Ivorytm

Optomechanical Modeling Tools

(Version 2.6)

and the preparation of the
Optomechanical Constraint Equationstm

Ivory User's Guide

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AEH Document Number 93859K

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Appendixes

1.0 Proprietary Information Notice

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2.0 Introduction

The Ivory Optomechanical Modeling Tools delivered to the user are contained in six computer files:

> IVORY26.EXE is Ivory's executable file,
> IVORY USER'S GUIDE.PDF is this document,
> IVORY LICENSE AGREEMENT.DOC is the document that defines the agreement between the user and AEH,
> FIRREC.DAT is a sample project's physical prescription geometry data file,
> FIRREC.IND is a sample project's index of refraction data file,
> BASELINE.OUT is a "validation" copy of the output file generated by Ivory for the FIRREC project.

This User's Guide is intended to instruct knowledgeable engineers and designers in managing Ivory's automated processes for generating the Optomechanical Constraint Equations (OCE) from an optical system's physical prescription data. It shows how to format the physical prescription data for use by Ivory and what to expect in the resulting output file from Ivory.

This User's Guide is not an applications booklet that shows the user how to apply the OCE to various problems faced by optomechanical engineers. Nor is it a treatise in the theory behind the OCE and the mathematical procedures used in developing the OCE from the optical physics of the system. For discussions of the theory and applications of the OCE refer to the Bibliography in Section 7.0.

The installation and operation procedures shown in this guide are explicitly for Windows XP but other Windows versions will behave similarly.

Ivory is case sensitive. The user must be consistent in the use of upper and lower case characters in naming files, naming projects and preparing the data files.

3.0 Installation and Testing of Ivory

3.1 Installation

In Windows Explorer create a folder named "Ivory." Upon receipt of the Ivory Optomechanical Modeling Tools copy all the files (6) into the Ivory folder. Make backup copies for safekeeping.

Read the file IVORY LICENSE AGREEMENT.DOC. The user must agree to the terms of this agreement in order to install Ivory on a computer or use any of the associated materials. Find your installation code. It is at the top of your license agreement.

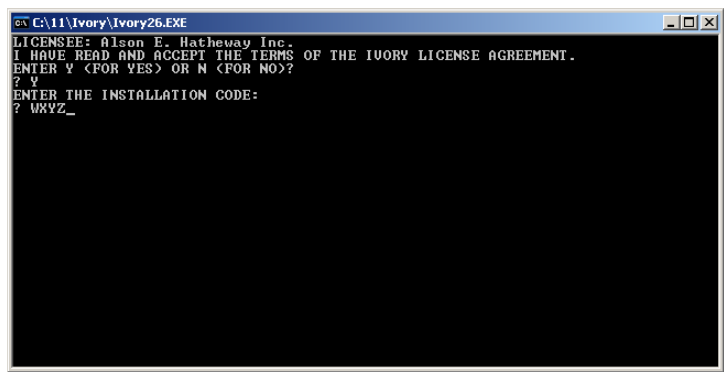


Figure 1.

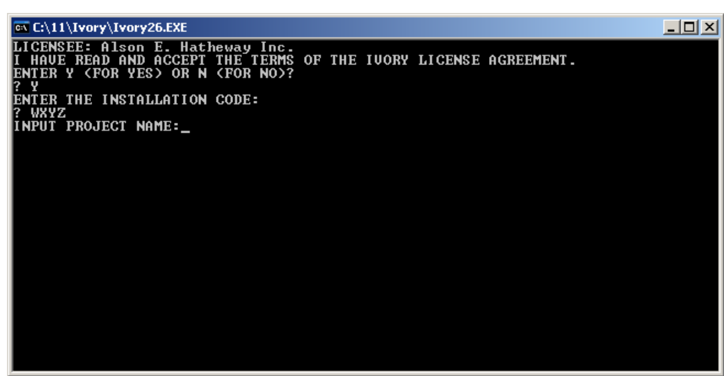


Figure 2.

1) In Windows Explorer open the Ivory folder.

