Tutorial 3

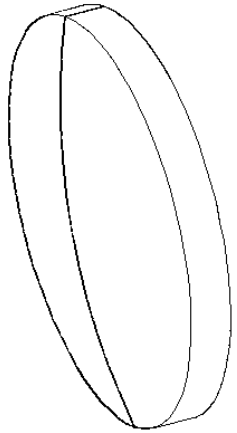
Optomechanical Tolerance Analysis

In this tutorial we shall:

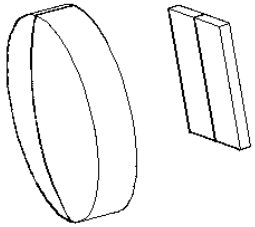
Prepare an ***Ivory*** optomechanical model from a telescope's optical prescription
Evaluate the optical faithfulness of the model in ***Ivory's*** output file
Establish an optical and a mechanical tolerancing plan
Import the ***Ivory*** optomechanical model into Excel
Apply the mechanical tolerances to the model in Excel
Apply the optical tolerances to the lenses in Excel
Calculate, in Excel, the registration errors between the image and the detector
Calculate, in Excel, the lens motions necessary to correct the registration errors
Evaluate nonlinearities in the effects of the lens motions.

AEH.
Optomechanics

The Telescope's Optical Prescription Data



Lens 1



det

Lens 2

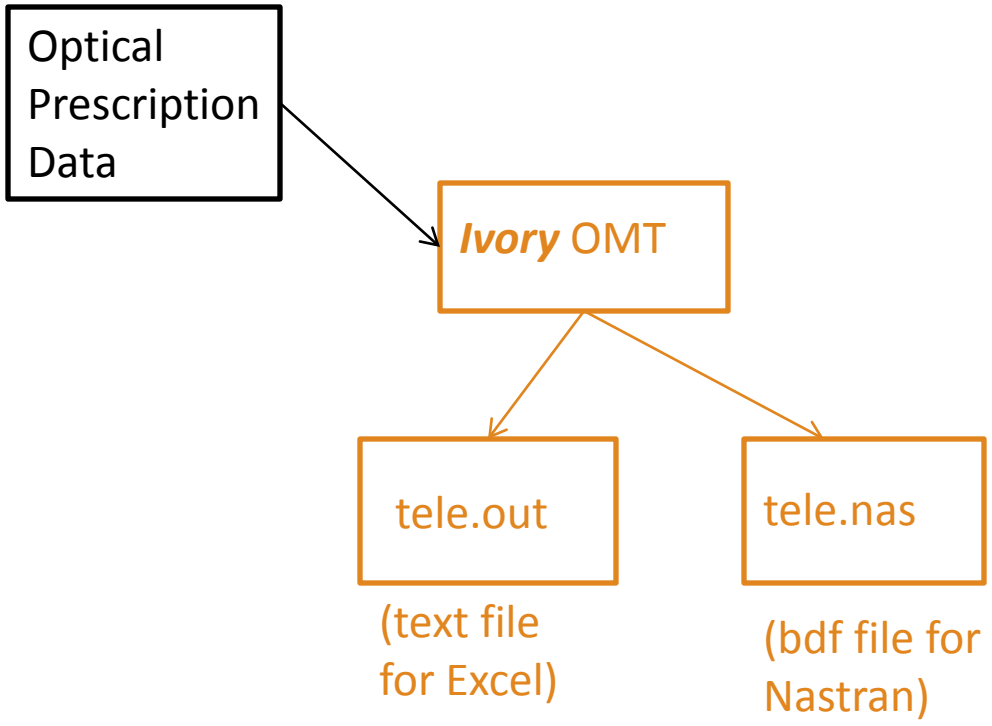
obj
(at infinity)

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

We shall call this project "tele."

AEH.
Optomechanics

Ivory Generates the *Unified* Models' Data Files



AEH.
Optomechanics

At the Top of the tele.out File:

Check the optical properties reported by *Ivory*

```
Output from -
                    IVORY Optomechanical Modeling Tools
                                                    Version 3.0
                                                                  Copyright 2014, Alson E. Hatheway Inc.

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

PROJECT NAME: 'TELE'        TIME AND DATE: 11:29:55 11-20-2014

PHYSICAL PRESCRIPTION INPUT ECHO IN OPTICAL CONVENTIONS

 Surf        Elem        Radius      Index       Thickness   Type        f1          f2          f3          f4
  1          obj         inf         1.0         inf         obj          1           1           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.
```

Check the data echos.

```
PHYSICAL PRESCRIPTION INPUT ECHO IN MECHANICAL CONVENTIONS

 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.
```

Focal length agrees with optical design.

```
GAUSSIAN PRESCRIPTION

 ELE         F           H1          H2          P           P/AIR       PHI         THETA       TYPE        PHI'
 obj         inf         0           0           0           inf         0           0            obj
 1           3.4565059   .12962156   .18517366   .1944479    3.0694484   0           0           LENS
 2           -1.4284694  -.21427469  -.1428498   .1285751    .5311502    0           0           LENS
 det         inf         0           0           0           0           0           0            det

 SYSTEM      4.741172    10.317298   4.0674085   9.3698891   4.7414085
```

Focus error is very small.

```
OBJECTS, IMAGES AND MAGNIFICATIONS

 ELE         F           S           S'          M           PHI         THETA       TYPE        e/Tzo       PHI'
 obj         inf         0           0           1.0         0           0            obj        0           0
 1           3.456506    0           -3.456506   0           0           0           LENS        0           0
 2           -1.428469   -.3870576   .5309138    1.371666    0           0           LENS        -.9602      0
 det         inf         2.36431E-4  2.36431E-4  +1.0        0           0            det        0           0
```

At the Bottom of the tele.out File for Excel:

Check the Influence coefficients with "validation sums."

