      1.
        1.      0.      0.

$ ELEMENT 4
$ FIRST PRINCIPAL POINT
GRID    4       10      0.      0.       22.312 4
$ ELEMENT COORDINATE SYSTEM
CORD2R  4       10      0.      0.       22.312  0.      0.      24.544
         1.      0.      22.312
$ INCIDENT OPTICAL AXIS COORDINATE SYSTEM
CORD2R  9       10      0.      0.       22.312  0.      0.      24.544
         1.      0.      22.312
```

Influence coefficients from OCE assigned to element GRID points and constraint set DOFs.

Element coordinate systems and P1s in *reverse* numerical order.

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Opto-mechanical Constraint Equations - Prepared by Ivory and Read into NASTRAN as Multipoint Constraints

```
$ ELEMENT 3
$ FIRST PRINCIPAL POINT
GRID     3       9       0.      0.      13.307 3
$ ELEMENT COORDINATE SYSTEM
CORD2R   3       9       0.      0.      13.307  0.      0.      14.638
         1.      0.      13.307
$ INCIDENT OPTICAL AXIS COORDINATE SYSTEM
CORD2R   8       9       0.      0.      13.307  0.      0.      14.638
         1.      0.      13.307

$ ELEMENT 2
$ FIRST PRINCIPAL POINT
GRID     2       8       0.      0.      19.872 2
$ ELEMENT COORDINATE SYSTEM
CORD2R   2       8       0.      0.      19.872  0.      0.      21.86
         1.      0.      19.872
$ INCIDENT OPTICAL AXIS COORDINATE SYSTEM
CORD2R   7       8       0.      0.      19.872  0.      0.      21.86
         1.      0.      19.872

$ ELEMENT 1
$ FIRST PRINCIPAL POINT
GRID     1       7       0.      0.      8.752  1
$ ELEMENT COORDINATE SYSTEM
CORD2R   1       7       0.      0.      8.752   0.      0.      9.627
         1.      0.      8.752
$ INCIDENT OPTICAL AXIS COORDINATE SYSTEM
CORD2R   6       7       0.      0.      8.752   0.      0.      9.627
         1.      0.      8.752

$ OBJECT AT INFINITY AND NOT MODELED

$                  MODEL PREPARED BY IVORY(TM) OPTOMECHANICAL MODELING TOOLS
$                        ALSON E. HATHEWAY INC., http://www.aehinc.com

ENDDATA
```

Element coordinate systems and P1s in *reverse* numerical order.

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Ivory - for Mechanical Engineers...

...*flows* the requirements down from the optical physics to the engineering implementation.

...*exploits* the "small displacement" domains in optics, structural mechanics, heat transfer and servo-controls.

...*formulates* mechanical challenges in mechanical design tools: *Unifies* the disciplines.

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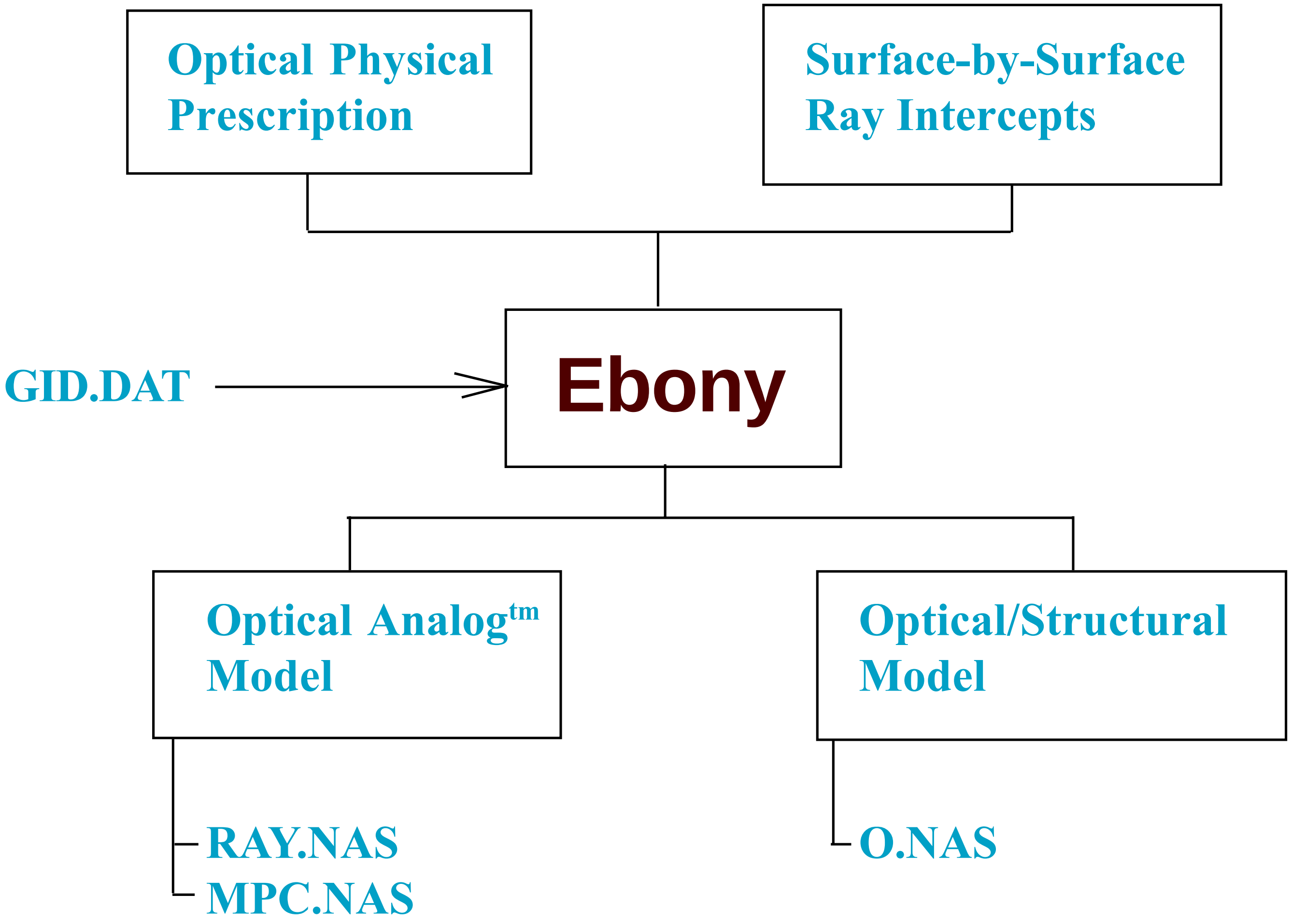
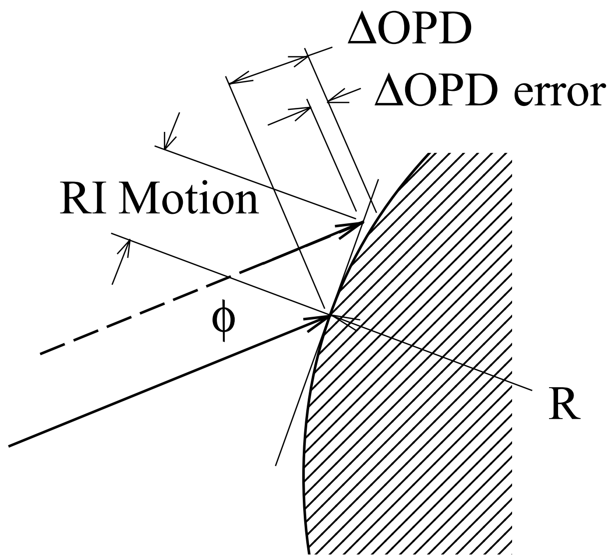
Ebony
Performs
Ray-tracing
in
NASTRAN

Ebony



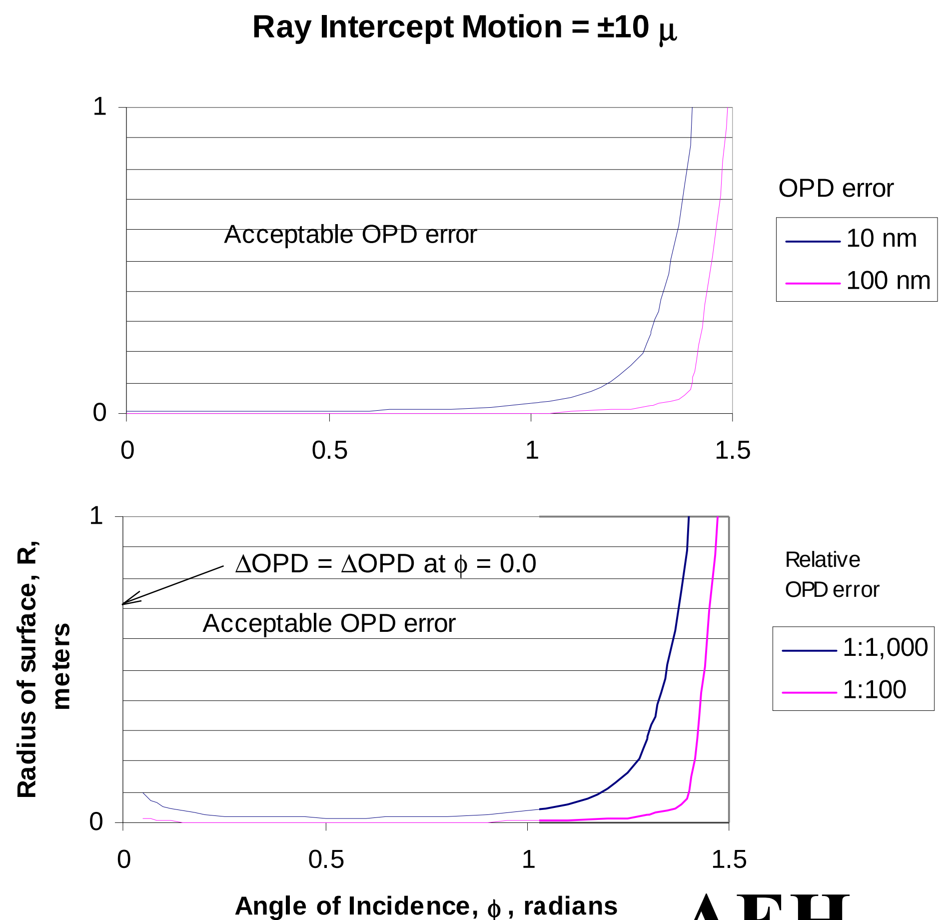
"Optical Analog" is a trademark of Alson E. Hatheway Inc.