2) Double click on IVORY26.EXE. You should see the Command Prompt window as shown in Figure 1. It asks you whether you accept the terms of Ivory's license agreement. Answer the question according to the prompt and then hit "Enter." If you accepted the terms of the license agreement you will be prompted to enter your installation code. You will find the code at the top of your license agreement that

came with Ivory.
3) You will now be prompted to enter a project file name as shown in Figure 2 (previous page). You may press “Enter” and you will see the screen shown in Figure 3. This is a normal response for not entering a project file for Ivory to use when prompted.

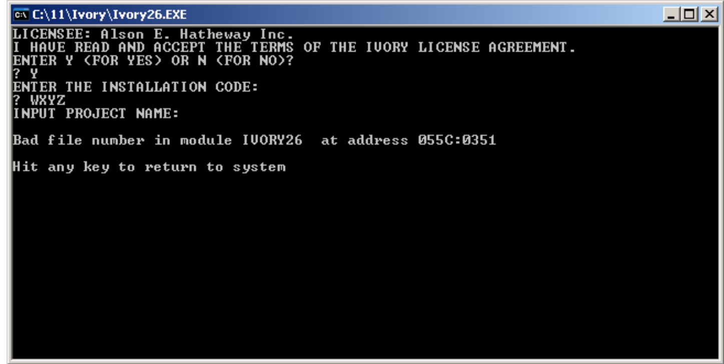


Figure 3.

4) Press “Enter” again and the command prompt window will close. You have now installed Ivory.

If you did not indicate your acceptance of the terms of the license agreement by entering “Y” in 2), above, the command prompt window will automatically close and Ivory will not have been installed. You may not install and operate Ivory unless you accept the terms of the license agreement.

If you again double click on IVORY26.EXE you will again be prompted to accept the terms of the license agreement. If you indicate your acceptance by entering “Y” at the prompt installation will then proceed as above.

3.2 Testing the Installation.

1) In Windows Explorer open the Ivory folder.

2) Double click on IVORY26.EXE. You will see

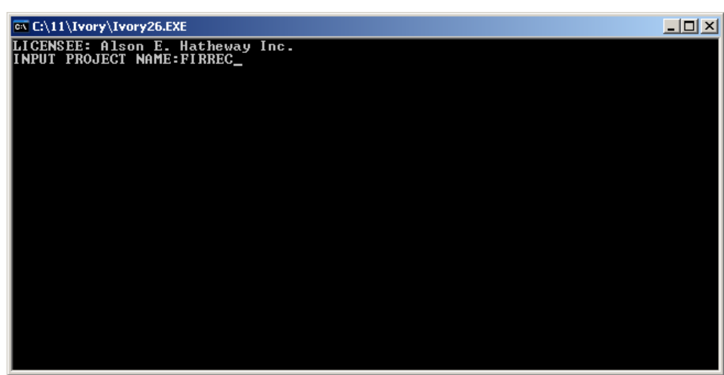


Figure 4.

the Command Prompt window as shown in Figure 4 (previous page). At the prompt for a project name type FIRREC, which is the name of the sample problem provided with the software. Hit “Enter.” Ivory will open both FIRREC.DAT and FIRREC.IND and prepare an output file, FIRREC.OUT, from them. Ivory will show on the screen its progress in preparing the Optomechanical Constraint Equations, Figure 5. The user may press “Enter” to close the command prompt window.