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,G	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	0.0	0.0	
Df,p,G	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
SYSTEM-OBJECT									
Tx	1.371666	0.0	0.0	0.0	0.0	0.0	0.0	-1.536252	Dt
Ty	0.0	1.371666	0.0	0.0	0.0	0.0	0.0	-3.035868	DR1
Tz	0.0	0.0	1.881468	0.0	0.0	0.0	-.9602349	1.356994	DR2
Rx	0.0	.2667176	0.0	1.371666	0.0	0.0	0.0	-1.184077	Dn
Ry	-.2667176	0.0	0.0	0.0	1.371666	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,G	0.0	0.0	-1.881468	0.0	0.0	0.0	1.249544	0.0	
ELEMENT-1									
Tx	-.3716662	0.0	0.0	0.0	0.0	0.0	0.0	-3.061093	Dt
Ty	0.0	-.3716662	0.0	0.0	0.0	0.0	0.0	-3.129063	DR1
Tz	0.0	0.0	-.8814681	0.0	0.0	0.0	.9602349	5.509846	DR2
Rx	0.0	.1285751	0.0	-.3716662	0.0	0.0	0.0	.4251073	Dn
Ry	-.1285751	0.0	0.0	0.0	-.3716662	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,G	0.0	0.0	-.1381358	0.0	0.0	0.0	.2601849	0.0	
ELEMENT-2									
Tx	-1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Dt
Ty	0.0	-1	0.0	0.0	0.0	0.0	0.0	0.0	DR1
Tz	0.0	0.0	-1	0.0	0.0	0.0	0.0	0.0	DR2
Rx	0.0	0.0	0.0	-1	0.0	0.0	0.0	0.0	Dn
Ry	0.0	0.0	0.0	0.0	-1	0.0	0.0	0.0	
Rz	0.0	0.0	0.0	0.0	0.0	-1	0.0	0.0	
Df,p,G	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 'TELE'.

Sums =	-0.0000002	-0.0000002	-0.0000001	-0.0000002	-0.0000002	0.0

The sums of the diagonal terms should be computational zeros. OK.

AEH.

Optomechanics

Establish the Tolerance Plan for the Optics

Lens #	Property	Tolerance (+/-)
1	t	0.0025 in.
	R1	0.035 in.
	R2	0.05 in.
	n	0.0001 dimless
2	t	0.002 in.
	R1	0.015 in.
	R2	0.010 in.
	n	0.0001 dimless

AEH.
Optomechanics

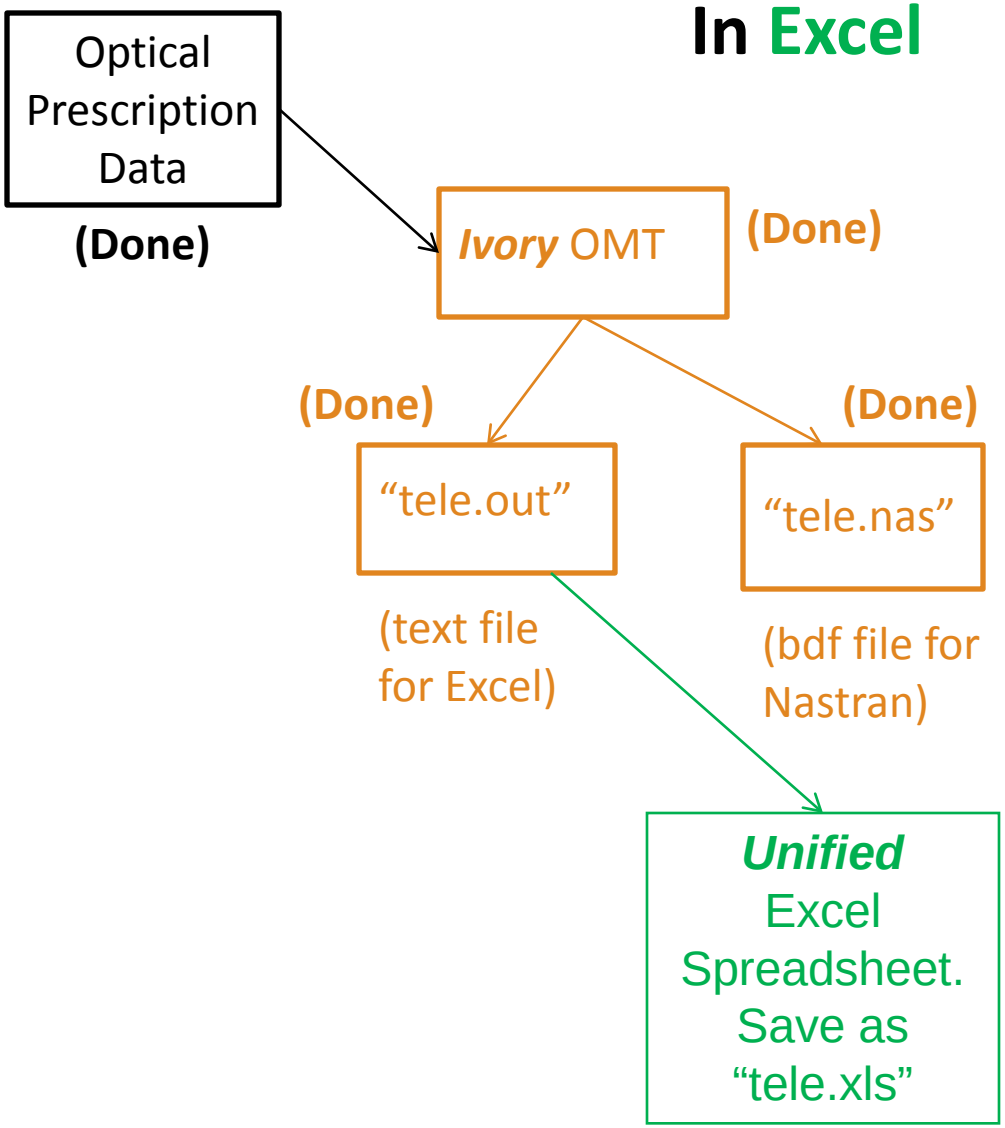
Establish a Tolerance Plan for the Optical Mounting Surfaces