Deviations in Ebony OPD Calculation



$$e = (\Delta OPD\ error)/\Delta OPD$$

$$= RI\ Motion/(2R\cos^3\phi\ \sin\phi + RI\ Motion)$$



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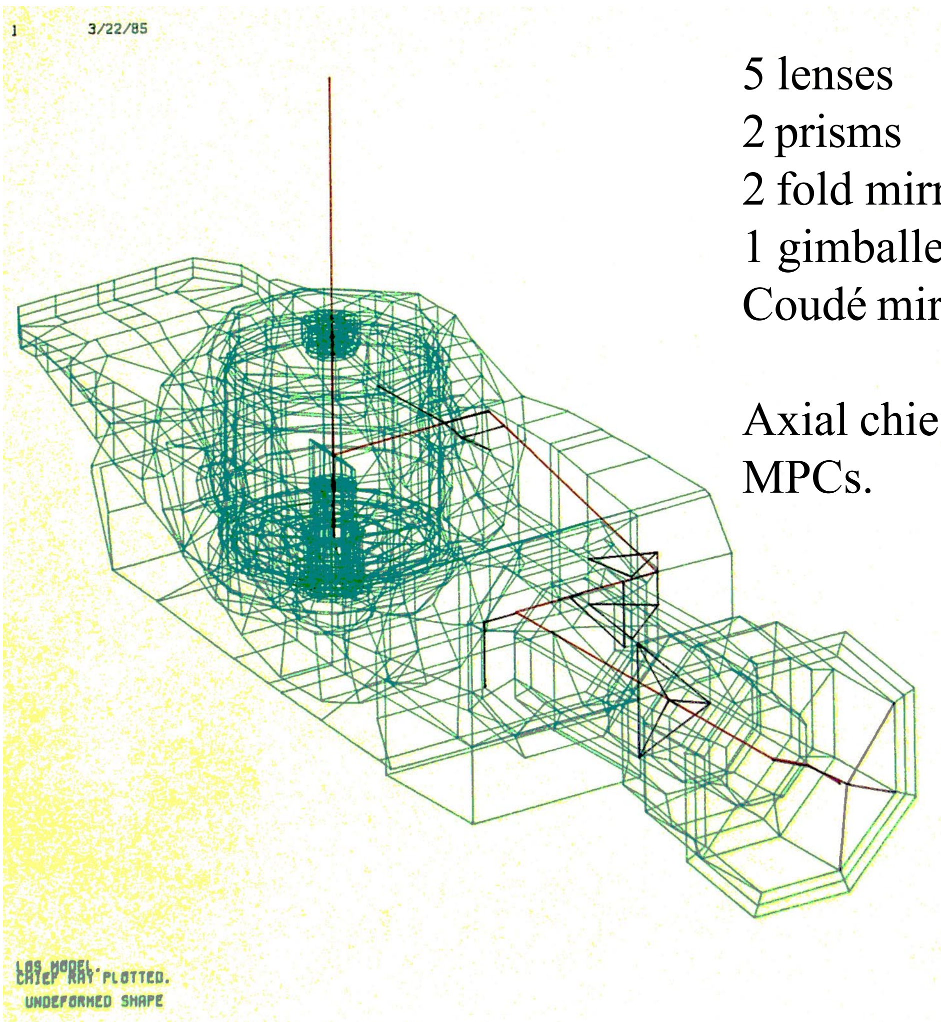
Ebony LOS Stability Analysis



Two-axis stable platform for an airborne laser-com system.

5 lenses
2 prisms
2 fold mirrors
1 gimballed telescope with primary, secondary and Coudé mirrors

Axial chief ray modeled with rigid elements and MPCs.

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Ebony's Optical Law MPCs

Axial chief ray read into NASTRAN Bulk Data file:

```
.
.
$ RAY INTERCEPTS.
$
GRID,1006,12,19.621,4.607,-1.289        $ FIELD LENS.
=,*1,=,12.46,4.232,0.0                  $ FOLD MIRROR.
=,*1,=,12.46,1.976,=                    $ PP2 RELAY.
=,*1,=,=,1.615,=                        $ PP1 RELAY.
=,*1,=,=,0.0,=                          $ FOLD.
=,*1,=,5.865,==                         $ PP2 RELAY.
=,*1,=,5.494,==                         $ PP1 RELAY.
=,*1,11,0.0,202.5,1.381                 $ PP2 PRISM.
=,*1,=,1.148,==                         $ PP1 PRISM.
=,*1,=,=,=,0.0                          $ INCOMING RAY.
$
$
$ RAY TRACE MPCS.
$
MPC,40,1014,1,-1.0,542,1,1.0,
,,542,2,1.0,1015,2,-1.0,
,,1015,6,-1.381
MPC,40,1014,2,-1.0,1015,2,1.0,
,,1015,6,1.381
MPC,40,1014,3,-1.0,1015,3,1.0,
,,1015,5,-1.381
MPC,40,1014,4,-1.0,542,4,1.0,
,,1015,5,1.0,542,5,-1.0
SPC,40,1014,5
MPC,40,1014,6,-1.0,1015,6,-1.0,
,,542,6,2.0
$
.
.
.
```

```
.
.
.
MPC,40,1013,1,-1.0,1014,1,1.0,
,,1014,6,1.148
MPC,40,1013,2,-1.0,1014,1,-1.0
,,1014,6,-1.148,541,1,1.0,
,,541,2,1.0
MPC,40,1013,3,-1.0,1014,3,1.0,
,,1014,4,-1.148
SPC,40,1013,4
MPC,40,1013,5,-1.0,1014,4,1.0,
,,541,5,1.0,541,4,-1.0
MPC,40,1013,6,-1.0,1014,6,-1.0,
,,541,6,2.0
$
MPC,40,1012,1,-1.0,532,1,1.0            $ RELAY PP1.
MPC,40,1012,2,-1.0,1013,2,1.0,
.
.
.
```

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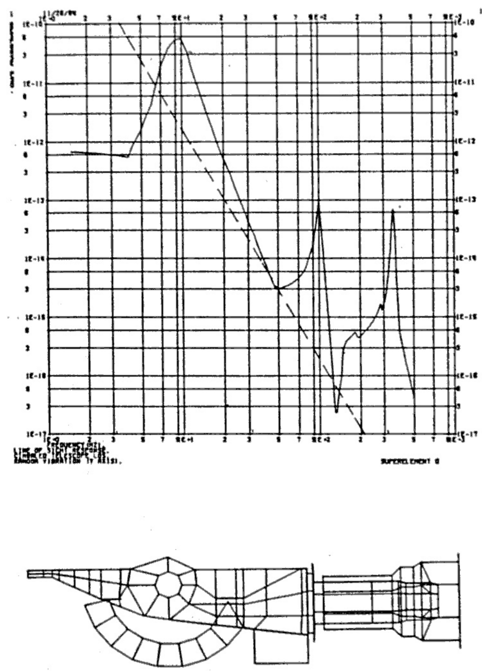
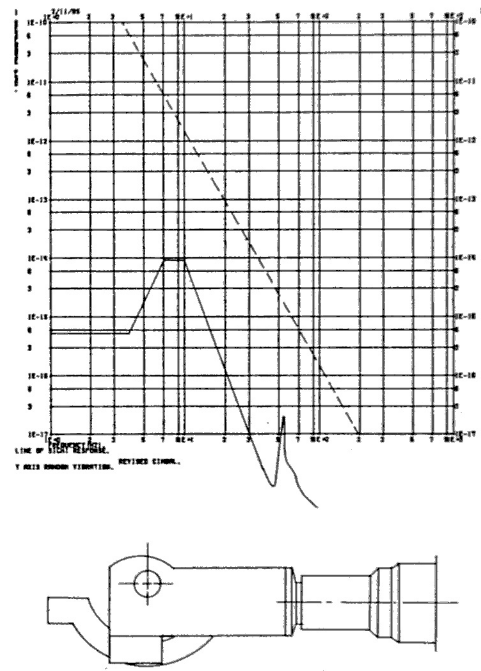
LOS Stability by Ebony

BASELINE DESIGN



ALTERNATE DESIGN



The controls engineers liked having the far-field LOS in the eigenvectors.