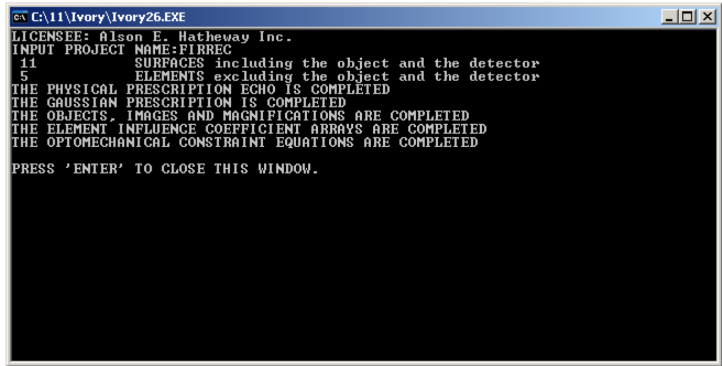
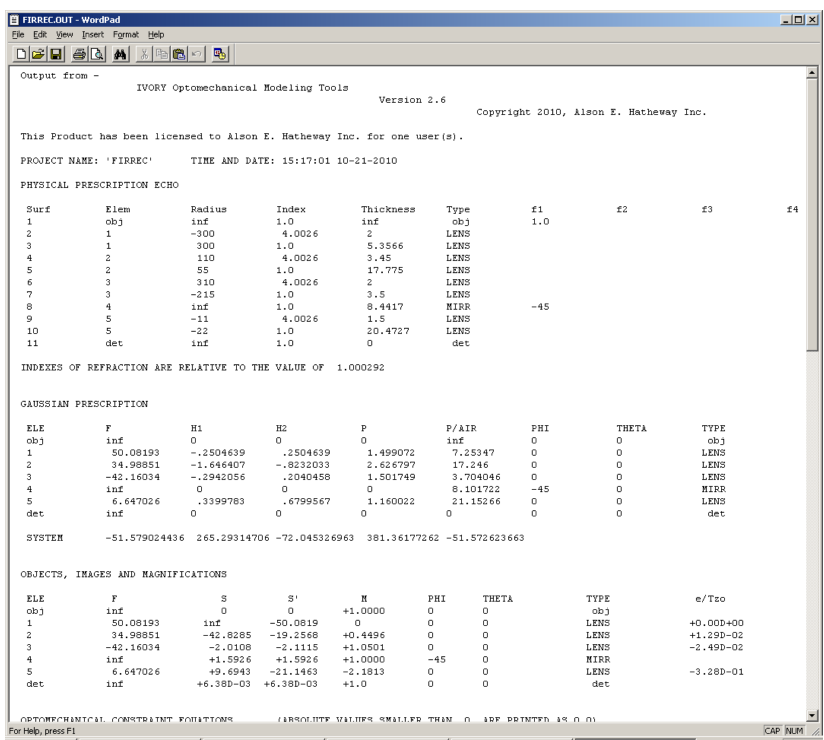


Figure 5.

3) In Windows Explorer open the Ivory folder and double click on FIRREC.OUT. This will open, in Microsoft Notepad or Wordpad, the output file prepared in 2) above (Figure 6). Also in Windows Explorer double click on the file BASELINE.OUT. The contents of FIRREC.OUT, except for the header information, should agree with the contents of BASELINE.OUT to demonstrate that your installation of Ivory has been successful. Compare the two files line-by-line.


FIRREC.OUT - WordPad

Output from -
IVORY Optomechanical Modeling Tools
Version 2.6
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PROJECT NAME: 'FIRREC' TIME AND DATE: 15:17:01 10-21-2010

PHYSICAL PRESCRIPTION ECHO

Surf	Elem	Radius	Index	Thickness	Type	f1	f2	f3	f4
1	obj	inf	1.0	inf	obj	1.0			
2	1	-300	4.0026	2	LENS				
3	1	300	1.0	5.3566	LENS				
4	2	110	4.0026	3.45	LENS				
5	2	55	1.0	17.775	LENS				
6	3	310	4.0026	2	LENS				
7	3	-215	1.0	3.5	LENS				
8	4	inf	1.0	8.4417	MIRR	-45			
9	5	-11	4.0026	1.5	LENS				
10	5	-22	1.0	20.4727	LENS				
11	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	inf	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	0	MIRR
5	6.647026	.3399783	.6799567	1.160022	21.15266	0	0	LENS
det	inf	0	0	0	0	0	0	det
SYSTEM	-51.579024436	265.29314706	-72.045326963	381.36177262	-51.572623663			

