The *Ivory* Optomechanical Modeling Tools

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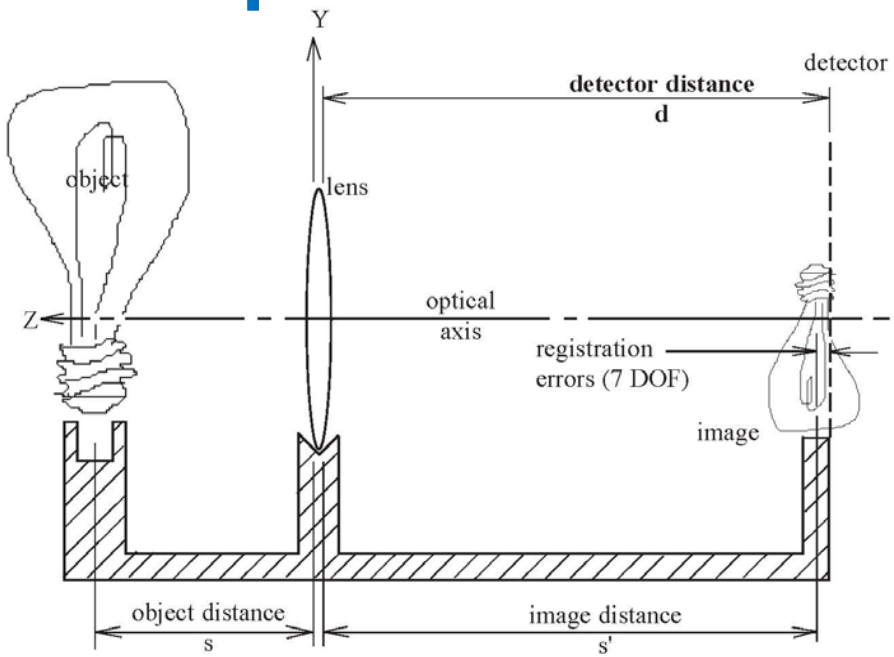
An Optomechanical System



Ivory determines changes in the position, orientation and size of the image on the detector.

There are seven image registration variables on the detector:

- **2 decenters, Tx_i and Ty_i**
- **1 defocus, Tz_i**
- **2 tips, Rx_i and Ry_i**
- **1 rotation, Rz_i**
- **1 change in size, $\Delta M/M_i$**

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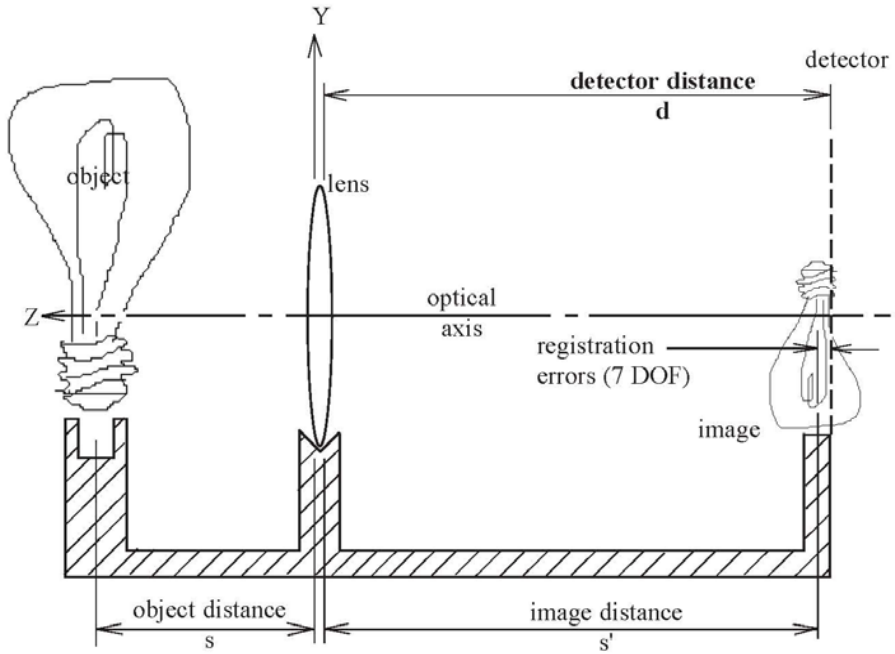
The Optomechanical Constraint Equations



The Optomechanical Constraint Equations determine the magnitude of these seven registration variables:

$$Tx_i=Tx_1(\partial Tx_i/\partial Tx_1)+Ty_1(\partial Tx_i/\partial Ty_1)+Tz_1(\partial Tx_i/\partial Tz_1)+Rx_1(\partial Tx_i/\partial Rx_1)+\ldots$$
$$Ty_i=Tx_1(\partial Ty_i/\partial Tx_1)+Ty_1(\partial Ty_i/\partial Ty_1)+Tz_1(\partial Ty_i/\partial Tz_1)+Rx_1(\partial Ty_i/\partial Rx_1)+\ldots$$
$$Tz_i=Tx_1(\partial Tz_i/\partial Tx_1)+Ty_1(\partial Tz_i/\partial Ty_1)+Tz_1(\partial Tz_i/\partial Tz_1)+Rx_1(\partial Tz_i/\partial Rx_1)+\ldots$$
$$Rx_i=Tx_1(\partial Rx_i/\partial Tx_1)+Ty_1(\partial Rx_i/\partial Ty_1)+Tz_1(\partial Rx_i/\partial Tz_1)+Rx_1(\partial Rx_i/\partial Rx_1)+\ldots$$
$$Ry_i=Tx_1(\partial Ry_i/\partial Tx_1)+Ty_1(\partial Ry_i/\partial Ty_1)+Tz_1(\partial Ry_i/\partial Tz_1)+TRx_1(\partial Ry_i/\partial Rx_1)+\ldots$$
$$Rz_i=Tx_1(\partial Rz_i/\partial Tx_1)+Ty_1(\partial Rz_i/\partial Ty_1)+Tz_1(\partial Rz_i/\partial Tz_1)+Rx_1(\partial Rz_i/\partial Rx_1)+\ldots$$
$$\Delta M_i/M_i=Tx_1(\partial M/M/\partial Tx_1)+Ty_1(\partial M/M/\partial Ty_1)+Tz_1(\partial M/M/\partial Tz_1)+\ldots$$

The partial derivatives are called “influence coefficients” (ICs).

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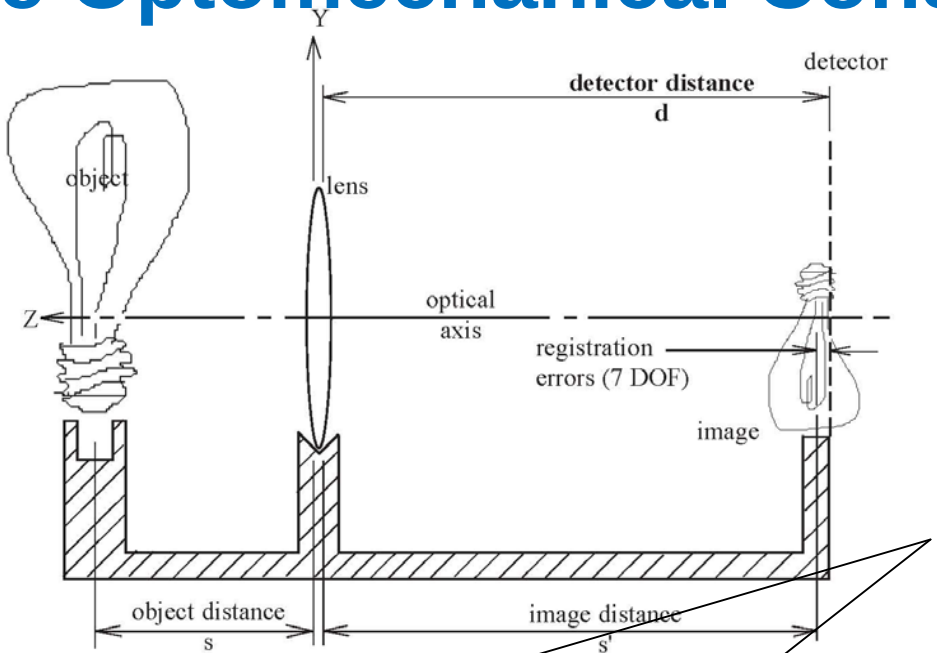
The Optomechanical Constraint Equations



The ICs for a single lens are calculated from its magnification, M, its focal length, f, and distance between its principal points, p (the principal thickness).

The ICs are assigned to the first principal point of each optical element.

$$
\begin{bmatrix} M & & & & & \\ & M & & & & \\ & & M^2 & & & \\ & & & M & & \\ & & & & M & \\ & & & & & 1.0 \\ & & & & & M/f \end{bmatrix}
+
\begin{bmatrix} 1-M & & -p & & & \\ & 1-M & & p & & \\ & & 1-M^2 & & -(M-1)^2 & \\ & & & 1-M & & \\ & & & & 1-M & \\ & & & & 0.0 & \\ & & & & -M/f & (1-M)/f \end{bmatrix}
+
\begin{bmatrix} -1 & & & & & \\ & -1 & & & & \\ & & -1 & & & \\ & & & -1 & & \\ & & & & -1 & \\ & & & & & -1 \\ & & & & & \end{bmatrix}
=
\begin{bmatrix} Tx \\ Ty \\ Tz \\ Rx \\ Ry \\ Rz \\ \Delta M/M \end{bmatrix}
$$