Unfortunate distribution of mass and stiffness.

Too late to make changes.

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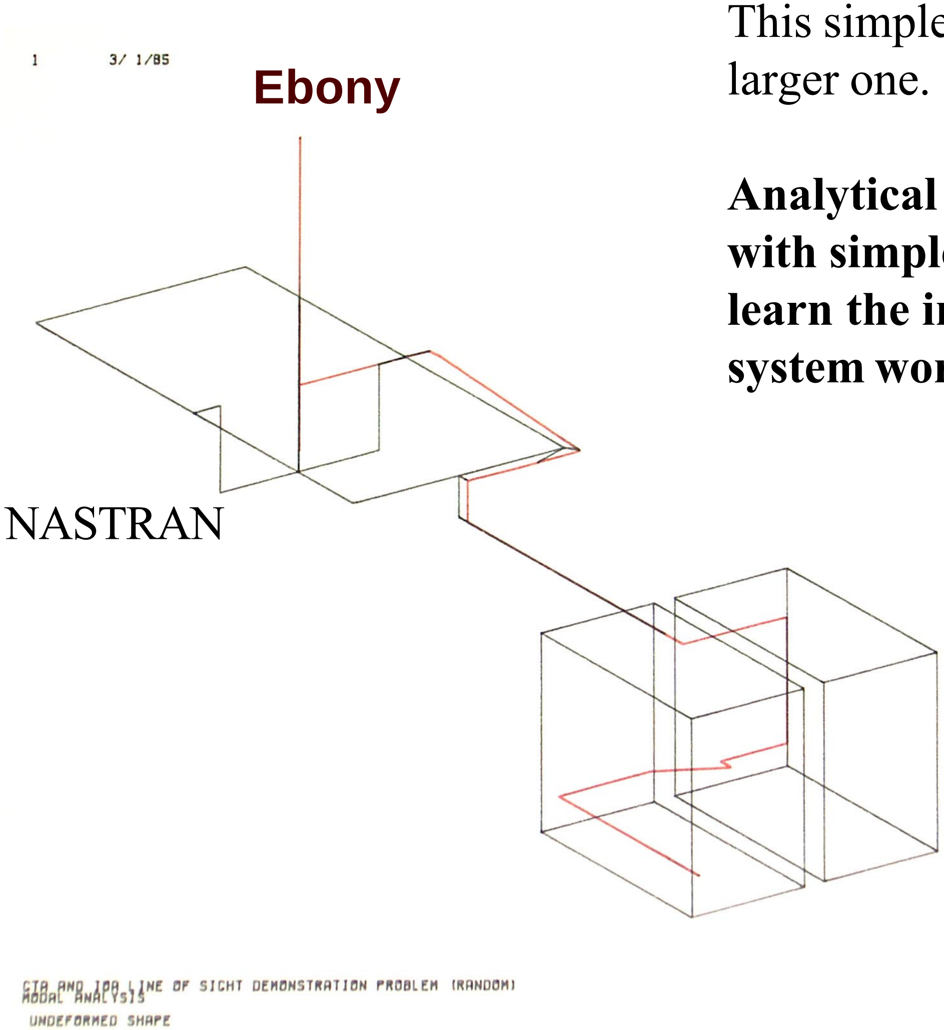
LOS Stability (Proposal)



This simple model could predict all the problems of the larger one.

Analytical tools need to be used early in a project with simple models with which the design team can learn the important characteristics that will make a system work.

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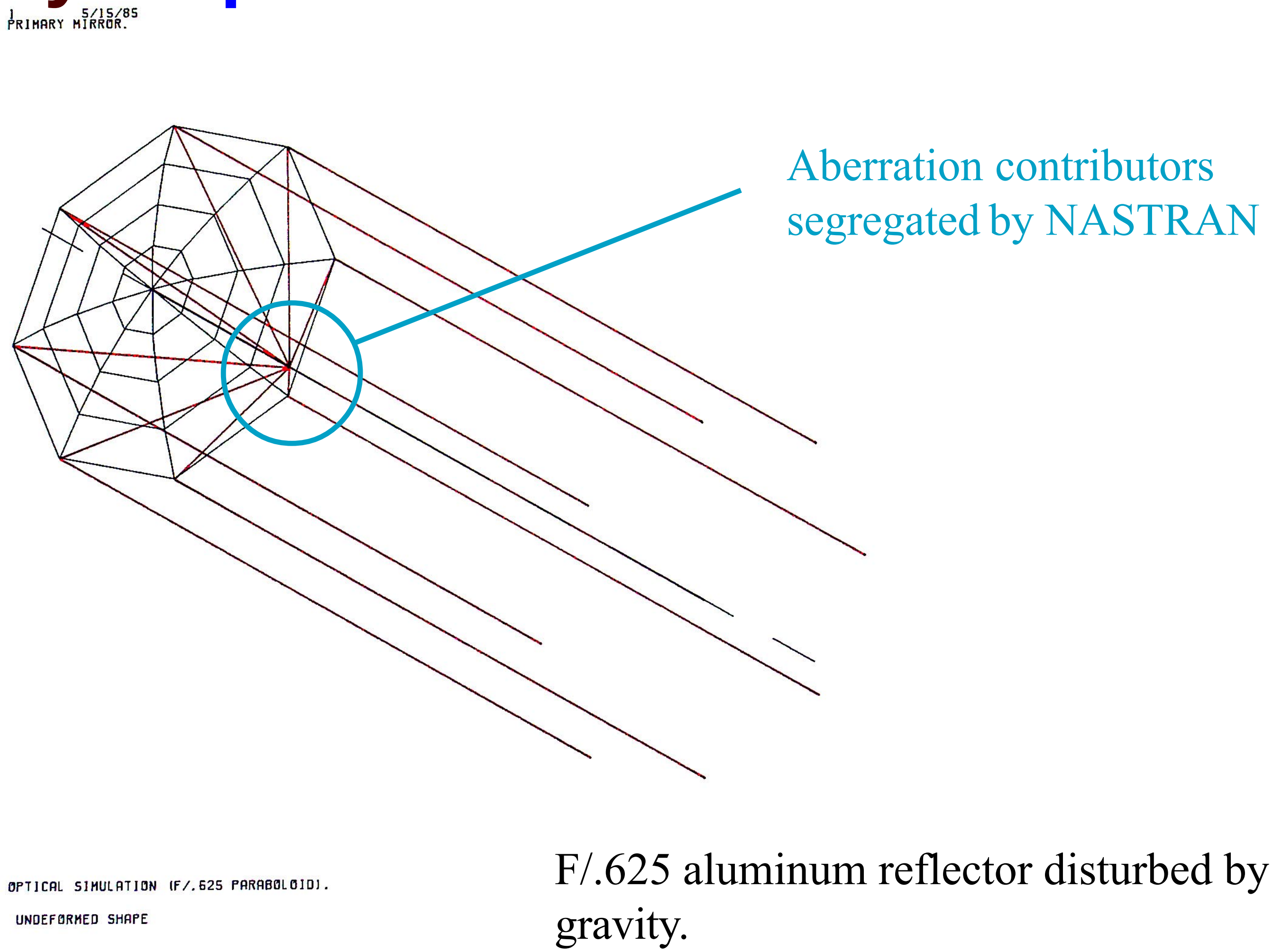
Ebony’s Optical Aberrations in NASTRAN



F/.625 aluminum reflector disturbed by heating and gravity.

Focused at infinity, rays modeled with rigid elements and reflection modeled with MPCs.