For both lenses and the detector:

Position	Tolerance (+/-)
Tx	0.003 in.
Ty	0.003 in.
Tz	0.003 in.
Rx	0.1 deg. (0.00175 rad,)
Ry	0.1 deg. (0.00175 rad,)
Rz	0.1 deg. (0.00175 rad,)

AEH.
Optomechanics

Open the *Unified* Optomechanical Model In Excel



AEH.
Optomechanics

Open tele.xls in Excel

Check against tele.out

Top half of tele.xls file:

Output	from	-										
	IVORY	Optomech	Modeling	Tools								
	Version	3										
	Copyright	2014,	Alson	E.	Hatheway	Inc.						
This	Product	has	been	licensed	to	Alson	E.	Hatheway	Inc.	for	one	user(s).
PROJECT	NAME:	'TELE'	TIME	AND	DATE:	11:29:55	########					
PHYSICAL	PRESCRIP	INPUT	ECHO	IN	OPTICAL	CONVENTIONS						
	Surf	Elem	Radius	Index	Thickness	Type	f1	f2	f3	f4		
	1	obj	inf	1	inf	obj	1	1	0	0		
	2	1	3.5	4.00024	0.25	LENS	0	0	0	0		
	3	1	5	1	2.67	LENS	0	0	0	0		
	4	2	1.5	4.00024	0.2	LENS	0	0	0	0		
	5	2	1	1	0.674	LENS	0	0	0	0		
	6	det	inf	1	0	det						
INDEXES	OF	REFRACTI	ARE	RELATIVE	TO	THE	VALUE	OF	1.000292.			
PHYSICAL	PRESCRIP	INPUT	ECHO	IN	MECHANI	CONVENTIONS						
	Surf	Elem	Radius	Index	Thickness	Type	f1	f2	f3	f4		
	1	obj	inf	1	inf	obj	1	0	0	0		
	2	1	-3.5	4.00024	0.25	LENS	0	0	0	0		
	3	1	-5	1	2.67	LENS	0	0	0	0		
	4	2	-1.5	4.00024	0.2	LENS	0	0	0	0		
	5	2	-1	1	0.674	LENS	0	0	0	0		
	6	det	inf	1	0	det						
INDEXES	OF	REFRACTI	ARE	RELATIVE	TO	THE	VALUE	OF	1.000292.			
GAUSSIAN	PRESCRIPTION											
	ELE	F	H1	H2	P	P/AIR	PHI	THETA	TYPE	PHI'		
	obj	inf	0	0	0	inf	0	0	obj			
	1	3.456506	0.129622	0.185174	0.194448	3.069448	0	0	LENS			
	2	-1.42847	-0.21427	-0.14285	0.128575	0.53115	0	0	LENS			
	det	inf	0	0	0	0	0	0	det			
	SYSTEM	4.741172	10.3173	4.067409	9.369889	4.741409						
OBJECTS,	IMAGES	AND	MAGNIFICATIONS									
	ELE	F	S	S'	M	PHI	THETA	TYPE	e/Tzo	PHI'		
	obj	inf	0	0	1	0	0	obj	0	0		
	1	3.456506	0	-3.45651	0	0	0	LENS	0	0		
	2	-1.42847	-0.38706	-0.53091	1.371666	0	0	LENS	-0.9602	0		
	det	inf	2.36E-04	2.36E-04	1	0	0	det	0	0		

Bottom half of tele.xls file:

OPTOMEC	CONSTRA	EQUATIO	(ABSOLUT	VALUES	SMALLER	THAN	0	ARE	PRINTED	AS	0.0)	
	REGISTRA	VARIABLES										
	TX	TY	TZ	RX	RY	RZ	DM/M	Df,p,G	LDesVar			
Tx	0	0	0	0	0	0	0	0	Dt			
Ty	0	0	0	0	0	0	0	0	DR1			
Tz	0	0	0	0	0	0	0	0	DR2			
Rx	0	0	0	0	0	0	0	0	Dn			
Ry	0	0	0	0	0	0	0	0				
Rz	0	0	0	0	0	1	0	0				
Df,p,G	0	0	0	0	0	0	0	0				
SYSTEM-OBJECT												
Tx	1.371666	0	0	0	0	0	0	-1.53625	Dt			
Ty	0	1.371666	0	0	0	0	0	-3.03587	DR1			
Tz	0	0	1.881468	0	0	0	-0.96023	1.356994	DR2			
Rx	0	0.266718	0	1.371666	0	0	0	-1.18408	Dn			
Ry	-0.26672	0	0	0	1.371666	0	0	0				
Rz	0	0	0	0	0	0	0	0				
Df,p,G	0	0	-1.88147	0	0	0	1.249544	0				
ELEMENT-1												
Tx	-0.37167	0	0	0	0	0	0	-3.06109	Dt			
Ty	0	-0.37167	0	0	0	0	0	-3.12906	DR1			
Tz	0	0	-0.88147	0	0	0	0.960235	5.509846	DR2			
Rx	0	0.128575	0	-0.37167	0	0	0	0.425107	Dn			
Ry	-0.12858	0	0	0	-0.37167	0	0	0				
Rz	0	0	0	0	0	0	0	0				
Df,p,G	0	0	-0.13814	0	0	0	0.260185	0				
ELEMENT-2												
Tx	-1	0	0	0	0	0	0	0	Dt			
Ty	0	-1	0	0	0	0	0	0	DR1			
Tz	0	0	-1	0	0	0	0	0	DR2			
Rx	0	0	0	-1	0	0	0	0	Dn			
Ry	0	0	0	0	-1	0	0	0				
Rz	0	0	0	0	0	-1	0	0				
Df,p,G	0	0	0	0	0	0	0	0				
DETECTOR												
Thank you for using IVORY(tm) to prepare the Optomechanical Constraint Equations for 'TELE'.												