Tx Ty Tz Rx Ry Rz — **Object Displacements**

Tx Ty Rz Rx Ry Rz Δf — **Lens Displacements**

Tx Ty Tz Rx Ry Rz — **Detector Diosplacements**

Registration Variables

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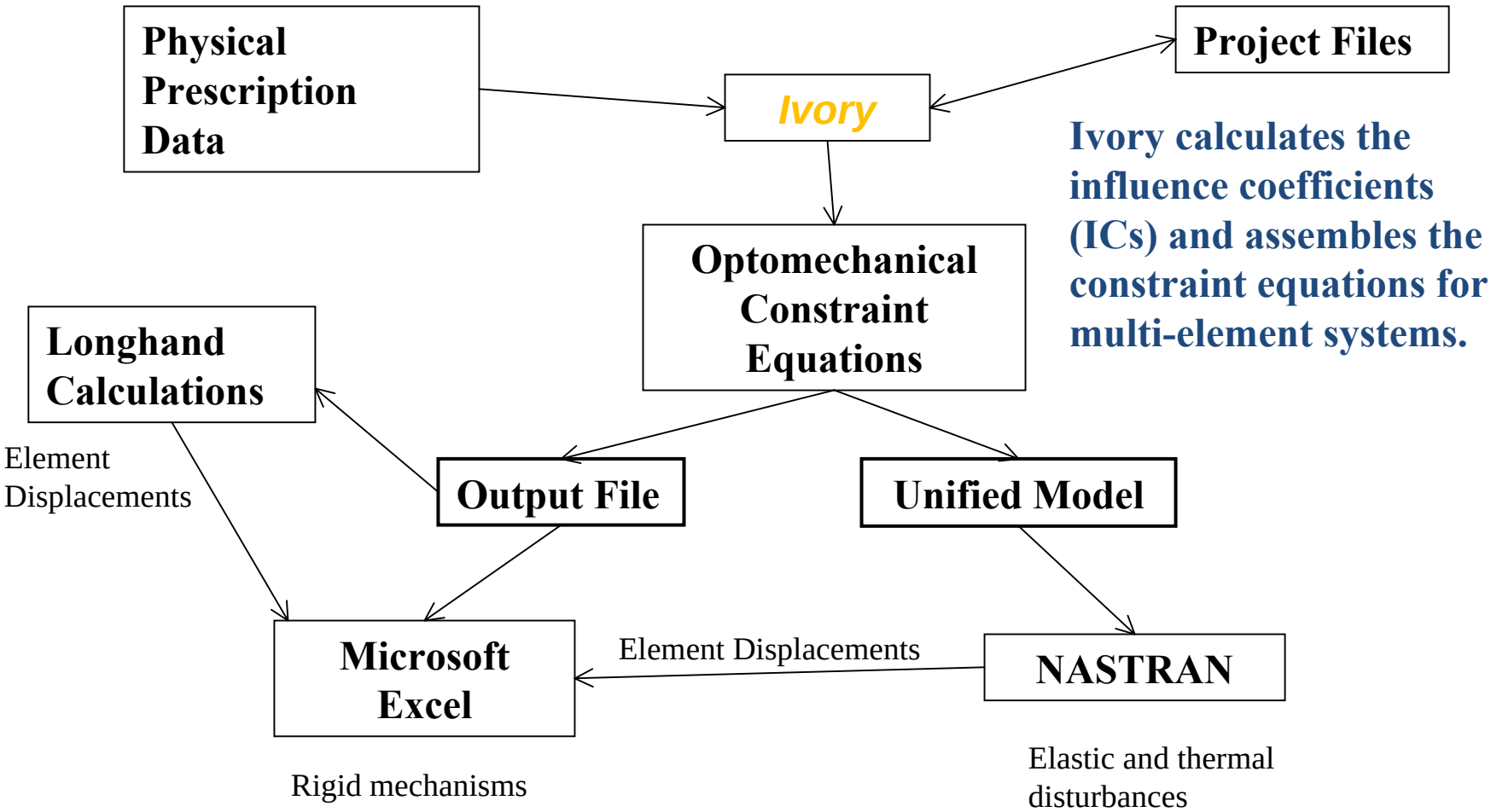
Ivory Optomechanical Modeling Tools



Ivory calculates the influence coefficients (ICs) and assembles the constraint equations for multi-element systems.

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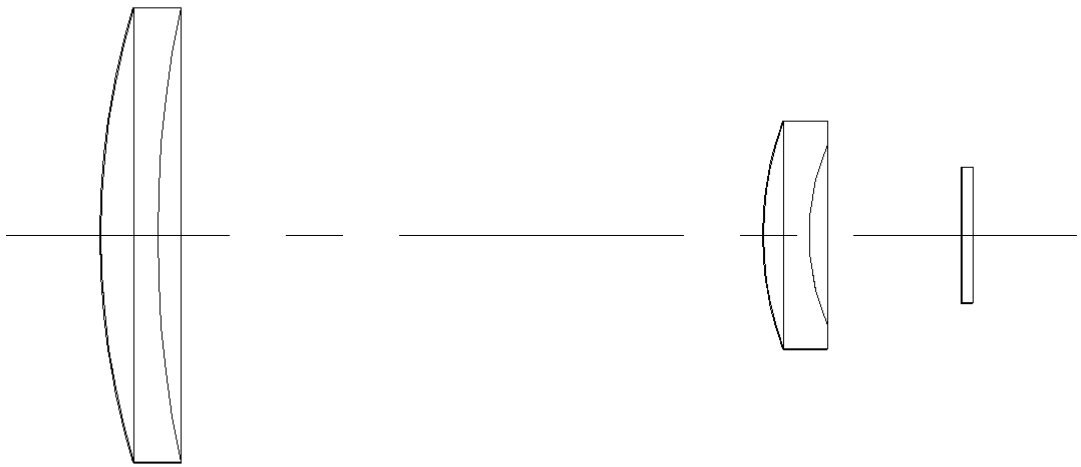
Example, an IR Imager



Surf	Elem	Radius	Index	Thickness
1	obj	inf	AIR	-inf
2	1	3.5	ge	-.25
3	1	5.	AIR	-2.67
4	2	1.5	ge	-.2
5	2	1	AIR	-.674
6	det	inf	AIR	0.0

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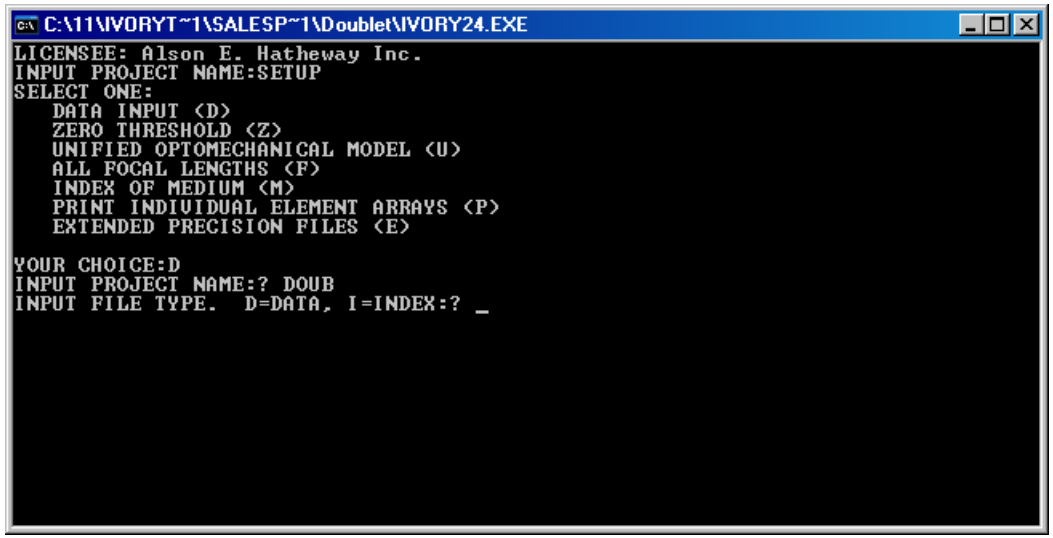
The *Ivory* Input Files

Open *Ivory*. Enter SETUP. It helps to prepare the prescription data in two "project" files.



Ivory operates from the command prompt window.

It helps format the "project" files from the optical prescription.

The first, "doub.dat," contains the geometry data.

Surf	Elem	Radius	Index	Thickness	Type	f1	f2	f3	f4
1	obj	inf	AIR	inf	obj	1.0000000	0.0000000	0.0000000	0.0000000
2	1	-3.5	ge	.25	LENS	0.0000000	0.0000000	0.0000000	0.0000000
3	1	-5.	AIR	2.67	LENS	0.0000000	0.0000000	0.0000000	0.0000000
4	2	-1.5	ge	.2	LENS	0.0000000	0.0000000	0.0000000	0.0000000
5	2	-1	AIR	.674	LENS	0.0000000	0.0000000	0.0000000	0.0000000
6	det	inf	AIR	0.0	det				

The second, "doub.ind," contains the index of refraction data.

MATERIAL	INDEX
AIR	1.0
ge	4.00024

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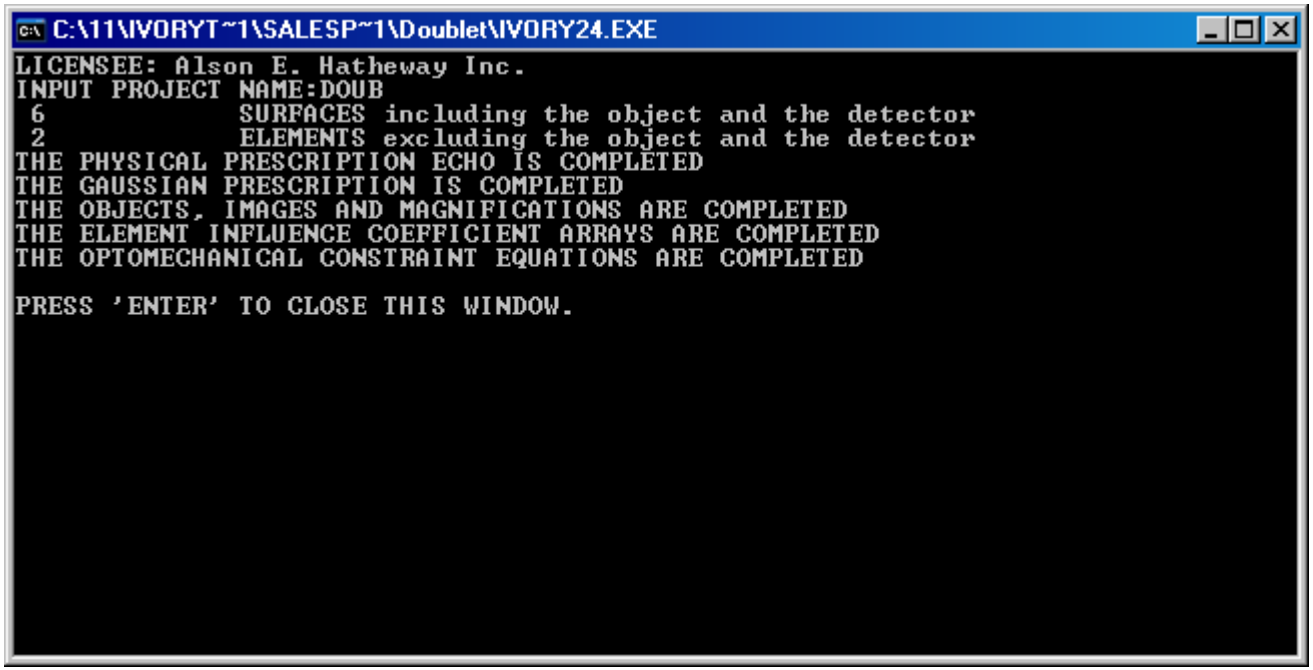
Running *Ivory*

Open *Ivory*. At the prompt for a “project” name enter “doub.”



Ivory runs the project files to produce the Optomechanical Constraint Equations in its output file.

Ivory has calculated the optomechanical constraint equations and written them to the “doub.out” file.