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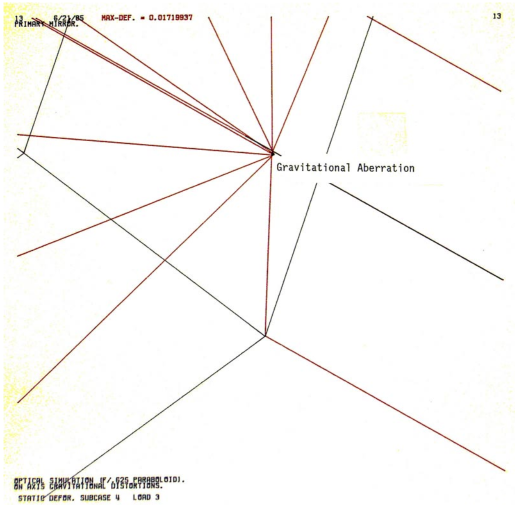
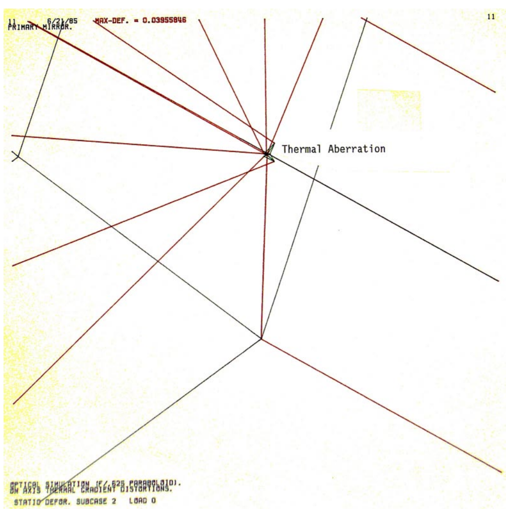
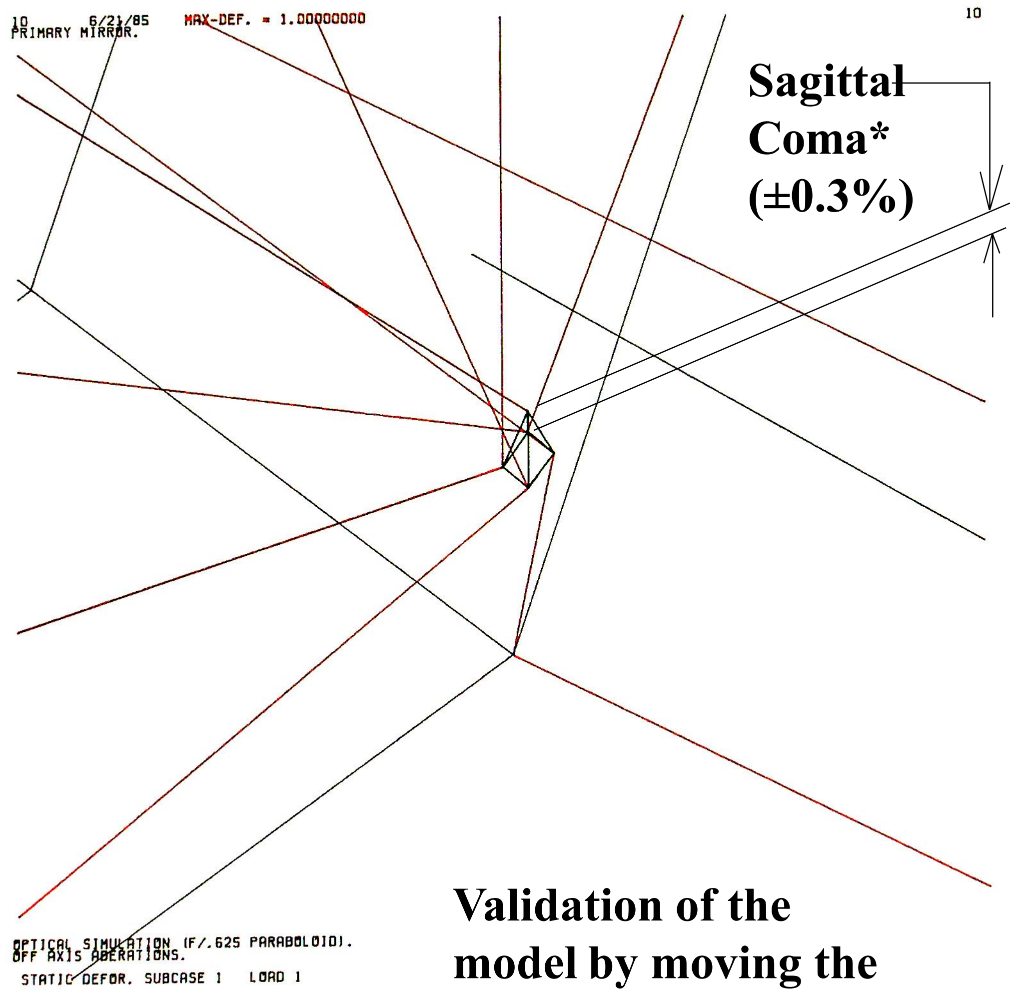
Ebony’s Third Order Coma in NASTRAN



Gravitational Sag of Mirror



Heating from Electronics



Validation of the model by moving the source off-axis.

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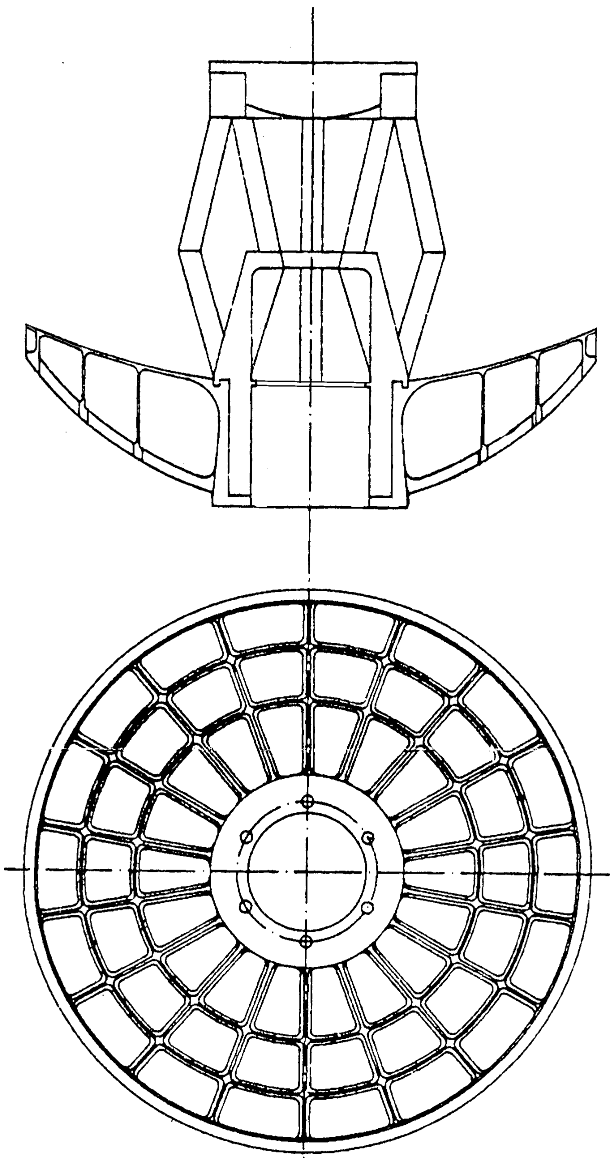
Optically Guided Ordnance in Ebony/NASTRAN



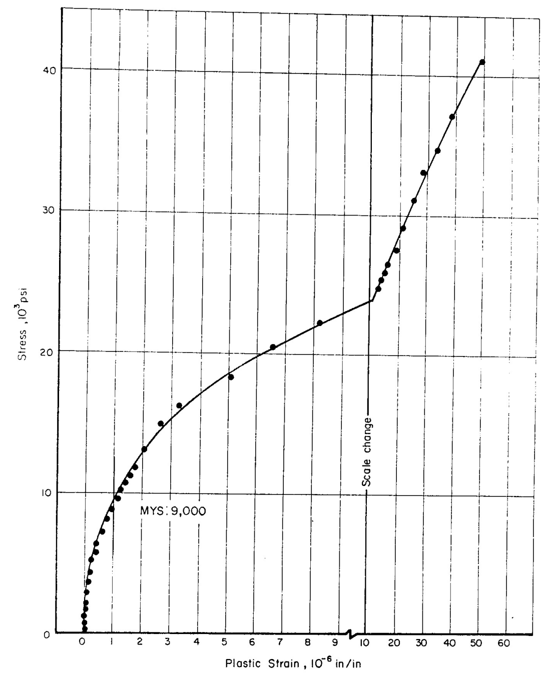


FIGURE A-41. MYS TEST ON I-400 Be, SPECIMEN No. 6, HEAT TREATED AT 1100 F FOR 1 HOUR

Beryllium has little-to-no strength without significant <u>permanent plastic deformation</u>.

Design had to account for plastic deformation.

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Optically Guided Ordnance Ebony Model

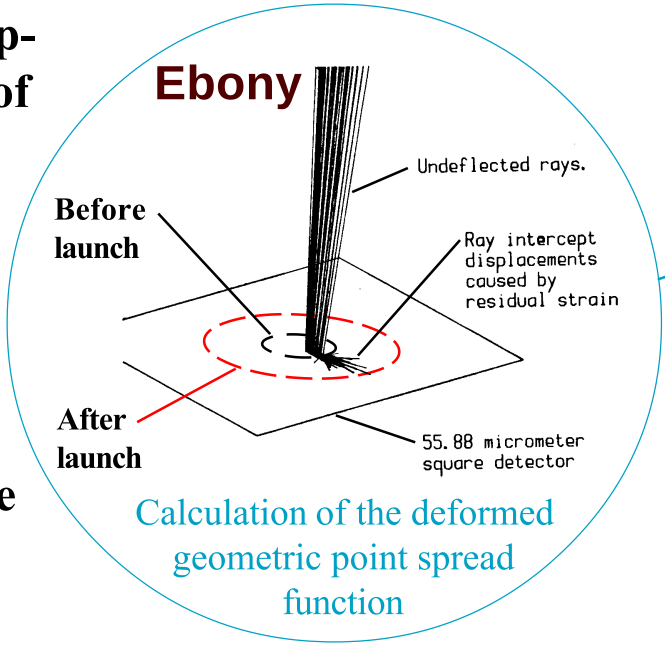
Displacements plotted as vectors.

Design sensitivity analysis applied to faceplate and webs of mirror.