Apply the Mounting Tolerances, 1, to the Influence Coefficients, 2, from tele.xls in Excel

OPTOMEC	CONSTRA	EQUATION	(ABSOLUT	VALUES	SMALLER	THAN	0	ARE	PRINTED	AS	0.0)							
	REGISTRA	VARIABLES								Assumed Mounting								
	TX	TY	TZ	RX	RY	RZ	DM/M	Df,p,G	LDesVar	Tol +/-		TX	TY	TZ	RX	RY	RZ	DM/M
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,G	0	0	0	0	0	0	0	0				0	0	0	0	0	0	0
SYSTEM-OBJECT				2						1					3			
Tx	1.371666	0	0	0	0	0	0	-1.53625	Dt	0.003		0.004115	0	0	0	0	0	0
Ty	0	1.371666	0	0	0	0	0	-3.03587	DR1	0.003		0	0.004115	0	0	0	0	0
Tz	0	0	1.881468	0	0	0	-0.96023	1.356994	DR2	0.003		0	0	0.005644	0	0	0	-0.00288
Rx	0	0.266718	0	1.371666	0	0	0	-1.18408	Dn	0.00175		0	0.000467	0	0.0024	0	0	0
Ry	-0.26672	0	0	0	1.371666	0	0	0		0.00175		-0.00047	0	0	0	0.0024	0	0
Rz	0	0	0	0	0	0	0	0		0.00175		0	0	0	0	0	0	0
Df,p,G	0	0	-1.88147	0	0	0	1.249544	0				0	0	0	0	0	0	0
ELEMENT-1																		
Tx	-0.37167	0	0	0	0	0	0	-3.06109	Dt	0.003		-0.00111	0	0	0	0	0	0
Ty	0	-0.37167	0	0	0	0	0	-3.12906	DR1	0.003		0	-0.00111	0	0	0	0	0
Tz	0	0	-0.88147	0	0	0	0.960235	5.509846	DR2	0.003		0	0	-0.00264	0	0	0	0.002881
Rx	0	0.128575	0	-0.37167	0	0	0	0.425107	Dn	0.00175		0	0.000225	0	-0.00065	0	0	0
Ry	-0.12858	0	0	0	-0.37167	0	0	0		0.00175		-0.00023	0	0	0	-0.00065	0	0
Rz	0	0	0	0	0	0	0	0		0.00175		0	0	0	0	0	0	0
Df,p,G	0	0	-0.13814	0	0	0	0.260185	0				0	0	0	0	0	0	0
ELEMENT-2																		
Tx	-1	0	0	0	0	0	0	0	Dt	0.003		-0.003	0	0	0	0	0	0
Ty	0	-1	0	0	0	0	0	0	DR1	0.003		0	-0.003	0	0	0	0	0
Tz	0	0	-1	0	0	0	0	0	DR2	0.003		0	0	-0.003	0	0	0	0
Rx	0	0	0	-1	0	0	0	0	Dn	0.00175		0	0	0	-0.00175	0	0	0
Ry	0	0	0	0	-1	0	0	0		0.00175		0	0	0	0	-0.00175	0	0
Rz	0	0	0	0	0	-1	0	0		0.00175		0	0	0	0	0	-0.00175	0
Df,p,G	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	0.004801	0.004801	0.00175	0.005761
												Worst case errors (+/-) due to element position tolerances						

3 = 1 x 2

Repeat

Repeat

Then Vertically Sum the Contributions of Each Element, 4, of tele.xls in Excel

The sum of absolute values, 5, gives the worst case results.

OPTOMEC	CONSTRA	EQUATION	(ABSOLUT	VALUES	SMALLER	THAN	0	ARE	PRINTED	AS	0.0)							
	REGISTRA	VARIABLES								Assumed Mounting								
	TX	TY	TZ	RX	RY	RZ	DM/M	Df,p,G	LDesVar	Tol +/-								
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,G	0	0	0	0	0	0	0	0				0	0	0	0	0	0	0
SYSTEM-OBJECT																		
Tx	1.371666	0	0	0	0	0	0	-1.53625	Dt	0.003		0.004115	0	0	0	0	0	0
Ty	0	1.371666	0	0	0	0	0	-3.03587	DR1	0.003		0	0.004115	0	0	0	0	0
Tz	0	0	1.881468	0	0	0	-0.96023	1.356994	DR2	0.003		0	0	0.005644	0	0	0	-0.00288
Rx	0	0.266718	0	1.371666	0	0	0	-1.18408	Dn	0.00175		0	0.000467	0	0.0024	0	0	0
Ry	-0.26672	0	0	0	1.371666	0	0	0		0.00175		-0.00047	0	0	0	0.0024	0	0
Rz	0	0	0	0	0	0	0	0		0.00175		0	0	0	0	0	0	0
Df,p,G	0	0	-1.88147	0	0	0	1.249544	0				0	0	0	0	0	0	0
ELEMENT-1																		
Tx	-0.37167	0	0	0	0	0	0	-3.06109	Dt	0.003		-0.00111	0	0	0	0	0	0
Ty	0	-0.37167	0	0	0	0	0	-3.12906	DR1	0.003		0	-0.00111	0	0	0	0	0
Tz	0	0	-0.88147	0	0	0	0.960235	5.509846	DR2	0.003		0	0	-0.00264	0	0	0	0.002881
Rx	0	0.128575	0	-0.37167	0	0	0	0.425107	Dn	0.00175		0	0.000225	0	-0.00065	0	0	0
Ry	-0.12858	0	0	0	-0.37167	0	0	0		0.00175		-0.00023	0	0	0	-0.00065	0	0
Rz	0	0	0	0	0	0	0	0		0.00175		0	0	0	0	0	0	0
Df,p,G	0	0	-0.13814	0	0	0	0.260185	0				0	0	0	0	0	0	0
ELEMENT-2																		
Tx	-1	0	0	0	0	0	0	0	Dt	0.003		-0.003	0	0	0	0	0	0
Ty	0	-1	0	0	0	0	0	0	DR1	0.003		0	-0.003	0	0	0	0	0
Tz	0	0	-1	0	0	0	0	0	DR2	0.003		0	0	-0.003	0	0	0	0
Rx	0	0	0	-1	0	0	0	0	Dn	0.00175		0	0	0	-0.00175	0	0	0
Ry	0	0	0	0	-1	0	0	0		0.00175		0	0	0	0	-0.00175	0	0
Rz	0	0	0	0	0	-1	0	0		0.00175		0	0	0	0	0	-0.00175	0
Df,p,G	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	0.004801	0.004801	0.00175	0.005761
												Worst case errors (+/-) due to element position tolerances						