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The Top of *Ivory's* "doub.out" File

```
Output from -
                  IVORY Optomechanical Modeling Tools
                                                    Version 2.4
                                                                 Copyright 2010, Alson E. Hatheway Inc.

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

PROJECT NAME: 'doub'        TIME AND DATE: 17:42:35 02-19-2010

PHYSICAL PRESCRIPTION ECHO

 Surf        Elem        Radius       Index        Thickness    Type         f1          f2          f3          f4
  1          obj         inf          1.0          inf          obj           1           0           0           0
  2          1           -3.5          4.00024      .25         LENS          0           0           0           0
  3          1           -5           1.0          2.67        LENS          0           0           0           0
  4          2           -1.5          4.00024      .2          LENS          0           0           0           0
  5          2           -1           1.0          .674        LENS          0           0           0           0
  6          det         inf          1.0          0           det

INDEXES OF REFRACTION ARE RELATIVE TO THE VALUE OF  1.000292


GAUSSIAN PRESCRIPTION

 ELE         F           H1          H2          P           P/AIR       PHI         THETA       TYPE
 obj         0           0           0           0           inf         0           0            obj
 1            3.456506    .1296216    .1851736    .1944479    3.069449    0           0           LENS
 2           -1.42847    -.2142747   -.1428498    .1285751    .5311502    0           0           LENS
 det         0           0           0           0           0           0           0            det

 SYSTEM       4.7411690902  10.317288630  4.0674066621  9.3698825682  4.7414066621

OBJECTS, IMAGES AND MAGNIFICATIONS

 ELE          F              S          S'          M          PHI        THETA        TYPE          e/Tzo
 obj         inf             0          0         +1.0000      0          0            obj
 1            3.456506      inf        -3.4565     0           0          0           LENS          +0.00D+00
 2           -1.42847        -0.3871   -0.5309    +1.3717      0          0           LENS          -9.60D-01
 det         inf            +2.38D-04  +2.38D-04  +1.0         0          0            det
```

effective focal length

Ivory's optical quality checks in the output file

residual focus error

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The Bottom of *Ivory's* "doub.out" File

OPTOMECHANICAL CONSTRAINT EQUATIONS (ABSOLUTE VALUES SMALLER THAN 0 ARE PRINTED AS 0.0)

	REGISTRATION VARIABLES								
	TX	TY	TZ	RX	RY	RZ	DM/M	Df,p	LDesVar
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	+1.00000	0.0	0.0	
Df,p	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
SYSTEM-OBJECT									
Tx	+1.37167	0.0	0.0	0.0	0.0	0.0	0.0	-1.53625	Dt
Ty	0.0	+1.37167	0.0	0.0	0.0	0.0	0.0	-3.03587	DR1
Tz	0.0	0.0	+1.88146	0.0	0.0	0.0	-0.96023	+1.35699	DR2
Rx	0.0	+0.26672	0.0	+1.37167	0.0	0.0	0.0	-1.18408	Dn
Ry	-0.26672	0.0	0.0	0.0	+1.37167	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	-1.88146	0.0	0.0	0.0	+1.24954	0.0	
ELEMENT-1									
Tx	-0.37167	0.0	0.0	0.0	0.0	0.0	0.0	-3.06110	Dt
Ty	0.0	-0.37167	0.0	0.0	0.0	0.0	0.0	-3.12907	DR1
Tz	0.0	0.0	-0.88146	0.0	0.0	0.0	+0.96023	+5.50985	DR2
Rx	0.0	+0.12858	0.0	-0.37167	0.0	0.0	0.0	+0.42511	Dn
Ry	-0.12858	0.0	0.0	0.0	-0.37167	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	-0.13813	0.0	0.0	0.0	+0.26018	0.0	
ELEMENT-2									
Tx	-1.00000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Dt
Ty	0.0	-1.00000	0.0	0.0	0.0	0.0	0.0	0.0	DR1
Tz	0.0	0.0	-1.00000	0.0	0.0	0.0	0.0	0.0	DR2
Rx	0.0	0.0	0.0	-1.00000	0.0	0.0	0.0	0.0	Dn
Ry	0.0	0.0	0.0	0.0	-1.00000	0.0	0.0	0.0	
Rz	0.0	0.0	0.0	0.0	0.0	-1.00000	0.0	0.0	
Df,p	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
DETECTOR									

Thank you for using IVORY(tm) to prepare the Optomechanical Constraint Equations for 'doub'.

The Optomechanical Constraint Equations for the seven registration variables.

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Position Tolerances in Excel…

OPTOMECH CONSTRAINT EQUATION (ABSOLUTE VALUES SMALLER THAN 0 ARE PRINTED AS 0.0)

	REGISTRAT VARIABLES									Assumed Position Tol:	IMAGE MOTION CONTRIBUTIONS						
	TX	TY	TZ	RX	RY	RZ	DM/M	Df,p	LDesVar								
Tx	0	0	0	0	0	0	0	0	Dt		0	0	0	0	0	0	0
Ty	0	0	0	0	0	0	0	0	DR1		0	0	0	0	0	0	0
Tz	0	0	0	0	0	0	0	0	DR2		0	0	0	0	0	0	0
Rx	0	0	0	0	0	0	0	0	Dn		0	0	0	0	0	0	0
Ry	0	0	0	0	0	0	0	0			0	0	0	0	0	0	0
Rz	0	0	0	0	0	1	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
SYSTEM-OBJECT											0	0	0	0	0	0	0
											0	0	0	0	0	0	0
Tx	1.3717	0	0	0	0	0	0	-1.5363	Dt	3.00E-03	0.004115	0	0	0	0	0	0
Ty	0	1.3717	0	0	0	0	0	-3.0359	DR1	3.00E-03	0	0.004115	0	0	0	0	0
Tz	0	0	1.8815	0	0	0	-0.9602	1.357	DR2	3.00E-03	0	0	0.005645	0	0	0	0.002881
Rx	0	0.2667	0	1.3717	0	0	0	-1.1841	Dn	1.75E-03	0	0.000467	0	0.002400475	0	0	0
Ry	-0.2667	0	0	0	1.3717	0	0	0		1.75E-03	0.000467	0	0	0	0.002400475	0	0
Rz	0	0	0	0	0	0	0	0		1.75E-03	0	0	0	0	0	0	0
Df,p	0	0	-1.8815	0	0	0	1.2495	0			0	0	0	0	0	0	0
ELEMENT-1											0	0	0	0	0	0	0
											0	0	0	0	0	0	0
Tx	-0.3717	0	0	0	0	0	0	-3.0611	Dt	3.00E-03	0.001115	0	0	0	0	0	0
Ty	0	-0.3717	0	0	0	0	0	-3.1291	DR1	3.00E-03	0	0.001115	0	0	0	0	0
Tz	0	0	-0.8815	0	0	0	0.9602	5.5099	DR2	3.00E-03	0	0	0.002645	0	0	0	0.002881
Rx	0	0.1286	0	-0.3717	0	0	0	0.4251	Dn	1.75E-03	0	0.000225	0	0.000650475	0	0	0
Ry	-0.1286	0	0	0	-0.3717	0	0	0		1.75E-03	0.000225	0	0	0	0.000650475	0	0
Rz	0	0	0	0	0	0	0	0		1.75E-03	0	0	0	0	0	0	0
Df,p	0	0	-0.1381	0	0	0	0.2602	0			0	0	0	0	0	0	0
ELEMENT-2											0	0	0	0	0	0	0
											0	0	0	0	0	0	0
Tx	-1	0	0	0	0	0	0	0	Dt	3.00E-03	0.003	0	0	0	0	0	0
Ty	0	-1	0	0	0	0	0	0	DR1	3.00E-03	0	0.003	0	0	0	0	0
Tz	0	0	-1	0	0	0	0	0	DR2	3.00E-03	0	0	0.003	0	0	0	0
Rx	0	0	0	-1	0	0	0	0	Dn	1.75E-03	0	0	0	0.00175	0	0	0
Ry	0	0	0	0	-1	0	0	0		1.75E-03	0	0	0	0	0.00175	0	0
Rz	0	0	0	0	0	-1	0	0		1.75E-03	0	0	0	0	0	0.00175	0
Df,p	0	0	0	0	0	0	0	0			0	0	0	0	0	0	0
DETECTOR																	

TX	TY	TZ	RX	RY	RZ	DM/M	
0.008922	0.008922	0.011289	0.00480095	0.00480095		0.00175	0.005761

ABSOLUTE WORST CASE IMAGE REGISTRATION ERRORS DUE TO ASSEMBLY

Ivory's ICs
x position tolerances
elements' individual contributions

Worst case image registration errors due to positioning tolerances.

AEH.
Optomechanics

… + Lens Tolerances in Excel

OPTOMECH CONSTRAINT EQUATION (ABSOLUTE VALUES SMALLER THAN 0 ARE PRINTED AS 0.0)

	REGISTRATION VARIABLES									Assumed Position Tol:	Assumed Lens Tol:	IMAGE MOTION CONTRIBUTIONS						
	TX	TY	TZ	RX	RY	RZ	DM/M	Df,p	LDesVar									
Tx	0	0	0	0	0	0	0	0	Dt			0	0	0	0	0	0	0
Ty	0	0	0	0	0	0	0	0	DR1			0	0	0	0	0	0	0
Tz	0	0	0	0	0	0	0	0	DR2			0	0	0	0	0	0	0
Rx	0	0	0	0	0	0	0	0	Dn			0	0	0	0	0	0	0
Ry	0	0	0	0	0	0	0	0				0	0	0	0	0	0	0
Rz	0	0	0	0	0	1	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
SYSTEM-OBJECT												0	0	0	0	0	0	0
												0	0	0	0	0	0	0
Tx	1.3717	0	0	0	0	0	0	-1.5363	Dt	3.00E-03	0.0025	0.004115	0	0	0	0	0	0
Ty	0	1.3717	0	0	0	0	0	-3.0359	DR1	3.00E-03	0.035	0	0.004115	0	0	0	0	0
Tz	0	0	1.8815	0	0	0	-0.9602	1.357	DR2	3.00E-03	0.05	0	0	0.005645	0	0	0	0.002881
Rx	0	0.2667	0	1.3717	0	0	0	-1.1841	Dn	1.75E-03	0.0001	0	0.000467	0	0.002400475	0	0	0
Ry	-0.2667	0	0	0	1.3717	0	0	0		1.75E-03		0.000467	0	0	0	0.002400475	0	0
Rz	0	0	0	0	0	0	0	0		1.75E-03		0	0	0	0	0	0	0
Df,p	0	0	-1.8815	0	0	0	1.2495	0		0.042366		0	0	0.079711	0	0	0	0.052936
ELEMENT-1												0	0	0	0	0	0	0
												0	0	0	0	0	0	0
Tx	-0.3717	0	0	0	0	0	0	-3.0611	Dt	3.00E-03	0.002	0.001115	0	0	0	0	0	0
Ty	0	-0.3717	0	0	0	0	0	-3.1291	DR1	3.00E-03	0.015	0	0.001115	0	0	0	0	0
Tz	0	0	-0.8815	0	0	0	0.9602	5.5099	DR2	3.00E-03	0.01	0	0	0.002645	0	0	0	0.002881
Rx	0	0.1286	0	-0.3717	0	0	0	0.4251	Dn	1.75E-03	0.0001	0	0.000225	0	0.000650475	0	0	0
Ry	-0.1286	0	0	0	-0.3717	0	0	0		1.75E-03		0.000225	0	0	0	0.000650475	0	0
Rz	0	0	0	0	0	0	0	0		1.75E-03		0	0	0	0	0	0	0
Df,p	0	0	-0.1381	0	0	0	0.2602	0		0.002083		0	0	0.000288	0	0	0	0.000542
ELEMENT-2												0	0	0	0	0	0	0
												0	0	0	0	0	0	0
Tx	-1	0	0	0	0	0	0	0	Dt	3.00E-03		0.003	0	0	0	0	0	0
Ty	0	-1	0	0	0	0	0	0	DR1	3.00E-03		0	0.003	0	0	0	0	0
Tz	0	0	-1	0	0	0	0	0	DR2	3.00E-03		0	0	0.003	0	0	0	0
Rx	0	0	0	-1	0	0	0	0	Dn	1.75E-03		0	0	0	0.00175	0	0	0
Ry	0	0	0	0	-1	0	0	0		1.75E-03		0	0	0	0	0.00175	0	0
Rz	0	0	0	0	0	-1	0	0		1.75E-03		0	0	0	0	0	0.00175	0
Df,p	0	0	0	0	0	0	0	0				0	0	0	0	0	0	0
DETECTOR																		

TX	TY	TZ	RX	RY	RZ	DM/M
0.008922	0.008922	0.091288	0.00480095	0.00480095	0.00175	0.059239

ABSOLUTE WORST CASE IMAGE REGISTRATION ERRORS DUE TO ASSEMBLY

Ivory's ICs

x position and lens tolerances

elements' individual contributions

Worst case image registration errors due to positioning and lens tolerances.