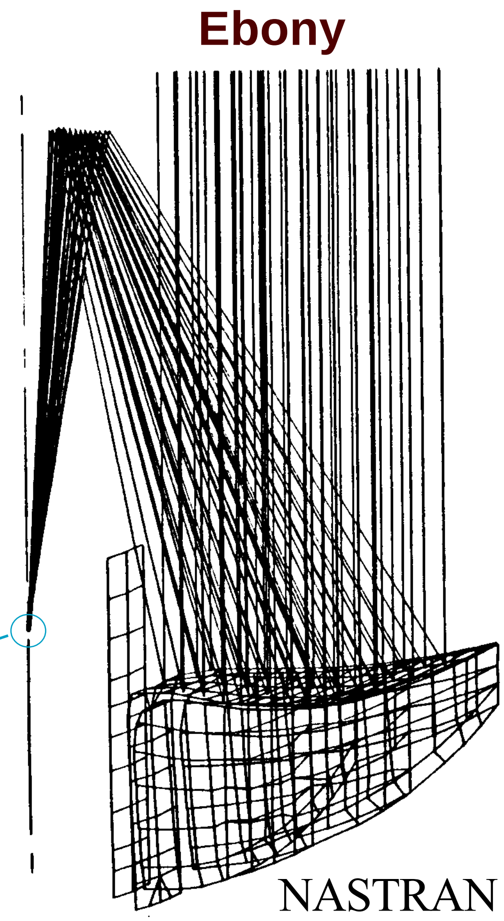
"Ensquared" energy after launch was calculated from vectors.

In acceptance test a pressure simulated the acceleration.

The deformed point spread function agreed with the NASTRAN analysis.



Calculation of the deformed geometric point spread function



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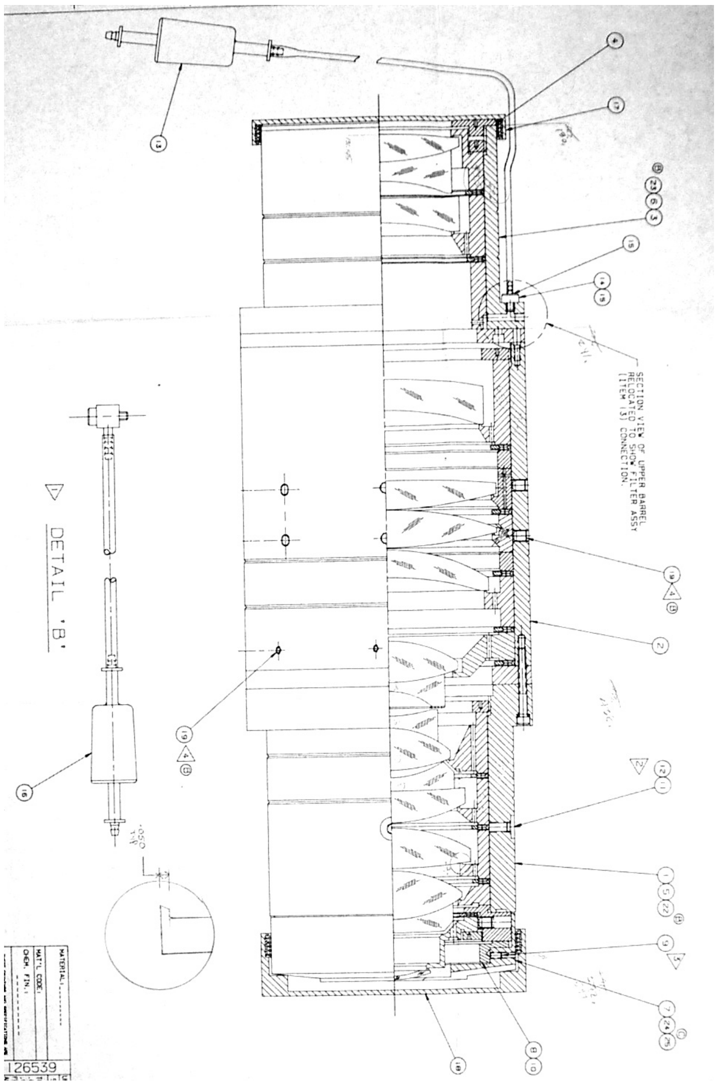
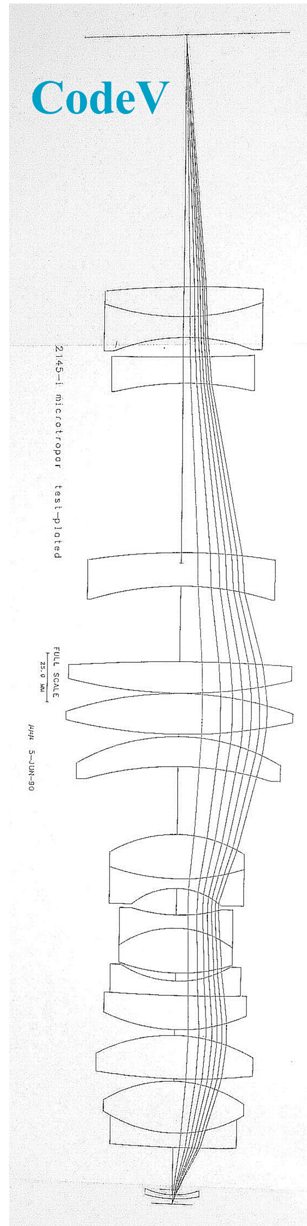
Ebony Stability of an Ultraviolet Lithographic Lens

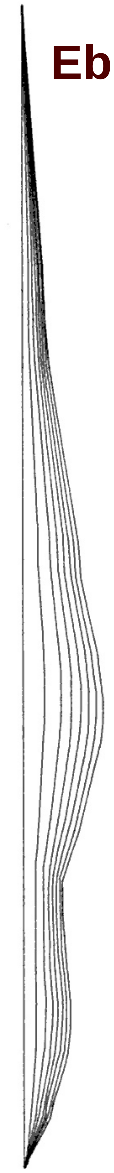
ProE



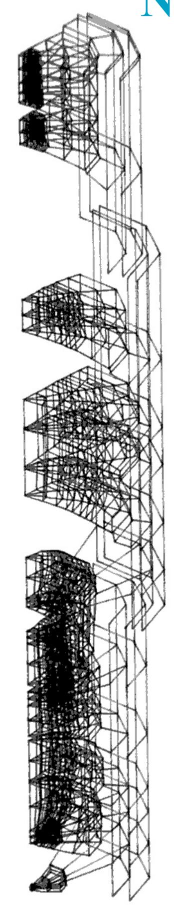
CodeV



Ebony



NASTRAN



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Optomechanical Solutions

Ebony Controls the Rays with MPCs

```
$   RAY INTERCEPT POSITION CHANGES.
$ 0 / 2  =  RAY / SURFACE
$
MPC,50,1013,1,-1.0,1008,1,1.,,
,,1008,3,8.742-8,1008,5,131.145,,
,,1015,3,-8.742-8,
MPC,50,1013,2,-1.0,1008,2,1.,,
,,1008,4,-131.145,1008,6,-1.146-5,,
MPC,50,1013,3,-1.0,1015,3,1.,,
MPC,50,1013,4,-1.0,1008,2,7.769-4,,
,,1008,4,.531001,1008,6,4.642-8,,
,,1015,2,-7.769-4,1015,4,.367105,,
MPC,50,1013,5,-1.0,1008,1,-7.769-4,,
,,1008,3,-6.79-11,1008,5,.531001,,
,,1015,1,7.769-4,1015,3,6.79-11,,
,,1015,5,.367105,3311,1,-5.531-8,,
,,2799,1,3.500-8,
SPC,50,1013, 6
$
```

```
$   RAY INTERCEPT POSITION CHANGES.
$ 0 / 3  =  RAY / SURFACE
$
MPC,50,1019,1,-1.0,1014,1,1.,,
,,1014,3,-8.742-8,1014,5,-15.5931,,
,,1021,3,8.742-8,
MPC,50,1019,2,-1.0,1014,2,1.,,
,,1014,4,15.5931,1014,6,-1.363-6,,
MPC,50,1019,3,-1.0,1021,3,1.,,
MPC,50,1019,4,-1.0,1014,2,-5.922-4,,
,,1014,4,1.06236,1014,6,-9.287-8,,
,,1021,2,5.922-4,1021,4,-7.160-2,,
MPC,50,1019,5,-1.0,1014,1,5.922-4,,
,,1014,3,-5.17-11,1014,5,1.06236,,
,,1021,1,-5.922-4,1021,3,5.17-11,,
,,1021,5,-7.160-2,3313,1,5.927-8,,
,,2801,1,-6.351-8,
SPC,50,1019, 6
$
```

```
$   RAY INTERCEPT POSITION CHANGES.
$ 0 / 4  =  RAY / SURFACE
MPC,50,...
.
.
.