4

5 = sum(abs(4))

Now, Apply the Optics Tolerances, 1, to the Lens Design's Influence Coefficients, 2, from tele.xls in Excel

OPTOMEC	CONSTRA	EQUATIO	(ABSOLUT	VALUES	SMALLER	THAN	0	ARE	PRINTED	AS	0.0)								
	REGISTRA	VARIABLES									Effect on	Assumed							
										Net	Focal	Lens							
	TX	TY	TZ	RX	RY	RZ	DM/M	Df,p,G	LDesVar	Df +/-	Length	Tol +/-							
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,G	0	0	0	0	0	0	0	0					0	0	0	0	0	0	0
SYSTEM-OBJECT								2			3	1							
Tx	1.371666	0	0	0	0	0	0	-1.53625	Dt=		-0.00384	0.0025	0	0	0	0	0	0	0
Ty	0	1.371666	0	0	0	0	0	-3.03587	DR1=		-0.10626	0.035	0	0	0	0	0	0	0
Tz	0	0	1.881468	0	0	0	-0.96023	1.356994	DR2=		0.06785	0.05	0	0	0	0	0	0	0
Rx	0	0.266718	0	1.371666	0	0	0	-1.18408	Dn=		-0.00012	0.0001	0	0	0	0	0	0	0
Ry	-0.26672	0	0	0	1.371666	0	0	0					0	0	0	0	0	0	0
Rz	0	0	0	0	0	0	0	0					0	0	0	0	0	0	0
Df,p,G	0	0	-1.88147	0	0	0	1.249544	0	Df=	0.178064			0	0	-0.33502	0	0	0	0.222499
ELEMENT-1																			
Tx	-0.37167	0	0	0	0	0	0	-3.06109	Dt		-0.00612	0.002	0	0	0	0	0	0	0
Ty	0	-0.37167	0	0	0	0	0	-3.12906	DR1		-0.04694	0.015	0	0	0	0	0	0	0
Tz	0	0	-0.88147	0	0	0	0.960235	5.509846	DR2		0.055098	0.01	0	0	0	0	0	0	0
Rx	0	0.128575	0	-0.37167	0	0	0	0.425107	Dn		4.25E-05	0.0001	0	0	0	0	0	0	0
Ry	-0.12858	0	0	0	-0.37167	0	0	0					0	0	0	0	0	0	0
Rz	0	0	0	0	0	0	0	0					0	0	0	0	0	0	0
Df,p,G	0	0	-0.13814	0	0	0	0.260185	0		0.108199			0	0	-0.01495	0	0	0	0.028152
ELEMENT-2																			
Tx	-1	0	0	0	0	0	0	0	Dt				0	0	0	0	0	0	0
Ty	0	-1	0	0	0	0	0	0	DR1				0	0	0	0	0	0	0
Tz	0	0	-1	0	0	0	0	0	DR2				0	0	0	0	0	0	0
Rx	0	0	0	-1	0	0	0	0	Dn				0	0	0	0	0	0	0
Ry	0	0	0	0	-1	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,G	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	0	0.349968	0	0	0	0.250651
													Worst case errors (+/-) due to element dimension tolerances						

3 = 1 x 2

Repeat

(The contributions to focal length changes)

Then, Sum the Focal Length Change Contributions, 3, to Get the Net Change in Focal Length, 4, from tele.xls in Excel,