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Example, *Unified* Nastran Model

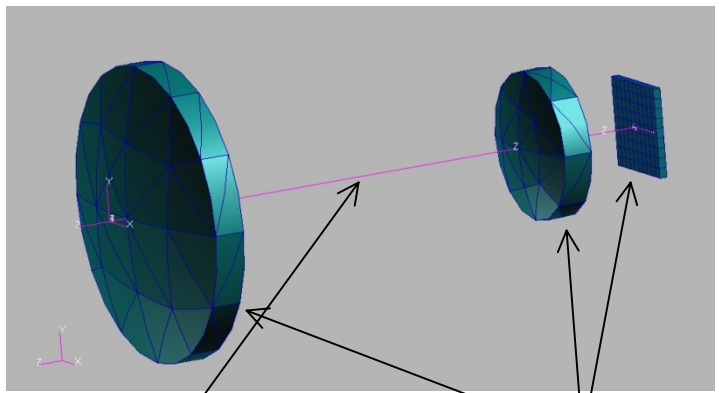
Ivory produces a Nastran file with its "Unified" option.

Ivory

```
Surf Elem Radius  Index   Thickness
1    obj  inf     AIR     inf
2    1    -3.5    ge      .25
3    1    -5.     AIR     2.67
4    2    -1.5    ge      .2
5    2    -1      AIR     .674
6    det  inf     AIR     0.0

MATERIAL   INDEX
AIR        1.0
ge         4.00024
```

```
NASTRAN MESH
CEND
TITLE=DOUB'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
BEGIN BULK
$ THE FOLLOWING GRID POINTS/DOFS HAVE BEEN ASSIGNED:
$  1  THRU  2 /123456 ARE ASSIGNED TO THE OPTICAL ELEMENTS IN ASCENDING ORDER.
$  3 /123456 ARE ASSIGNED TO THE SYSTEM DETECTOR.
$  4 /123456 ARE ASSIGNED TO THE SYSTEM OBJECT.
$  5 /123456 ARE ASSIGNED TO THE REGISTRATION VARIABLES TX, TY, TZ, RX, RY, RZ.
$  6 /1 IS ASSIGNED TO THE REGISTRATION VARIABLE DM/M.
GRID    5               0.      0.      0.
GRID    6               0.      0.      0.
MPC     1000    5       1       -1.     1       1        1.3717
                1       5       -.2667  2       1       -.3717
                2       5       -.1286  3       1       -1.

MPC     1000    5       2       -1.     1       2        1.3717
                1       4        .2667  2       2       -.3717
                2       4        .1286  3       2       -1.

MPC     1000    5       3       -1.     1       3        1.8815
                2       3       -.8815  3       3       -1.

MPC     1000    5       4       -1.     1       4        1.3717
                2       4       -.3717  3       4       -1.

MPC     1000    5       5       -1.     1       5        1.3717
                2       5       -.3717  3       5       -1.

MPC     1000    5       6       -1.     3       6       -1.
.
.
.
```

Beginnings of the Nastran model:



Optical elements from ".stp" files

Optomechanical Constraint Equations from ***Ivory's*** "*Unified*" option.

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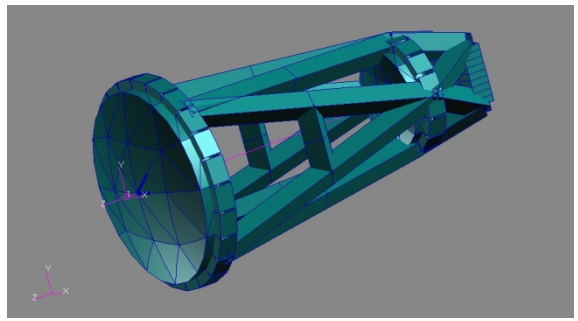
Rigid Body Check of a *Unified* Model



For unit displacements with an object at infinity (f=4.741169):

D I S P L A C E M E N T V E C T O R

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
BASE MOTION:							
1.0 Tx	5	G	-1.239011E-10	9.571148E-12	-1.010361E-13	-1.980658E-13	-3.283262E-13	-9.969587E-12
	6	G	3.545340E-14	0.0	0.0	0.0	0.0	0.0
1.0 Ty	5	G	4.249783E-11	-8.842371E-12	5.046801E-13	4.182508E-13	4.095761E-13	-5.423809E-12
	6	G	-2.176852E-13	0.0	0.0	0.0	0.0	0.0
1.0 Tz	5	G	4.585644E-11	1.080863E-11	-1.085557E-12	-2.709695E-13	-6.882338E-13	8.544233E-13
	6	G	4.827250E-13	0.0	0.0	0.0	0.0	0.0
1.0 Rx	5	G	-8.676349E-11	-4.739557E+00	1.405411E-12	3.416156E-13	-1.469747E-12	1.259602E-11
	6	G	7.719834E-13	0.0	0.0	0.0	0.0	0.0
1.0 Ry	5	G	4.739557E+00	3.172970E-11	-9.775003E-13	-1.338907E-13	-3.279599E-13	1.546279E-12
	6	G	4.457545E-13	0.0	0.0	0.0	0.0	0.0
1.0 Rz	5	G	2.361326E-12	2.262890E-11	-3.414756E-13	-3.825188E-13	-9.552226E-14	-1.000000E+00
	6	G	1.344123E-13	0.0	0.0	0.0	0.0	0.0
REGISTRATION VARIABLES			TX DM/M	TY	TZ	RX	RY	RZ

OK

***Unified* model accuracy = 0.99966**

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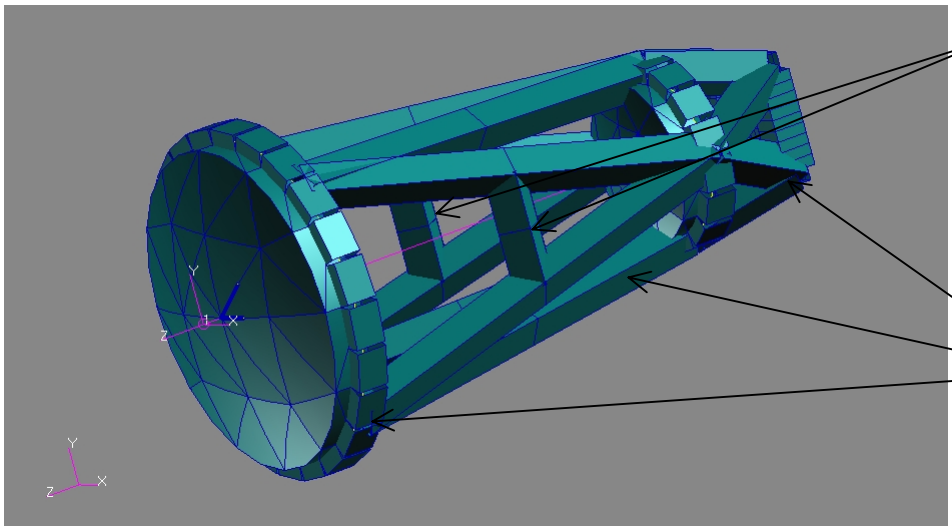
Unified Modeling Results



Mounting is at two points near the center of gravity.

Metering structure is a truss of square bars.

Displacements of the three optical elements are shown in blue.

Displacements of the image on the detector are shown in red.

0 SUBCASE 1

D I S P L A C E M E N T V E C T O R

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
1	G	2.522854E-07	8.796902E-03	-1.325016E-06	-2.856999E-03	-3.063985E-06	7.688029E-05
2	G	1.031466E-06	-4.884142E-04	6.866323E-07	-2.474126E-03	2.430291E-06	1.644103E-04
3	G	2.493282E-06	-2.096096E-03	-8.548020E-07	-2.529933E-03	-8.048320E-07	1.847545E-04
5	G	-2.025989E-06	1.326422E-02	-2.243482E-06	-4.693801E-04	-4.301375E-06	-1.847545E-04
6	G	1.931585E-06	0.0	0.0	0.0	0.0	0.0
7	G	6.786152E-05	-5.099613E-04	1.035619E-03	0.0	0.0	0.0
8	G	5.557859E-05	-3.271386E-04	8.008423E-04	0.0	0.0	0.0
9	G	7.444958E-05	-4.035432E-04	1.089830E-03	0.0	0.0	0.0
10	G	-6.545581E-05	-5.099232E-04	-1.034720E-03	0.0	0.0	0.0
11	G	-5.199726E-05	-3.248876E-04	-7.873403E-04	0.0	0.0	0.0
12		.					
		.					
		. (the rest of the Nastran output file)					

DM/M of image

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Unified Modeling Details in Excel

OPTOMECH- CONSTRAIN EQUATIONS (ABSOLUTE VALUES SMALLER THAN 0 ARE PRINTED AS 0.0)