```

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Ebony Lithographic Lens Model Checkout

Magnification at *Best Focus*:

	Ebony	Code V
X axis	0.19955	0.200
Y axis	0.19966	0.200

magnification = (image motion)/(object motion)
"Wiggle" the mask (the object)

Isothermal Sensitivity of *Best Focus*:

	Ebony	Code V
Glass only	0.7684×10^{-6} m/°K	0.77×10^{-6} m/°K

V_1 of each element held stationary

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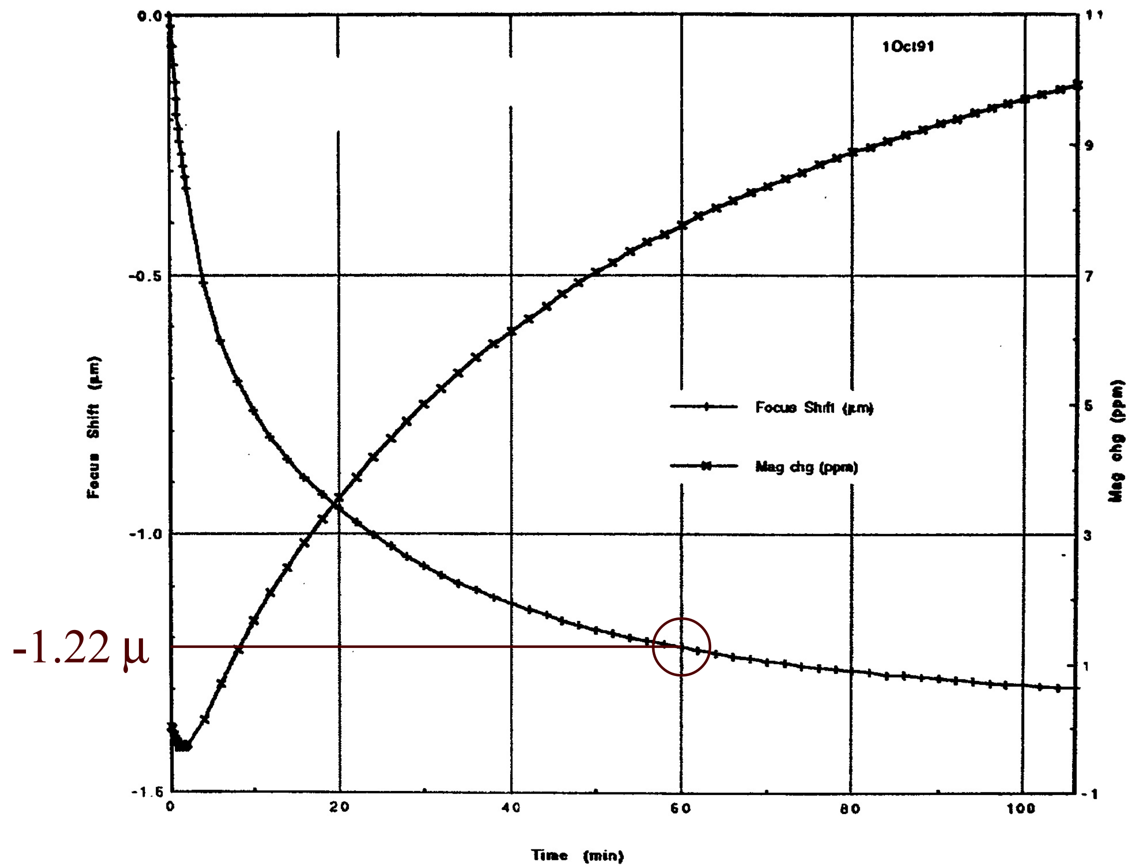
Ebony Thermal Transient

Ebony/
NASTRAN
Unified
Model



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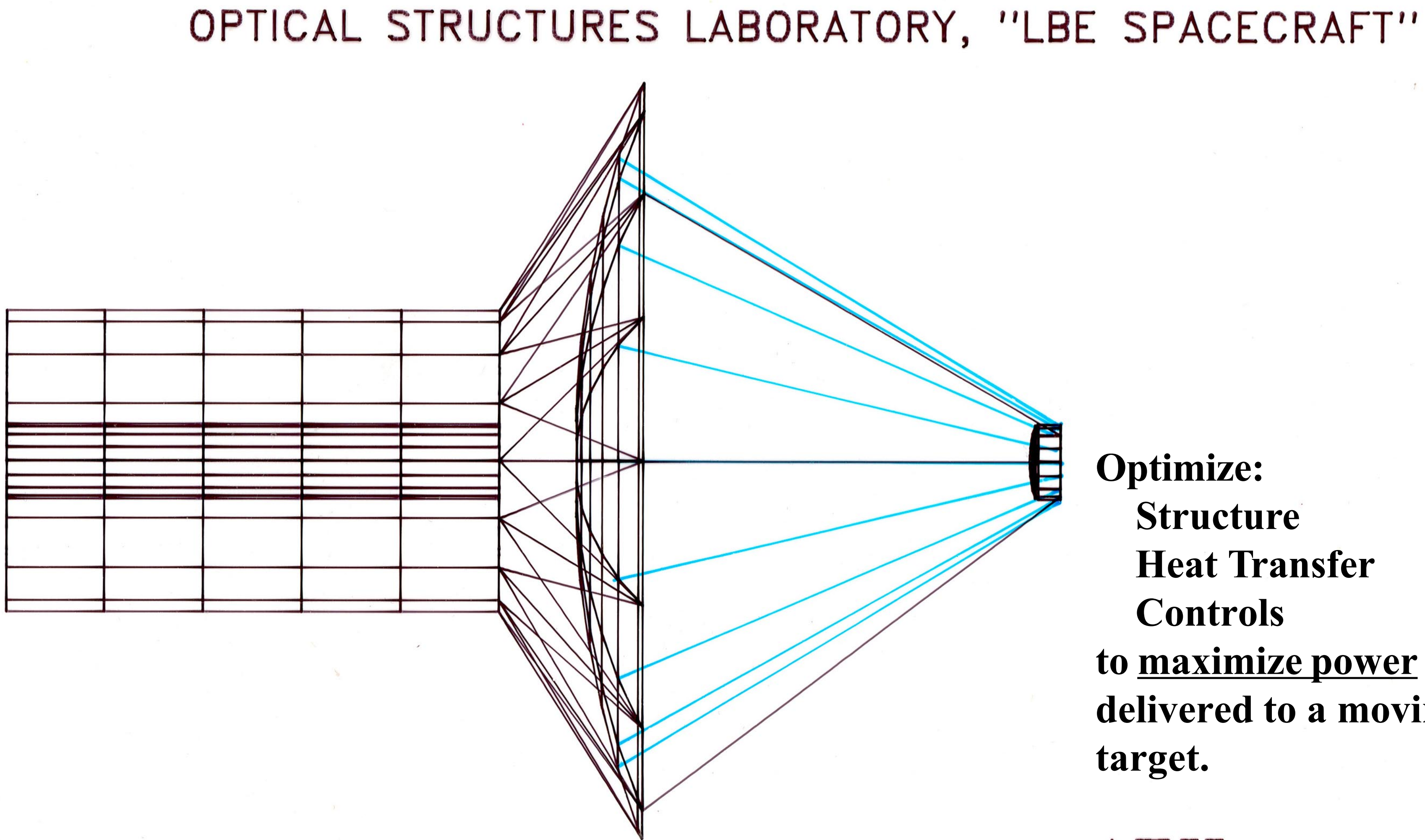
LBE Testbed Analysis in Ebony

3 5/21/87 3



Optimize:
Structure
Heat Transfer
Controls
to <u>maximize power</u> delivered to a moving target.

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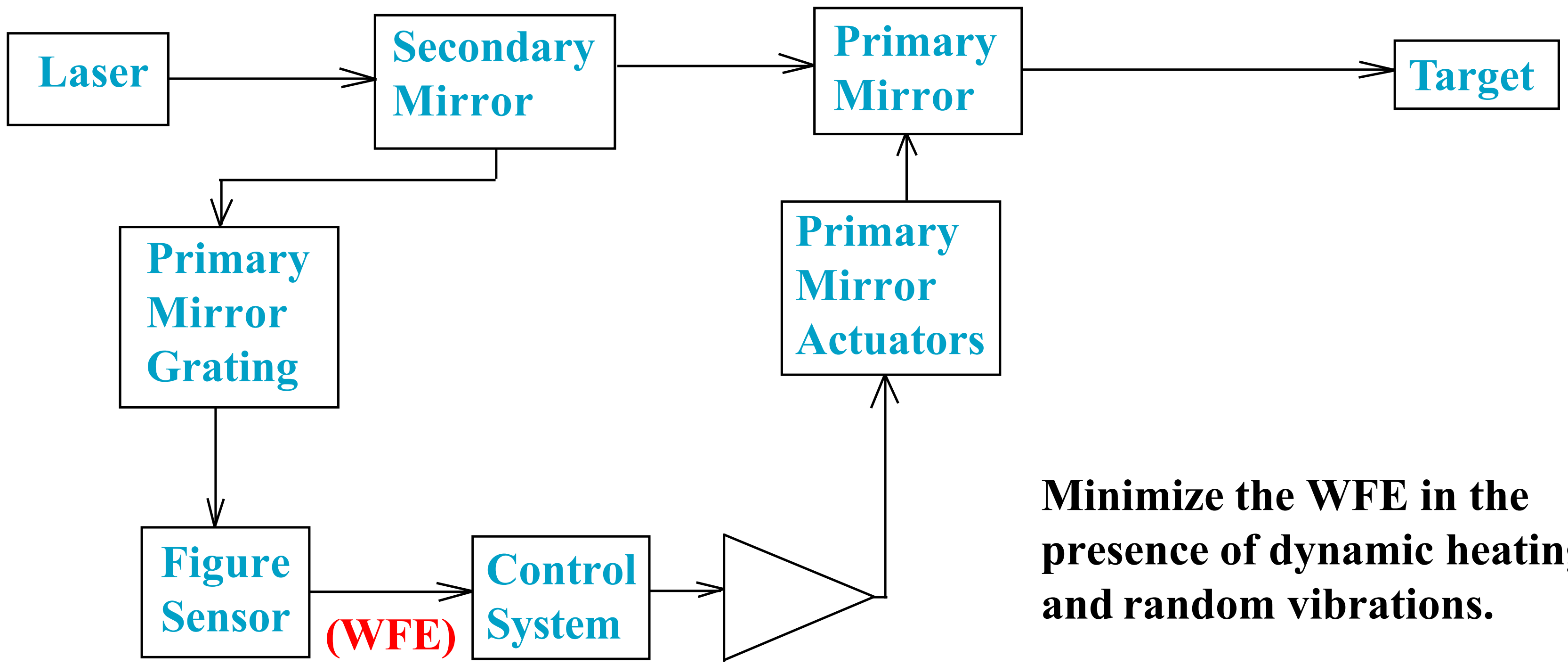
LBE Block Diagram



Minimize the WFE in the presence of dynamic heating and random vibrations.