OPTOMEC	CONSTRA	EQUATIO	(ABSOLUT	VALUES	SMALLER	THAN	0	ARE	PRINTED	AS	0.0)								
	REGISTRA	VARIABLES									Effect on	Assumed							
										Net	Focal	Lens							
	TX	TY	TZ	RX	RY	RZ	DM/M	Df,p,G	LDesVar	Df +/-	Length	Tol +/-							
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,G	0	0	0	0	0	0	0	0					0	0	0	0	0	0	0
SYSTEM-OBJECT											3								
Tx	1.371666	0	0	0	0	0	0	-1.53625	Dt=		-0.00384	0.0025	0	0	0	0	0	0	0
Ty	0	1.371666	0	0	0	0	0	-3.03587	DR1=		-0.10626	0.035	0	0	0	0	0	0	0
Tz	0	0	1.881468	0	0	0	-0.96023	1.356994	DR2=		0.06785	0.05	0	0	0	0	0	0	0
Rx	0	0.266718	0	1.371666	0	0	0	-1.18408	Dn=		-0.00012	0.0001	0	0	0	0	0	0	0
Ry	-0.26672	0	0	0	1.371666	0	0	0		4			0	0	0	0	0	0	0
Rz	0	0	0	0	0	0	0	0					0	0	0	0	0	0	0
Df,p,G	0	0	-1.88147	0	0	0	1.249544	0	Df=	0.178064			0	0	-0.33502	0	0	0	0.222499
ELEMENT-1																			
Tx	-0.37167	0	0	0	0	0	0	-3.06109	Dt		-0.00612	0.002	0	0	0	0	0	0	0
Ty	0	-0.37167	0	0	0	0	0	-3.12906	DR1		-0.04694	0.015	0	0	0	0	0	0	0
Tz	0	0	-0.88147	0	0	0	0.960235	5.509846	DR2		0.055098	0.01	0	0	0	0	0	0	0
Rx	0	0.128575	0	-0.37167	0	0	0	0.425107	Dn		4.25E-05	0.0001	0	0	0	0	0	0	0
Ry	-0.12858	0	0	0	-0.37167	0	0	0					0	0	0	0	0	0	0
Rz	0	0	0	0	0	0	0	0					0	0	0	0	0	0	0
Df,p,G	0	0	-0.13814	0	0	0	0.260185	0		0.108199			0	0	-0.01495	0	0	0	0.028152
ELEMENT-2																			
Tx	-1	0	0	0	0	0	0	0	Dt				0	0	0	0	0	0	0
Ty	0	-1	0	0	0	0	0	0	DR1				0	0	0	0	0	0	0
Tz	0	0	-1	0	0	0	0	0	DR2				0	0	0	0	0	0	0
Rx	0	0	0	-1	0	0	0	0	Dn				0	0	0	0	0	0	0
Ry	0	0	0	0	-1	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,G	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	0	0.349968	0	0	0	0.250651

Worst case errors (+/-) due to element dimension tolerances

4 = sum(abs(3))

The sum of absolute values, 3, gives the worst case results.

AEH.

Optomechanics

Multiply the Change in Focal Length, 4, and the Influence Coefficients, 5, from tele.xls in Excel,

OPTOMEC	CONSTRA	EQUATIO	(ABSOLUT	VALUES	SMALLER	THAN	0	ARE	PRINTED	AS	0.0)								
	REGISTRA	VARIABLES									Effect on	Assumed							
										Net	Focal	Lens							
	TX	TY	TZ	RX	RY	RZ	DM/M	Df,p,G	LDesVar	Df +/-	Length	Tol +/-							
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,G	0	0	0	0	0	0	0	0					0	0	0	0	0	0	0
SYSTEM-OBJECT																			
Tx	1.371666	0	0	0	0	0	0	-1.53625	Dt=		-0.00384	0.0025	0	0	0	0	0	0	0
Ty	0	1.371666	0	0	0	0	0	-3.03587	DR1=		-0.10626	0.035	0	0	0	0	0	0	0
Tz	0	0	1.881468	0	0	0	-0.96023	1.356994	DR2=		0.06785	0.05	0	0	0	0	0	0	0
Rx	0	0.266718	0	1.371666	0	0	0	-1.18408	Dn=		-0.00012	0.0001	0	0	0	0	0	0	0
Ry	-0.26672	0	0	0	1.371666	5	0	0		4			0	0	0	6	0	0	0
Rz	0	0	0	0	0	0	0	0					0	0	0	0	0	0	0
Df,p,G	0	0	-1.88147	0	0	0	1.249544	0	Df=	0.178064			0	0	-0.33502	0	0	0	0.222499
ELEMENT-1																			
Tx	-0.37167	0	0	0	0	0	0	-3.06109	Dt		-0.00612	0.002	0	0	0	0	0	0	0
Ty	0	-0.37167	0	0	0	0	0	-3.12906	DR1		-0.04694	0.015	0	0	0	0	0	0	0
Tz	0	0	-0.88147	0	0	0	0.960235	5.509846	DR2		0.055098	0.01	0	0	0	0	0	0	0
Rx	0	0.128575	0	-0.37167	0	0	0	0.425107	Dn		4.25E-05	0.0001	0	0	0	0	0	0	0
Ry	-0.12858	0	0	0	-0.37167	0	0	0					0	0	0	0	0	0	0
Rz	0	0	0	0	0	0	0	0					0	0	0	0	0	0	0
Df,p,G	0	0	-0.13814	0	0	0	0.260185	0		0.108199			0	0	-0.01495	0	0	0	0.028152
ELEMENT-2																			
Tx	-1	0	0	0	0	0	0	0	Dt				0	0	0	0	0	0	0
Ty	0	-1	0	0	0	0	0	0	DR1				0	0	0	0	0	0	0
Tz	0	0	-1	0	0	0	0	0	DR2				0	0	0	0	0	0	0
Rx	0	0	0	-1	0	0	0	0	Dn				0	0	0	0	0	0	0
Ry	0	0	0	0	-1	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,G	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	0	0.349968	0	0	0	0.250651
													Worst case errors (+/-) due to element dimension tolerances						

6 = 4 x 5

AEH.

Optomechanics

And Vertially Sum the Contributions of Each Element, 7,from tele.xls in Excel

The sum of absolute values, 8, gives the worst case results.