	REGISTRATI VARIABLES									Nastran Displacement Vector:	IMAGE MOTION CONTRIBUTIONS						
	TX	TY	TZ	RX	RY	RZ	DM/M	Df,p	LDesVar								
Tx	0	0	0	0	0	0	0	0	Dt		0	0	0	0	0	0	0
Ty	0	0	0	0	0	0	0	0	DR1		0	0	0	0	0	0	0
Tz	0	0	0	0	0	0	0	0	DR2		0	0	0	0	0	0	0
Rx	0	0	0	0	0	0	0	0	Dn		0	0	0	0	0	0	0
Ry	0	0	0	0	0	0	0	0			0	0	0	0	0	0	0
Rz	0	0	0	0	0	1	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
SYSTEM-OBJECT											0	0	0	0	0	0	0
											0	0	0	0	0	0	0
Tx	1.3717	0	0	0	0	0	0	-1.5363	Dt	2.52E-07	3.461E-07	0	0	0	0	0	0
Ty	0	1.3717	0	0	0	0	0	-3.0359	DR1	8.80E-03	0	0.0120667	0	0	0	0	0
Tz	0	0	1.8815	0	0	0	-0.9602	1.357	DR2	-1.33E-06	0	0	-2.49E-06	0	0	0	1.272E-06
Rx	0	0.2667	0	1.3717	0	0	0	-1.1841	Dn	-2.86E-03	0	-0.000762	0	-0.003919	0	0	0
Ry	-0.2667	0	0	0	1.3717	0	0	0		-3.06E-06	8.172E-07	0	0	0	-4.2E-06	0	0
Rz	0	0	0	0	0	0	0	0		7.69E-05	0	0	0	0	0	0	0
Df,p	0	0	-1.8815	0	0	0	1.2495	0			0	0	0	0	0	0	0
ELEMENT-1											0	0	0	0	0	0	0
											0	0	0	0	0	0	0
Tx	-0.3717	0	0	0	0	0	0	-3.0611	Dt	1.03E-06	-3.83E-07	0	0	0	0	0	0
Ty	0	-0.3717	0	0	0	0	0	-3.1291	DR1	-4.88E-04	0	0.0001815	0	0	0	0	0
Tz	0	0	-0.8815	0	0	0	0.9602	5.5099	DR2	6.87E-07	0	0	-6.05E-07	0	0	0	6.593E-07
Rx	0	0.1286	0	-0.3717	0	0	0	0.4251	Dn	-2.47E-03	0	-0.000318	0	0.0009196	0	0	0
Ry	-0.1286	0	0	0	-0.3717	0	0	0		2.43E-06	-3.13E-07	0	0	0	-9.03E-07	0	0
Rz	0	0	0	0	0	0	0	0		1.64E-04	0	0	0	0	0	0	0
Df,p	0	0	-0.1381	0	0	0	0.2602	0			0	0	0	0	0	0	0
ELEMENT-2											0	0	0	0	0	0	0
											0	0	0	0	0	0	0
Tx	-1	0	0	0	0	0	0	0	Dt	2.49E-06	-2.49E-06	0	0	0	0	0	0
Ty	0	-1	0	0	0	0	0	0	DR1	-2.10E-03	0	0.0020961	0	0	0	0	0
Tz	0	0	-1	0	0	0	0	0	DR2	-8.55E-07	0	0	8.548E-07	0	0	0	0
Rx	0	0	0	-1	0	0	0	0	Dn	-2.53E-03	0	0	0	0.0025299	0	0	0
Ry	0	0	0	0	-1	0	0	0		-8.05E-07	0	0	0	0	8.048E-07	0	0
Rz	0	0	0	0	0	-1	0	0		1.85E-04	0	0	0	0	0	-0.000185	0
Df,p	0	0	0	0	0	0	0	0			0	0	0	0	0	0	0
DETECTOR																	

TX	TY	TZ	RX	RY	RZ	DM/M
-2.03E-06	0.0132642	-2.24E-06	-0.000469	-4.3E-06	-0.000185	1.932E-06

Image registration errors

Ivory's ICs
x Nastran's displacements =
elements' individual contributions

(Compare to Nastran on page 15)

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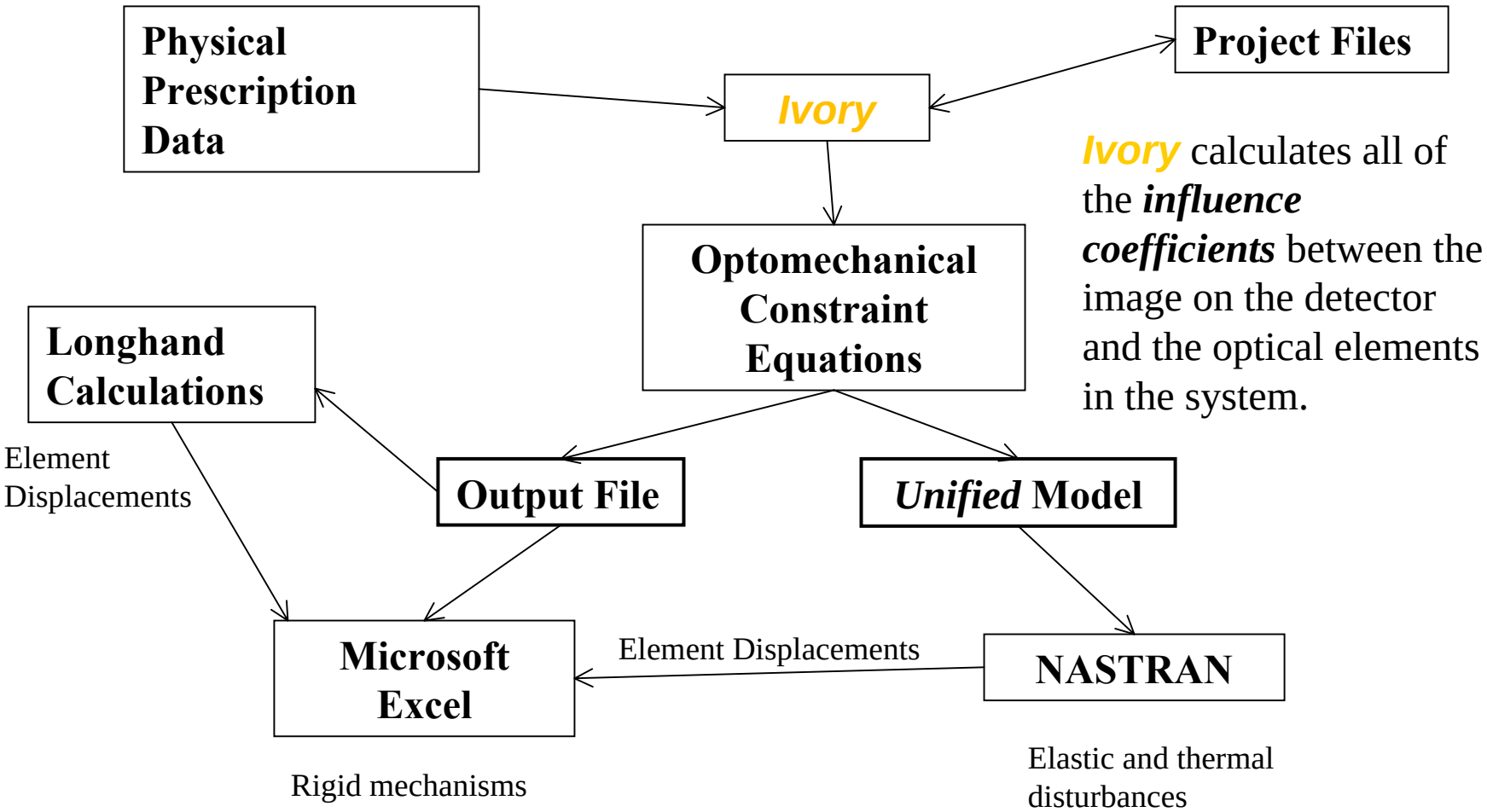
Ivory Optomechanical Modeling Tools



Ivory calculates all of the ***influence coefficients*** between the image on the detector and the optical elements in the system.

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Ivory Applied to Align an Optical Image Correlator

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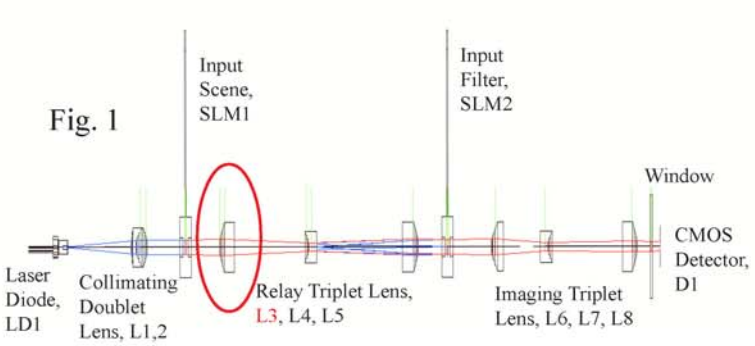
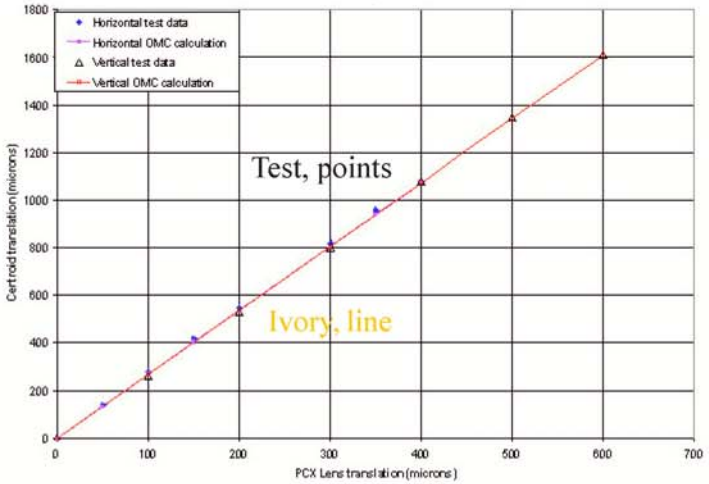
Optomechanics