{Stear the resulting beam onto moving a target.}

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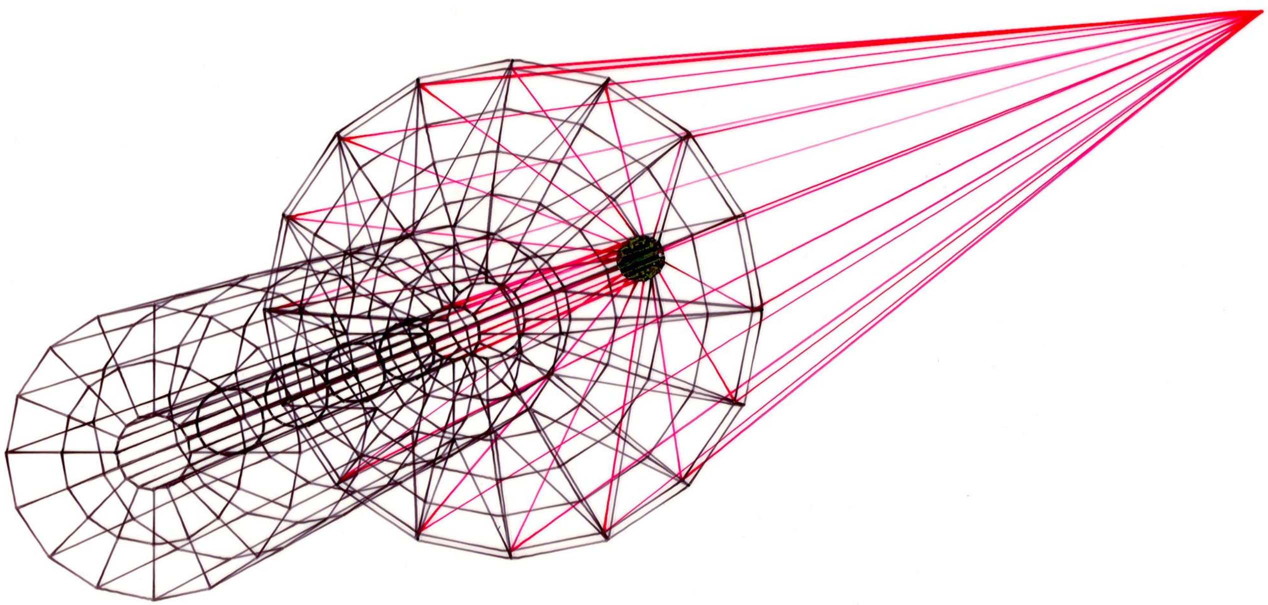
LBE All Fired-Up



Ebony/NASTRAN Model:

- **Optics**
- **Elasticity**
- **Heat Transfer**
- **Control Systems**

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BEAM EXPANDER DYNAMICS STUDY.

UNDEFORMED SHAPE

CT16

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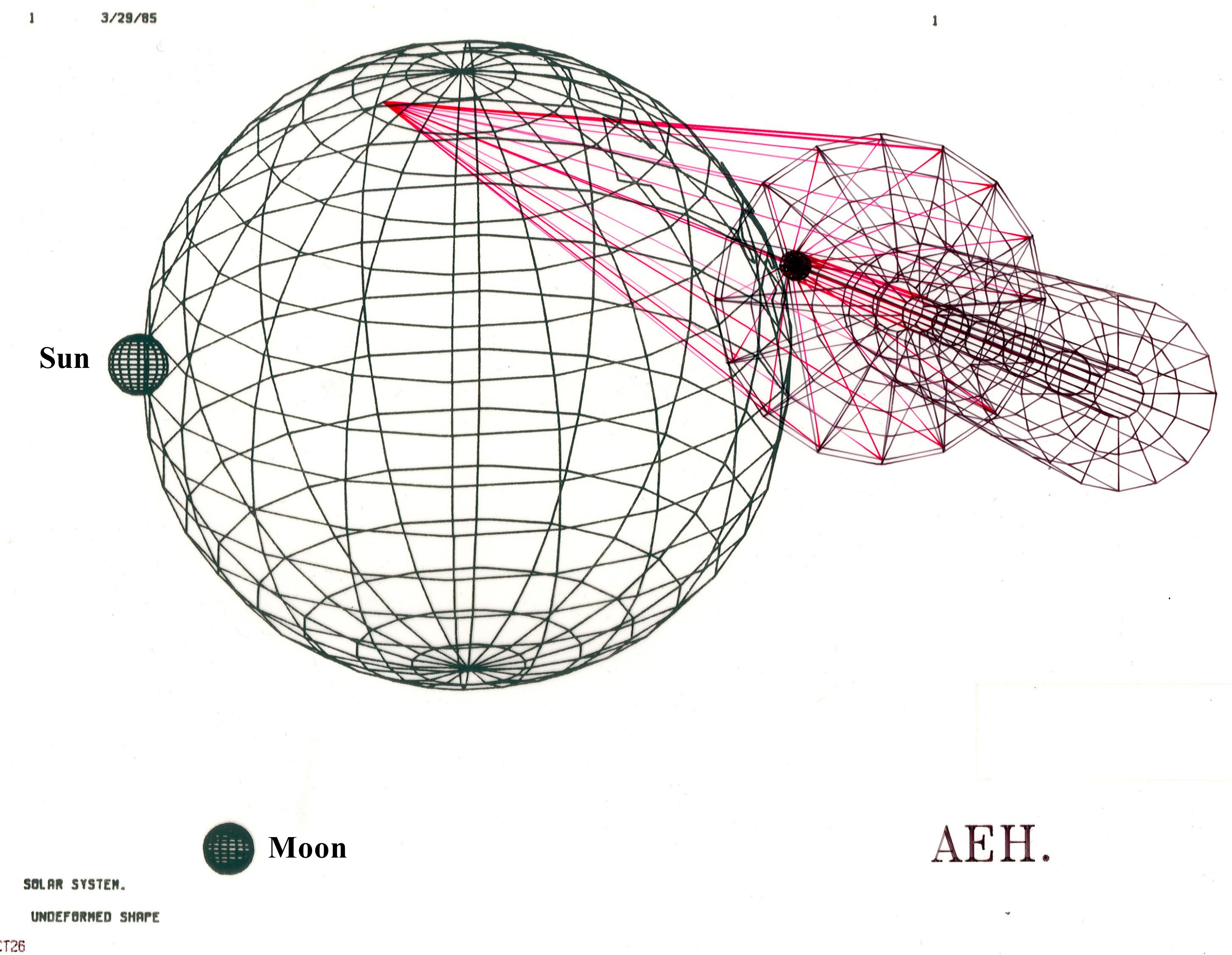
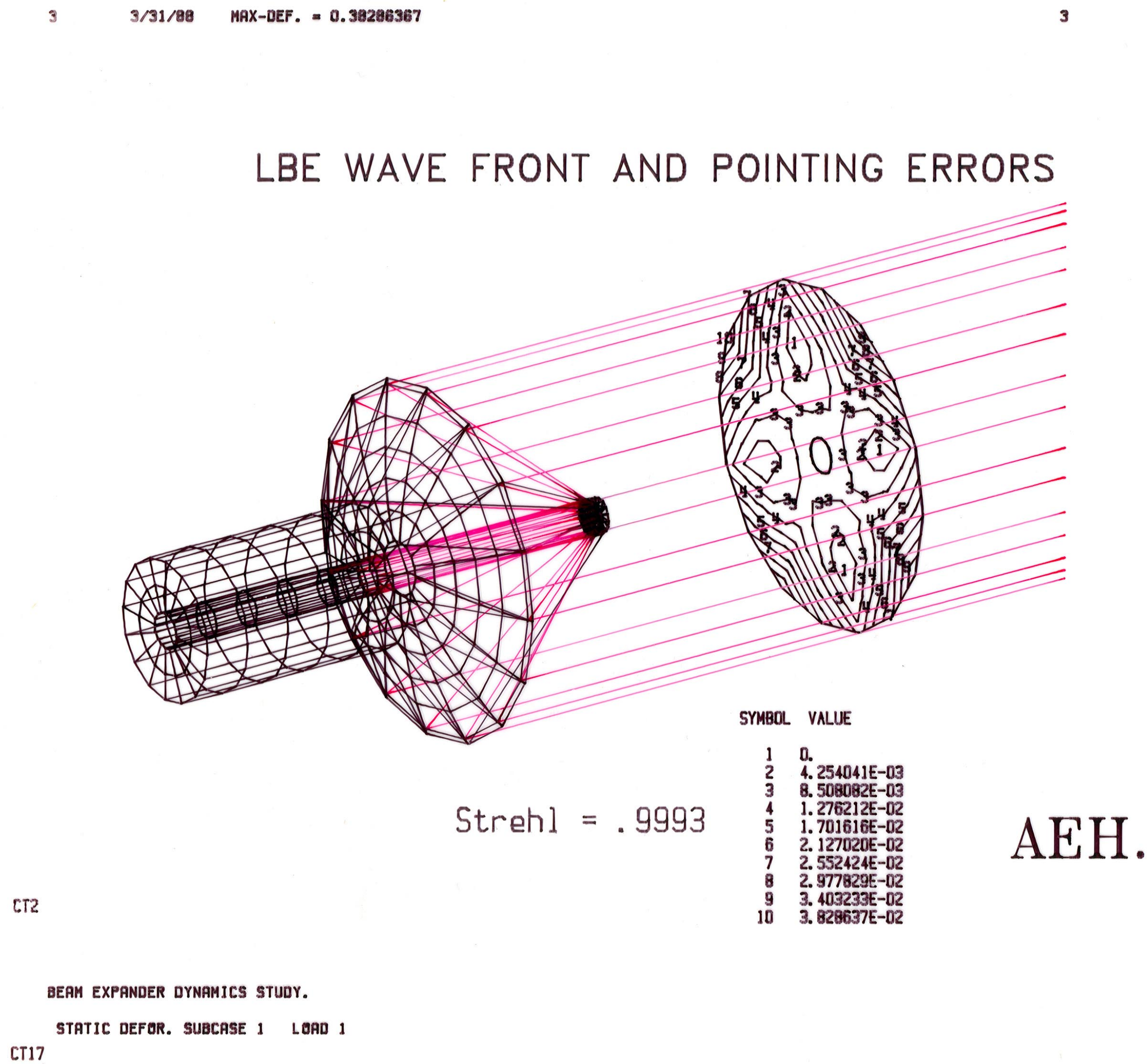
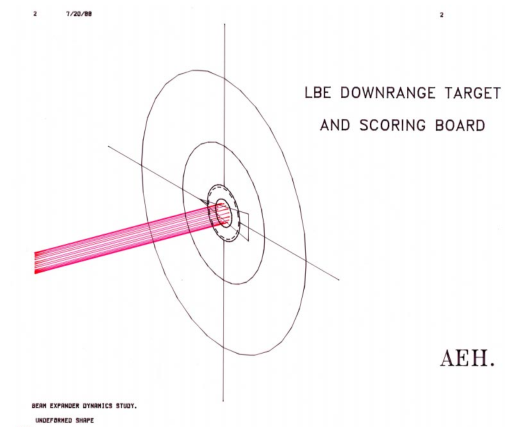
Test Range Populated with Constellation of LBEs



Ebony Calculates OPD, Strehl Definition and Drift on Target





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Ebony - for Mechanical Engineers...