OPTOMEC	CONSTRA	EQUATIO	(ABSOLUT	VALUES	SMALLER	THAN	0	ARE	PRINTED	AS	0.0)							
	REGISTRA	VARIABLES									Effect on	Assumed						
										Net	Focal	Lens						
	TX	TY	TZ	RX	RY	RZ	DM/M	Df,p,G	LDesVar	Df +/-	Length	Tol +/-						
Tx	0	0	0	0	0	0	0	0	Dt				0	0	0	0	0	0
Ty	0	0	0	0	0	0	0	0	DR1				0	0	0	0	0	0
Tz	0	0	0	0	0	0	0	0	DR2				0	0	0	0	0	0
Rx	0	0	0	0	0	0	0	0	Dn				0	0	0	0	0	0
Ry	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
Df,p,G	0	0	0	0	0	0	0	0					0	0	0	0	0	0
SYSTEM-OBJECT																		
Tx	1.371666	0	0	0	0	0	0	-1.53625	Dt=		-0.00384	0.0025	0	0	0	0	0	0
Ty	0	1.371666	0	0	0	0	0	-3.03587	DR1=		-0.10626	0.035	0	0	0	0	0	0
Tz	0	0	1.881468	0	0	0	-0.96023	1.356994	DR2=		0.06785	0.05	0	0	0	0	0	0
Rx	0	0.266718	0	1.371666	0	0	0	-1.18408	Dn=		-0.00012	0.0001	0	0	0	0	0	0
Ry	-0.26672	0	0	0	1.371666	0	0	0					0	0	0	0	0	0
Rz	0	0	0	0	0	0	0	0					0	0	0	0	0	0
Df,p,G	0	0	-1.88147	0	0	0	1.249544	0	Df=	0.178064			0	0	-0.33502	0	0	0.222499
ELEMENT-1																		
Tx	-0.37167	0	0	0	0	0	0	-3.06109	Dt		-0.00612	0.002	0	0	0	0	0	0
Ty	0	-0.37167	0	0	0	0	0	-3.12906	DR1		-0.04694	0.015	0	0	0	0	0	0
Tz	0	0	-0.88147	0	0	0	0.960235	5.509846	DR2		0.055098	0.01	0	0	0	0	0	0
Rx	0	0.128575	0	-0.37167	0	0	0	0.425107	Dn		4.25E-05	0.0001	0	0	0	0	0	0
Ry	-0.12858	0	0	0	-0.37167	0	0	0					0	0	0	0	0	0
Rz	0	0	0	0	0	0	0	0					0	0	0	0	0	0
Df,p,G	0	0	-0.13814	0	0	0	0.260185	0		0.108199			0	0	-0.01495	0	0	0.028152
ELEMENT-2																		
Tx	-1	0	0	0	0	0	0	0	Dt				0	0	0	0	0	0
Ty	0	-1	0	0	0	0	0	0	DR1				0	0	0	0	0	0
Tz	0	0	-1	0	0	0	0	0	DR2				0	0	0	0	0	0
Rx	0	0	0	-1	0	0	0	0	Dn				0	0	0	0	0	0
Ry	0	0	0	0	-1	0	0	0					0	0	0	0	0	0
Rz	0	0	0	0	0	-1	0	0					0	0	0	0	0	0
Df,p,G	0	0	0	0	0	0	0	0					0	0	0	0	0	0
DETECTOR																		

TX	TY	TZ	RX	RY	RZ	DM/M
0	0	0.349968	0	0	0	0.250651

Worst case errors (+/-) due to element dimension tolerances

7

8 = sum(abs(7))

AEH.

Optomechanics

Image Registration Errors Due to Tolerances

Image Reg. Errors:	Tx_i	Ty_i	Tz_i	Rx_i	Ry_i	Rz_i	DM/M_i
Sources:							
Positioning Tolerances (+/-)	0.0089	0.0089	0.0113	0.0048	0.0048	0.0018	0.0058
Lens Tolerances (+/-)			0.3500				0.2507
Net Registration Errors (+/-)	0.0089	0.0089	**0.3613**	0.0048	0.0048	0.0018	**0.2565**

The image registration errors due to tolerances are dominated by the focus term, Tz_i, and the change in size term, DM/M_i.

AEH.

Optomechanics

Correcting the Assembly Registration Errors

There are two possible combinations for these Tz_i and DM/M_i registration errors: They can either be of the same sense (+ and + or – and -) or they can be of opposite sense (+ and - or - and +).

Since the influence coefficients in the constraint equations are of opposite sense for Tz_i and DM/M_i only oppositely sensed registration errors can occur simultaneously.

To determine the motions of Lenses 1 and 2 that are necessary to correct the registration errors we shall set up, from the coefficients in the constraint equations, two equations in two unknowns, Tz_1 and $Tz_{2:}$

$$Tz_i = 1.881\ Tz_1 – 0.881\ Tz_2 = 0.3613 \quad \text{(reg. error)}$$
$$DM/M_i = -0.960\ Tz_1 + 0.960\ Tz_2 = -0.2565 \quad \text{(reg. error).}$$