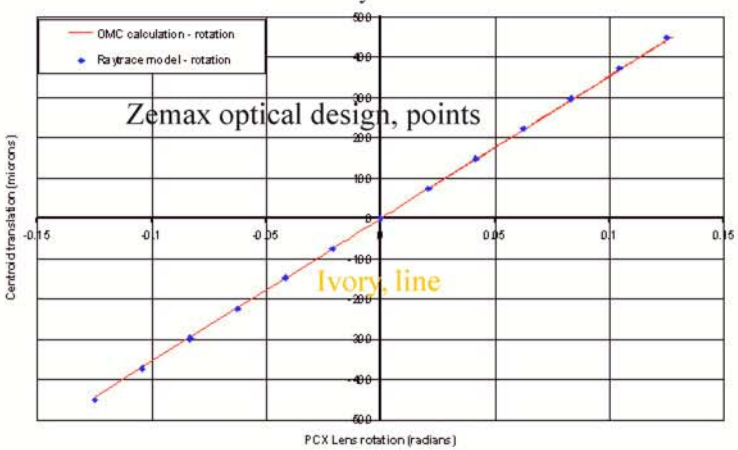
AEH/*Ivory* Validation



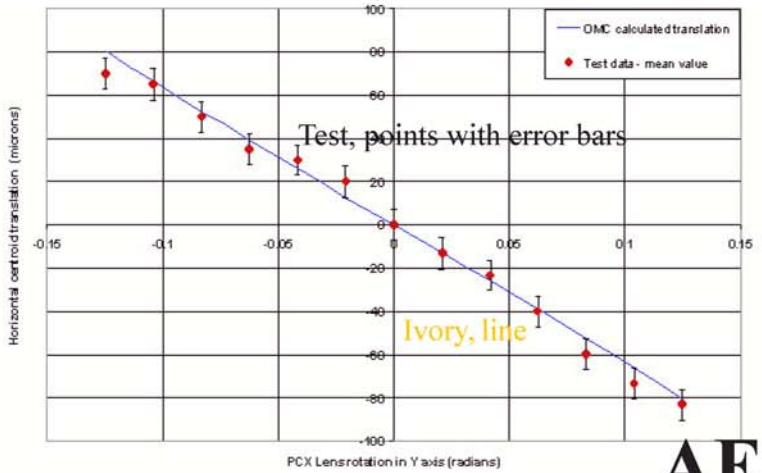
L3 T_x & T_y Translations



L3 R_x & R_y Rotations



L3 Combined Translations & Rotations



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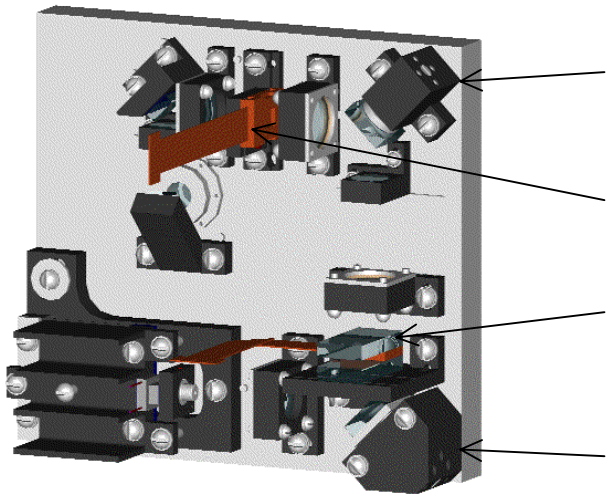
Aligning Spatial Light Modulators



Requirement:
Align the image of SLM1 on SLM2 to less than 0.1 pixel (1.5 μ) in Tx, Ty and Rz.

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**		
DM/M			0.000208							-0.031			
Registration	Tx	Ty	Tz	Rx	Ry	Rz	Tx	Ty	Tz	Rx	Ry	Rz	
Variables			M1 Motions							M2 Motions			

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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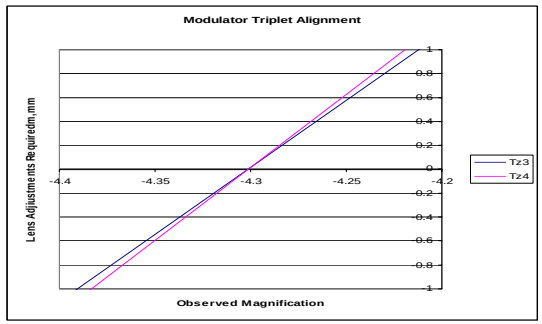
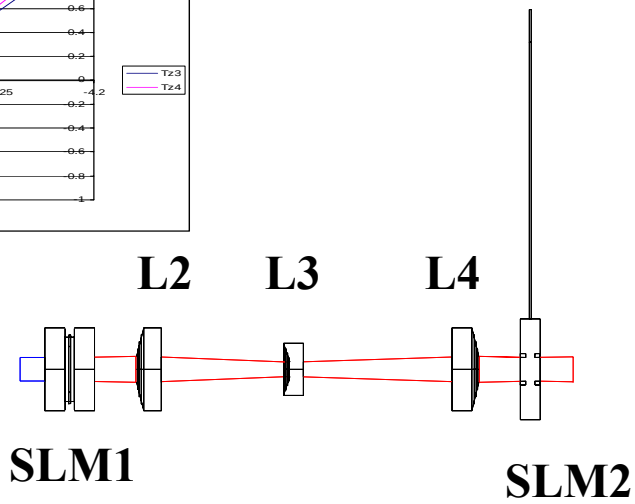
Scaling the Diffracted Light

Requirement:
Align the image focus and numerical aperture at SLM2 using lenses 3 and 4.





Registration Variables													
Tx	-2.68			3.54			1.91			0.52			
Ty		2.68		3.54				-1.91		0.52			
Tz			7.14			-7.21			-6.55			-3.63	
Rx				2.68						-1.91			
Ry					-2.68						1.91		
Rz													
DM/M			0.0335			-0.0081			-0.0117			0.0301	
	Tx	Ty	Tz	Rx	Ry	Rz	Df	Tx	Ty	Tz	Rx	Ry	Rz	Df
			L3 Motions							L4 Motions				

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Ivory Applied to Align an Optical Image Correlator

Designed alignment mirrors
Designed alignment charts

Reduced assembly time by 2/3
Reduced electrical power by 3/4

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Ivory Applied to Register Images in a Two-color Camera

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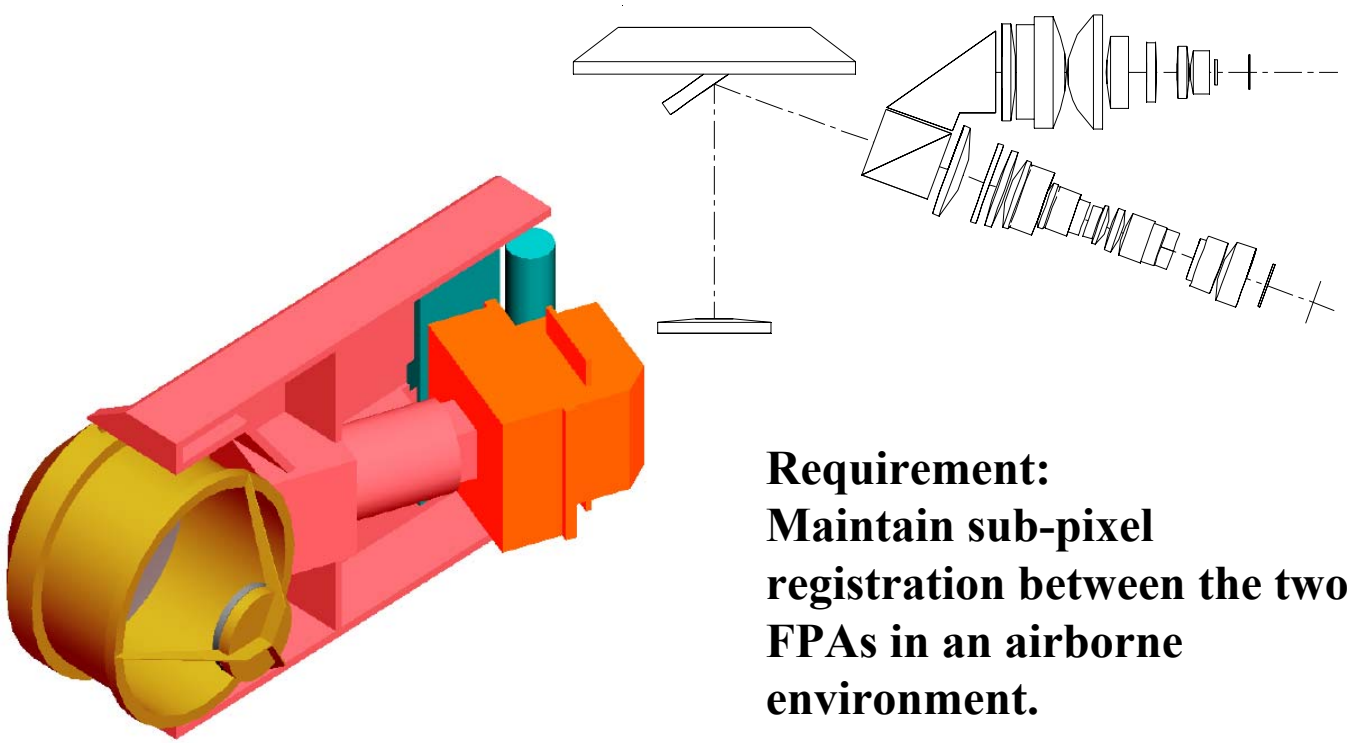
Optomechanics

A Two-color Camera



Requirement:
Maintain sub-pixel registration between the two FPAs in an airborne environment.

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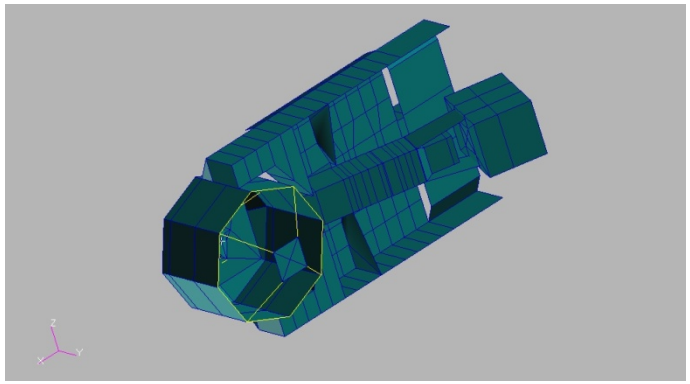
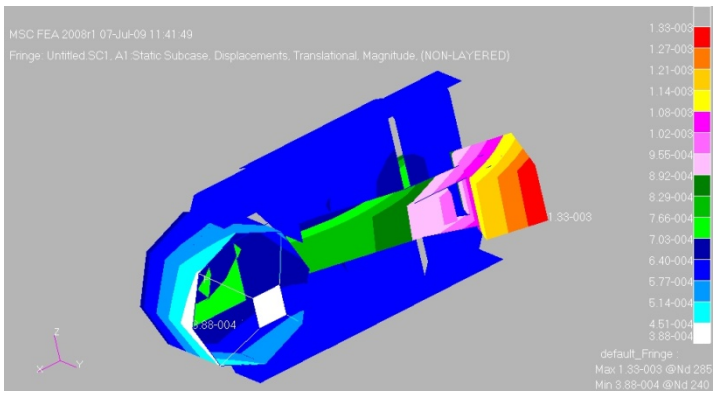
FE Analysis of Element Displacements