...*flows* the requirements down from the optical physics to the engineering implementation.

...*exploits* the "small displacement" domains in optics, structural mechanics, heat transfer and servo-controls.

...*formulates* mechanical challenges in mechanical design tools: *Unifies* the disciplines.

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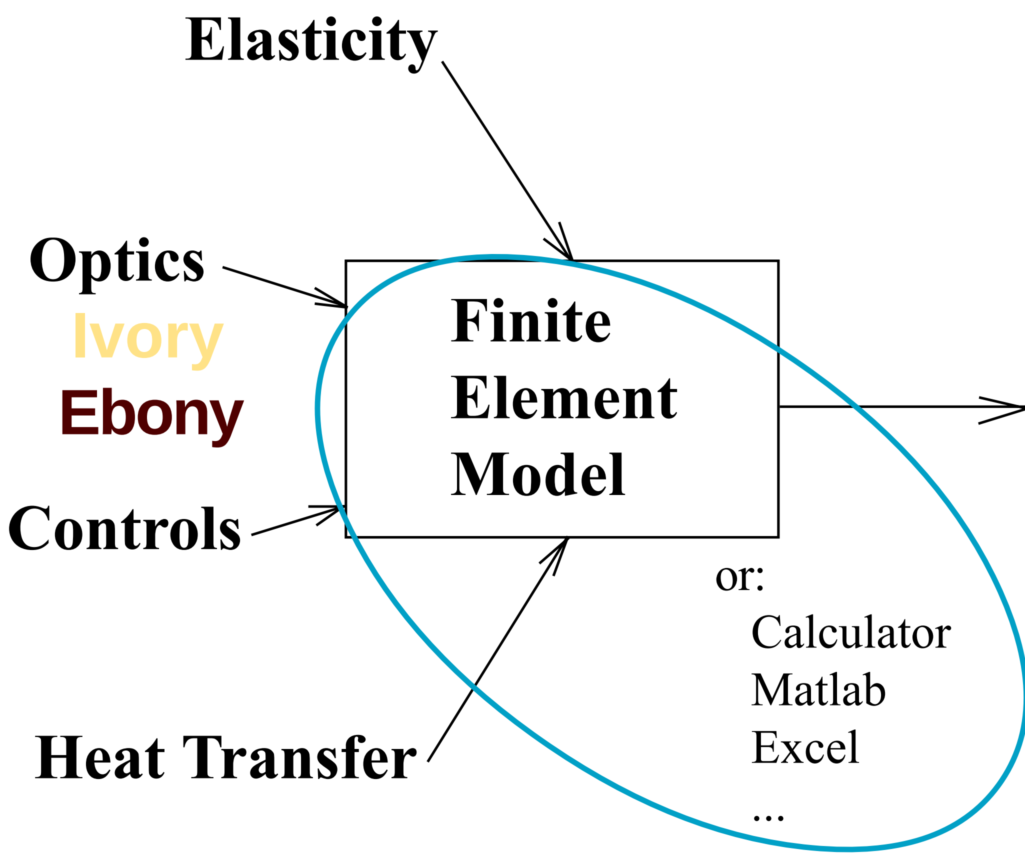
Unified Modeling: Solutions and Opportunities



Mechanical Design Tools

FEM output data:

OPD
WFE map at exit pupil
Zernike polynomials
Plane of best focus
Image position, orientation and size
Point spread function
LOS errors

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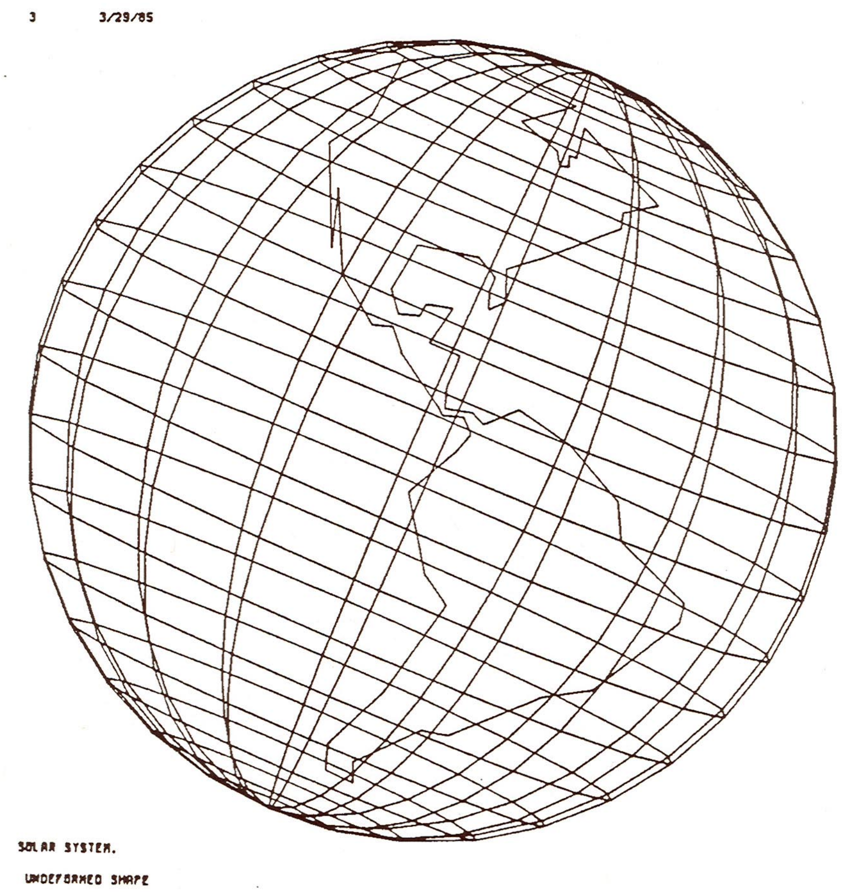
Thank You



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