Solving them simultaneously,

$$Tz_1 = 0.1259$$
$$Tz_2 = -0.1413\ .$$

AEH.
Optomechanics

Checking the Assembly Registration Error Correction Calculations

Substitute the values for Tz_1 and Tz_2 into Excel

OPTOMEC	CONSTRA	EQUATION	(ABSOLUT	VALUES	SMALLER	THAN		0	ARE	PRINTED	AS	0.0)
	REGISTRA	VARIABLES									Masximum Adjustments	
	TX	TY	TZ	RX	RY	RZ	DM/M	Df,p,G	LDesVar		+/-	
Tx	0	0	0	0	0	0	0	0	Dt			
Ty	0	0	0	0	0	0	0	0	DR1			
Tz	0	0	0	0	0	0	0	0	DR2			
Rx	0	0	0	0	0	0	0	0	Dn			
Ry	0	0	0	0	0	0	0	0				
Rz	0	0	0	0	0	1	0	0				
Df,p,G	0	0	0	0	0	0	0	0				
SYSTEM-OBJECT												
Tx	1.371666	0	0	0	0	0	0	-1.53625	Dt			
Ty	0	1.371666	0	0	0	0	0	-3.03587	DR1			
Tz	0	0	1.881468	0	0	0	-0.96023	1.356994	DR2		0.1259	
Rx	0	0.266718	0	1.371666	0	0	0	-1.18408	Dn			
Ry	-0.26672	0	0	0	1.371666	0	0	0				
Rz	0	0	0	0	0	0	0	0				
Df,p,G	0	0	-1.88147	0	0	0	1.249544	0				
ELEMENT-1												
Tx	-0.37167	0	0	0	0	0	0	-3.06109	Dt			
Ty	0	-0.37167	0	0	0	0	0	-3.12906	DR1			
Tz	0	0	-0.88147	0	0	0	0.960235	5.509846	DR2		-0.1413	
Rx	0	0.128575	0	-0.37167	0	0	0	0.425107	Dn			
Ry	-0.12858	0	0	0	-0.37167	0	0	0				
Rz	0	0	0	0	0	0	0	0				
Df,p,G	0	0	-0.13814	0	0	0	0.260185	0				
ELEMENT-2												
Tx	-1	0	0	0	0	0	0	0	Dt			
Ty	0	-1	0	0	0	0	0	0	DR1			
Tz	0	0	-1	0	0	0	0	0	DR2			
Rx	0	0	0	-1	0	0	0	0	Dn			
Ry	0	0	0	0	-1	0	0	0				
Rz	0	0	0	0	0	-1	0	0				
Df,p,G	0	0	0	0	0	0	0	0				
DETECTOR												

TX	TY	TZ	RX	RY	RZ	DM/M
0	0	0.361428	0	0	0	-0.25657

Registration errors corrected with L1 and L2 adjustments

and observe Tz_i and DM/M_i corrections on the detector.

Evaluating Nonlinearities in Tz_2 (*Ivory* User's Guide)

Top half of tele.out file:

Output	from	-									
	IVORY	Optomech	Modeling	Tools							
	Version	3									
	Copyright	2014,	Alson	E.	Hatheway	Inc.					
This	Product	has	been	licensed	to	Alson	E.	Hatheway	Inc.	for	one	user(s).
PROJECT	NAME:	'TELE'	TIME	AND	DATE:	11:29:55	########				
PHYSICAL	PRESCRIP'	INPUT	ECHO	IN	OPTICAL	CONVENTIONS					
	Surf	Elem	Radius	Index	Thickness	Type	f1	f2	f3	f4	
	1	obj	inf	1	inf	obj	1	1	0	0	
	2	1	3.5	4.00024	0.25	LENS	0	0	0	0	
	3	1	5	1	2.67	LENS	0	0	0	0	
	4	2	1.5	4.00024	0.2	LENS	0	0	0	0	
	5	2	1	1	0.674	LENS	0	0	0	0	
	6	det	inf	1	0	det					
INDEXES	OF	REFRACTI	ARE	RELATIVE	TO	THE	VALUE	OF	1.000292.		
PHYSICAL	PRESCRIP'	INPUT	ECHO	IN	MECHANI	CONVENTIONS					
	Surf	Elem	Radius	Index	Thickness	Type	f1	f2	f3	f4	
	1	obj	inf	1	inf	obj	1	0	0	0	
	2	1	-3.5	4.00024	0.25	LENS	0	0	0	0	
	3	1	-5	1	2.67	LENS	0	0	0	0	
	4	2	-1.5	4.00024	0.2	LENS	0	0	0	0	
	5	2	-1	1	0.674	LENS	0	0	0	0	
	6	det	inf	1	0	det					
INDEXES	OF	REFRACTI	ARE	RELATIVE	TO	THE	VALUE	OF	1.000292.		
GAUSSIAN	PRESCRIPTION										
	ELE	F	H1	H2	P	P/AIR	PHI	THETA	TYPE	PHI'	
	obj	inf	0	0	0	inf	0	0	obj		
	1	3.456506	0.129622	0.185174	0.194448	3.069448	0	0	LENS		
	2	-1.42847	-0.21427	-0.14285	0.128575	0.53115	0	0	LENS		
	det	inf	0	0	0	0	0	0	det		
	SYSTEM	4.741172	10.3173	4.067409	9.369889	4.741409					
OBJECTS,	IMAGES	AND	MAGNIFICATIONS								
	ELE	F	S	S'	M	PHI	THETA	TYPE	e/Tzo	PHI'	
	obj	inf	0	0	1	0	0	obj		0	0
	1	3.456506	0	-3.45651	0	0	0	LENS		0	0
	2	-1.42847	-0.38706	-0.53091	1.371666	0	0	LENS	-0.9602	0	
	det	inf	2.36E-04	2.36E-04	1	0	0	det	0	0	

From the Objects, Images and Magnifications section of the tele.xls file it may be seen that L2 is nonlinear in the Z direction:

$e/Tz_o = -0.9602$

$e = -0.9602 \times +/-0.1413 = -/+0.1357$

$r = e + 1 = 1.1357$ or 0.8643

True Tz_2 = (linear value)/r = -0.1413/r

Max Tz_2 position = 0.1096

Min Tz_2 position = -0.1440

The required motions of L2 are slightly smaller that the linear estimate of +/-0.1413 .

AEH.
Optomechanics

Unified Optomechanical Static Analysis

In this tutorial we did:

Prepare an ***Ivory*** optomechanical model from a telescope's optical prescription
Evaluate the optical faithfulness of the model in ***Ivory's*** output file
Establish an optical and a mechanical tolerancing plan
Import the ***Ivory*** optomechanical model into Excel
Apply the mechanical tolerances to the model in Excel
Apply the optical tolerances to the lenses in Excel
Calculate, in Excel, the registration errors between the image and the detector
Calculate, in Excel, the lens motions necessary to correct the registration errors
Evaluate nonlinearities in the effects of the lens motions.

AEH.
Optomechanics