1.5 GS ALONG THE X (ROLL) AXIS

NODE	X TRANS	Y TRANS	Z TRANS	X ROT	Y ROT	Z ROT
1	-7.4365E-04	2.7726E-06	6.7300E-07	3.2085E-07	-4.6245E-05	-2.1854E-05
2	-4.5475E-04	-2.0027E-05	4.1551E-06	3.0762E-07	-1.1534E-07	-4.8295E-05
3	-8.0244E-04	8.8353E-06	8.6687E-08	2.8875E-05	2.3929E-05	-5.5360E-05
4	-7.0552E-04	2.5088E-04	-1.8926E-07	-1.3864E-06	4.8634E-07	3.9087E-05
5	-7.2517E-04	1.9579E-04	-2.7311E-07	-1.3896E-06	4.9393E-07	3.9220E-05
6	-7.6405E-04	8.9584E-05	-4.8932E-07	-1.7689E-06	4.3251E-07	3.9460E-05
7	-7.7197E-04	6.7650E-05	-6.5347E-07	-2.2127E-06	5.6940E-07	3.9213E-05
8	-7.7667E-04	5.2098E-05	-1.0905E-06	-1.3148E-06	-1.5381E-07	4.0670E-05
9	-7.8787E-04	2.2585E-05	-1.4003E-06	-1.5766E-07	-2.3795E-07	4.0344E-05
10	-7.9793E-04	-3.4134E-06	-1.5584E-06	-7.2602E-08	-2.6334E-07	4.0037E-05
11	-8.1214E-04	-4.0650E-05	-1.7627E-06	5.8725E-08	-3.6616E-07	4.0027E-05
12	-8.2012E-04	-6.1790E-05	-1.8442E-06	2.9572E-09	-4.1944E-07	4.0000E-05
13	-8.1836E-04	-5.6886E-05	-1.8126E-06	2.8440E-07	-5.1638E-07	3.9998E-05
14	-8.3497E-04	-1.0156E-04	-2.0556E-06	6.4894E-07	-5.2880E-07	4.0136E-05
15	-8.4091E-04	-1.1746E-04	-2.1336E-06	7.5641E-07	-5.8834E-07	4.0202E-05
16	-8.5049E-04	-1.4312E-04	-2.2435E-06	8.0778E-07	-6.3497E-07	4.0292E-05
17	-8.5774E-04	-1.6249E-04	-2.3040E-06	8.6741E-07	-6.8204E-07	4.0442E-05
18	-8.6771E-04	-1.8889E-04	-2.4746E-06	1.3983E-06	-7.3197E-07	4.0482E-05
19	-8.6854E-04	-1.9125E-04	-2.5160E-06	1.4982E-06	-7.9809E-07	4.0476E-05
20	-8.7789E-04	-2.2005E-04	-2.5080E-06	1.5741E-06	-9.9234E-07	4.0512E-05
21	-9.1048E-04	-3.0888E-04	-3.1540E-06	1.6964E-06	-7.8557E-07	4.0388E-05
22	-9.1807E-04	-3.2971E-04	-3.2335E-06	1.6898E-06	-8.4878E-07	4.0404E-05
23	-9.5055E-04	-3.9985E-04	-3.9234E-06	1.7104E-06	-8.2646E-07	4.5268E-05
24	-5.9238E-04	1.2553E-04	3.9390E-06	-1.2148E-06	-3.2840E-07	3.8068E-05
25	-5.9515E-04	3.5638E-05	3.2778E-06	-2.6629E-06	-9.5080E-08	3.8707E-05
26	-5.9357E-04	-2.5492E-05	3.8154E-06	-1.2173E-06	1.6194E-07	3.7504E-05
27	-5.9332E-04	-5.0600E-05	4.0013E-06	-1.4054E-06	1.7431E-07	3.7292E-05
28	-5.9335E-04	-7.6025E-05	4.2174E-06	-1.5854E-06	2.0532E-07	3.7178E-05
29	-5.9271E-04	-1.7649E-04	5.2699E-06	-2.3304E-06	3.5810E-07	3.6830E-05
30	-5.9298E-04	-2.0618E-04	5.5929E-06	-2.2995E-06	4.2450E-07	3.6836E-05
31	-5.9109E-04	-2.8380E-04	6.3397E-06	-2.2851E-06	6.0361E-07	3.6382E-05
32	-9.0787E-04	-3.7085E-04	3.8561E-06	-1.1076E-06	1.8081E-09	-8.6392E-05
33	-9.0780E-04	-2.3755E-04	3.8588E-06	-1.0989E-06	1.8059E-09	-8.6393E-05
34	-9.0755E-04	-5.1807E-05	3.8634E-06	-1.0885E-06	1.7708E-09	-8.6599E-05

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Registration Errors in Excel

								0	
3.2335E-06	-0.00091807	Tx	1.19381E-06	0	0	0	0	0	0
-0.000623822	-0.00032971	Ty	0	-0.000230315	0	0	0	0	0
-0.000749937	-3.2335E-06	Tz	0	0	-0.000451537	0	0	0	5.47108E-07
-0.000040404	1.6898E-06	Rx	0	-1.41374E-05	0	-1.49E-05	0	0	0
-2.19651E-07	-8.4878E-07	Ry	7.68559E-08	0	0	0	-8.10951E-08	0	0
1.87819E-06	0.000040404	Rz	0	0	0	0	0	0	0
		Df,p							0
		ELEMENT NO. 22							0
									0
3.9234E-06	-0.00095055	Tx	-3.9234E-06	0	0	0	0	0	0
-0.000700841	-0.00039985	Ty	0	0.000700841	0	0	0	0	0
-0.000756469	-3.9234E-06	Tz	0	0	0.000756469	0	0	0	0
-0.000045268	1.7104E-06	Rx	0	0	0	4.527E-05	0	0	0
-1.91631E-07	-8.2646E-07	Ry	0	0	0	0	1.91631E-07	0	0
1.88991E-06	0.000045268	Rz	0	0	0	0	0	-1.88991E-06	0
		Df,p							
		DETECTOR							

VISIBLE IMAGE MOTION FOR 1.5 G IN THE GLOBAL X DIRECTION:

0.000473949	-0.000637835	-0.000219041	-1.71E-05	-7.08205E-05	-1.88991E-06	7.9771E-06
TX	TY	TZ	RX	RY	RZ	DM/M

DETECTOR LOCAL COORDINATE SYSTEM
(ALL DIMENSIONS IN INCHES AND RADIANS)

	PR-X		0.000473949				1.87503E-06	7.91428E-06	0.000483738
	PR-Y			0.000637835			1.87503E-06	7.91428E-06	0.000647624
	FOCUS				0.000219041	1.7E-05	7.02628E-05		

Wavelength=	700	nm.=	2.76E-05	in.	
Airy disk dia.=			0.000269181	in.	
One pixel=	0.01	mm.=	0.000394	in.	
	NET PR:	0.000808344	in.=	2.0516343	pixels
	NET FOCUS:	0.000306301	in.=	0.1938613	GDF
DDF = ±	22816.39929	nm.= ±	0.000898966	in.	
GDF = ±	0.04	mm.= ±	0.00158	in.	

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Ivory Applied to Register Images in a Two-color Camera

Calculated dynamic boresight error between two optical paths

Operational boresight stability would be *problematic*
(verified in flight tests)

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Ivory Applied to Stabilize a Mid-wavelength FLIR

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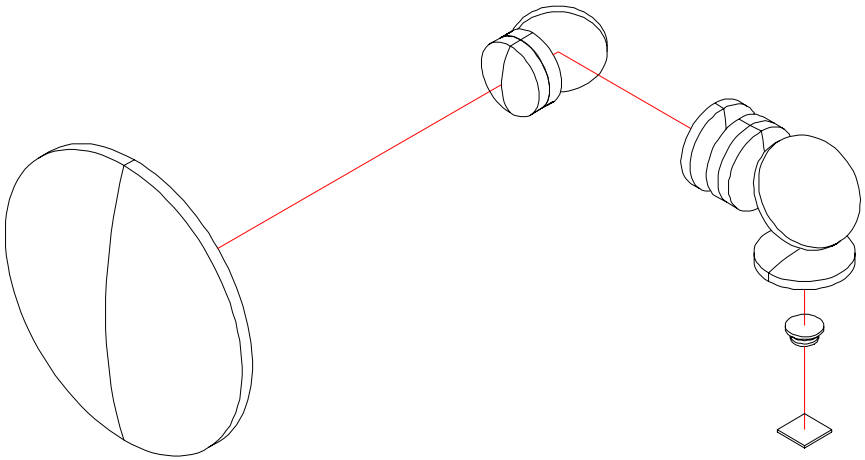
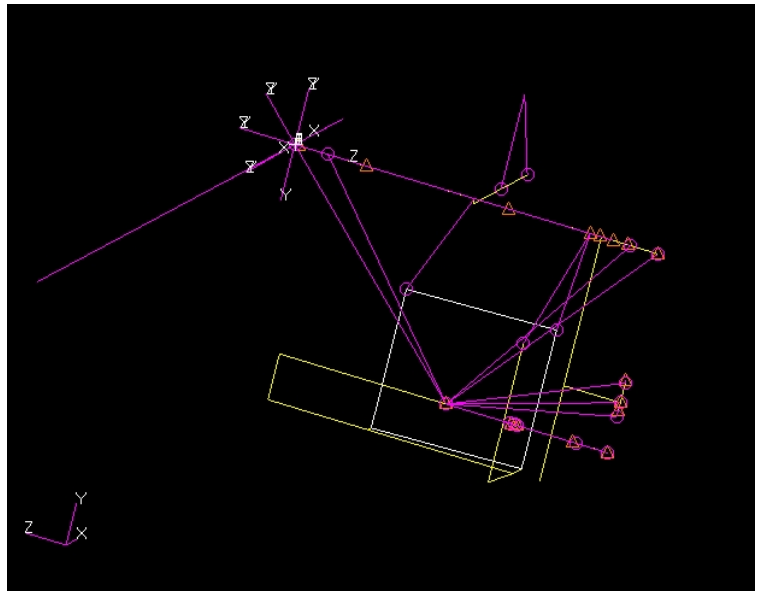
A Mid-wavelength FLIR





The task:
Verify that the line of sight will be stable to less than 10 μr rms in thermal extremes and random vibration environment.

The method:
A simple (but carefully constructed) beam-element **Nastran** model with lumped masses for the lenses and ***Ivory's*** influence coefficients driving the image motions.

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Thermal Image Stability in Nastran

```
NASTRAN MESH
CEND
TITLE=NF'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
BEGIN BULK
$ THE FOLLOWING GRID POINTS/DOFS HAVE BEEN ASSIGNED:
$  1  THRU  12 /123456 ARE ASSIGNED TO THE OPTICAL ELEMENTS IN ASCENDING ORDER.
$  13 /123456 ARE ASSIGNED TO THE SYSTEM DETECTOR.
$  14 /123456 ARE ASSIGNED TO THE SYSTEM OBJECT.
$  15 /123456 ARE ASSIGNED TO THE REGISTRATION VARIABLES TX, TY, TZ, RX, RY, RZ.
$  16 /1 IS ASSIGNED TO THE REGISTRATION VARIABLE DM/M.
GRID    15               0.      0.      0.
GRID    16               0.      0.      0.
MPC     1000    15      1       -1.     1       1       -2.28034
                1       5        .51305 2       1       -.51904
                2       5        3.2867 3       1        1.62407
                3       5        .15684 4       5       -2.45353
                5       1       -1.382265       5        .03296
                6       1        2.114816       5       -.2064
                7       1       -1.347517       5       -.09949
                8       5       -3.347539       1        1.56036
                9       5       -.13952 10      5       -.01585
                11      5       -.01503 12      5       -.01585
                13      1       -1.
MPC     1000    15      2       -1.     1       2       -2.28034
                1       4       -.51305 2       2       -.51904
                2       4       -3.2867 3       2        1.62407
                3       4       -.15684 4       3       -1.66214
```

D I S P L A C E M E N T V E C T O R

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
125	G	2.600000E-05	-5.811000E-05	-2.562690E-05	-6.987358E-18	-1.024498E-18	4.521079E-19
126	G	2.600000E-05	-5.811000E-05	-6.511700E-06	-6.913750E-18	-9.915638E-19	4.521079E-19
151	G	0.0	0.0	0.0	0.0	0.0	0.0
152	G	7.800000E-05	-5.158406E-20	2.499171E-18	-3.257421E-18	-3.933409E-19	5.972928E-20
1000	G	5.200000E-09	-4.404351E-09	3.450281E-03	-1.333385E-18	-1.452332E-18	-7.63793E-19
1001	G	-2.206333E-03	0.0	0.0	0.0	0.0	0.0
2011	G	1.444440E-06	0.0	0.0	0.0	0.0	0.0
2012	G	-2.606998E-05	0.0	0.0	0.0	0.0	0.0
2013	G	-7.711902E-05	0.0	0.0	0.0	0.0	0.0

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Thermal Image Stability in Excel

.
.
.
. (Bottom of ***Ivory's*** *.out file in Excel)
.
.

Tx	0	0	0	0	0	0	0	0.3964	Dt	0 TX
Ty	0	0	0	0	0	0	0	0	DR1	5.811E-05 TY
Tz	0	0	0	0	0	0	0	0	DR2	7.892E-05 TZ
Rx	0	-0.0159	0	0	0	0	0	0.0146	Dn	RX
Ry	-0.0159	0	0	0	0	0	0	0		RY
Rz	0	0	0	0	0	0	0	0		RZ
Df,p	0	0	-1	0	0	0	0	0		1.401E-07 Df,p
ELEMENT-12										

Tx	-1	0	0	0	0	0	0	0	Dt	0 TX
Ty	0	-1	0	0	0	0	0	0	DR1	5.811E-05 TY
Tz	0	0	-1	0	0	0	0	0	DR2	5.981E-05 TZ
Rx	0	0	0	-1	0	0	0	0	Dn	RX
Ry	0	0	0	0	-1	0	0	0		RY
Rz	0	0	0	0	0	-1	0	0		RZ
Df,p	0	0	0	0	0	0	0	0		Df,p
DETECTOR										

	0	**-9.73129E-09**	**0.00345025**	**0**	**0**	**0**	**-0.00220631**
		TX	TY	TZ	RX	RY	RZ DM/M

REGISTRATION ERRORS PER DEGREE F

Compare to Nastran on previous page

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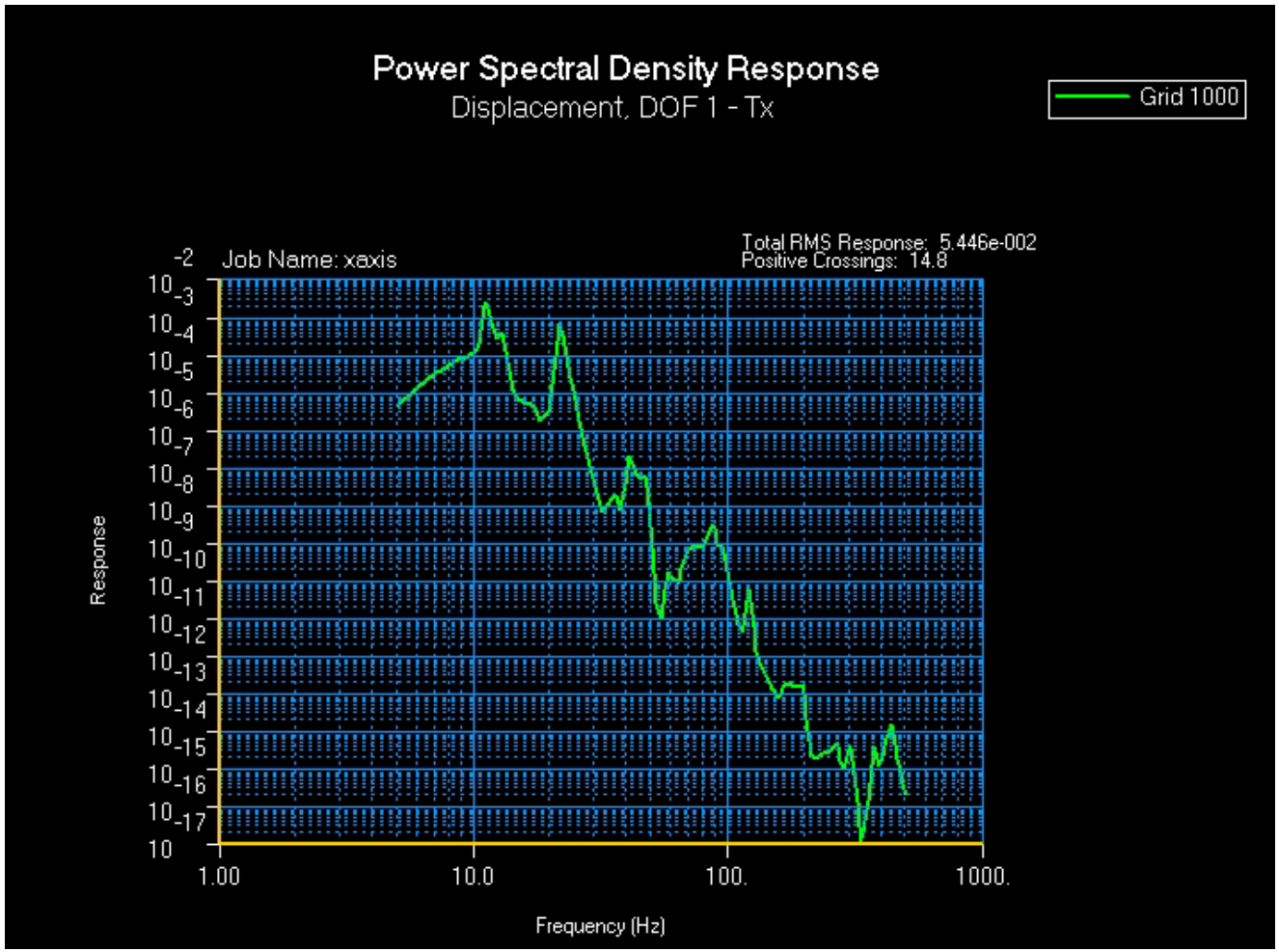
Dynamic Image Response in Nastran



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Dynamic Image Stability in Nastran

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:		
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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Ivory Applied to Stabilize a Mid-wavelength FLIR

Analyzed the image's thermal stability
Analyzed image's rms jitter in random vibration

Large margins of safety in both analyses (verified in flight tests)

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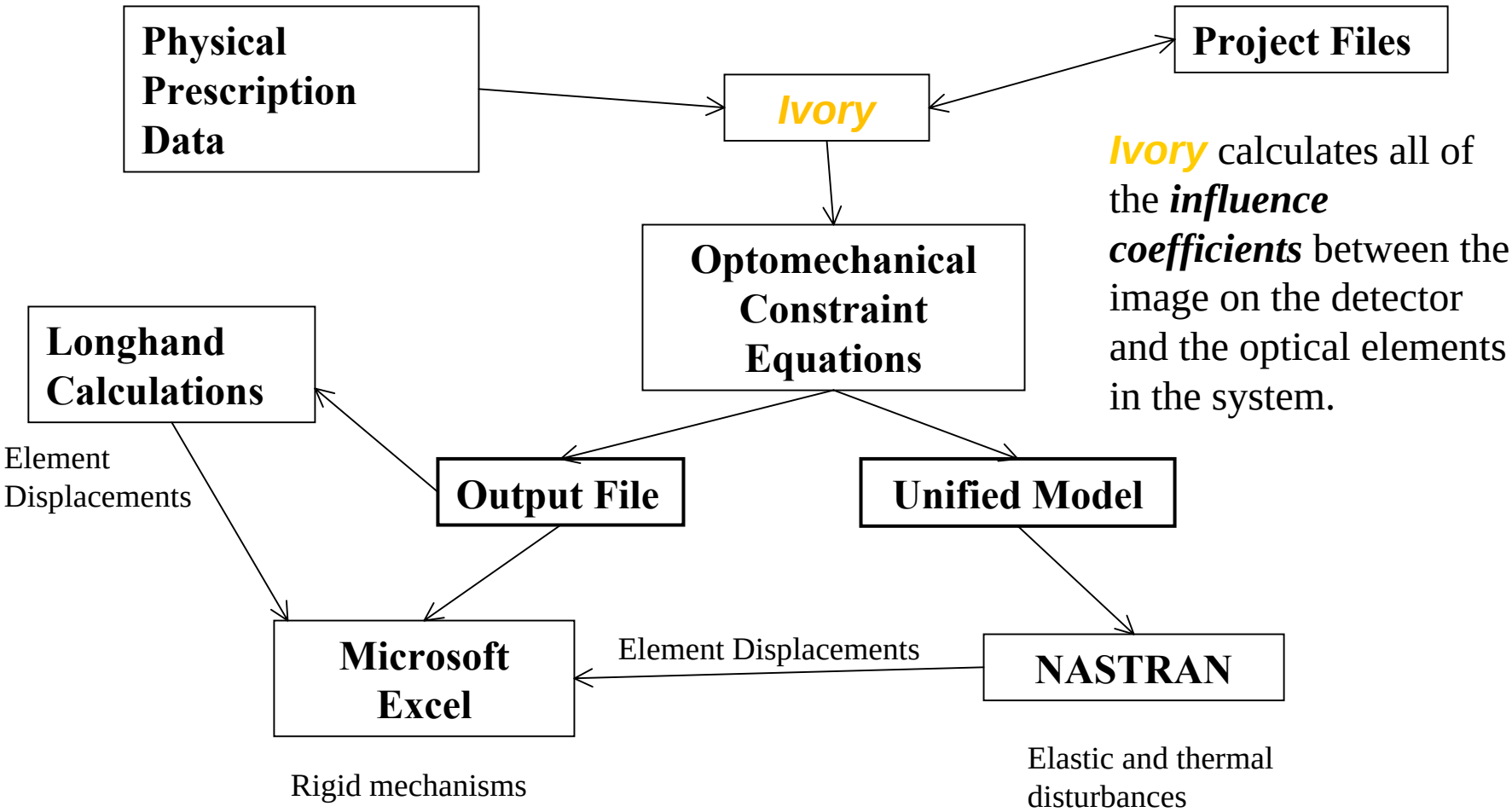
Ivory Optomechanical Modeling Tools



Ivory calculates all of the ***influence coefficients*** between the image on the detector and the optical elements in the system.

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Ivory Optomechanical Modeling Tools

Ivory **provides *quantitative* answers to challenges in**

Tolerancing
Alignment
Rigid mechanisms
Elastic structures
Thermal distortion
Environmental sensitivity
Image stability
and much, much more.

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