OBJECTS, IMAGES AND MAGNIFICATIONS

ELE	F	S	S'	M	PHI	THETA	TYPE	e/Tzo
obj	inf	0	0	+1.0000	0	0	obj	
1	50.08193	inf	-50.0819	0	0	0	LENS	+0.00D+00
2	34.98851	-42.8285	-19.2568	+0.4496	0	0	LENS	+1.29D-02
3	-42.16034	-2.0108	-2.1115	+1.0501	0	0	LENS	-2.49D-02
4	inf	+1.5926	+1.5926	+1.0000	-45	0	MIRR	
5	6.647026	+9.6943	-21.1463	-2.1813	0	0	LENS	-3.28D-01
det	inf	+6.38D-03	+6.38D-03	+1.0	0	0	det	

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

For Help, press F1

Figure 6.

You are now ready to apply Ivory to your own projects.

3.3 Using Ivory

There are many different ways to apply the Ivory Optomechanical Modeling Tools but perhaps the easiest is to simply copy the executable file, IVORY26.EXE in this case, into the folder where the user wants to perform the analysis and save the files. Let’s assume that you want to study the sample problem supplied with the software, FIRREC.

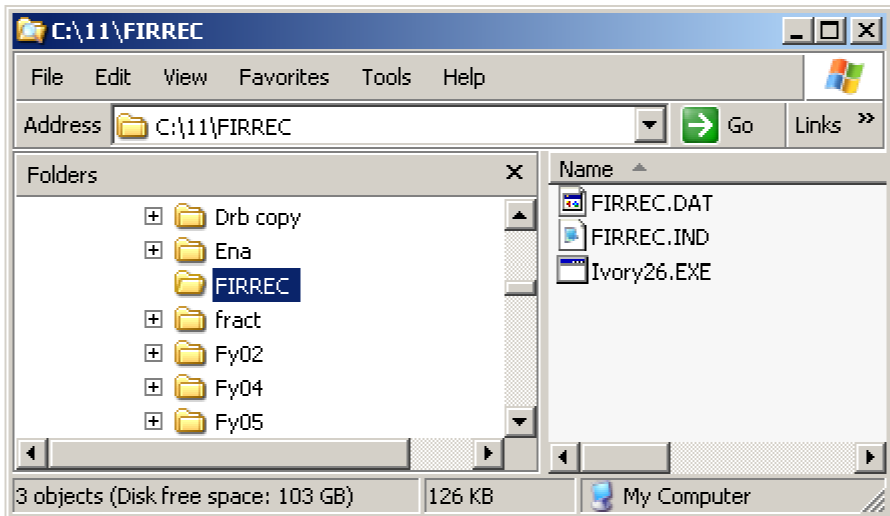


Figure 7.

You create a folder (or directory) called “FIRREC” and copy the project files (FIRREC.DAT and FIRREC.IND) into the folder. You also copy IVORY26.EXE into the folder. The results are shown in Figure 7.

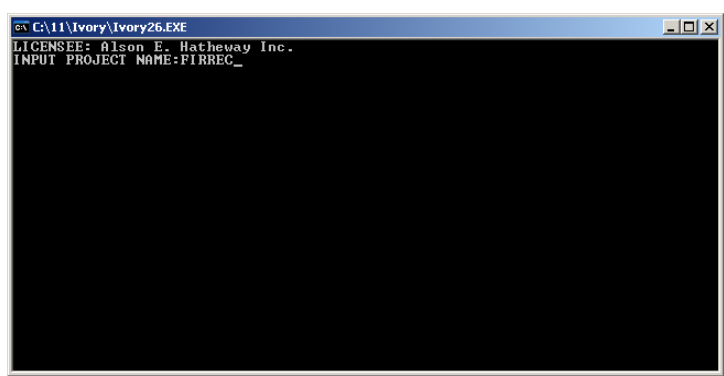


Figure 8.

To re-run the FIRREC project you simply double-click IVORY26.EXE giving the command prompt window of Figure 8. You enter “FIRREC” for the project name (as shown), press “Enter” and Ivory runs. You press the “Enter” key again to close the window and see that Ivory has produced the FIRREC.OUT file in the project directory (Figure 9.) This output file will be identical to the original file produced when you set up Ivory.

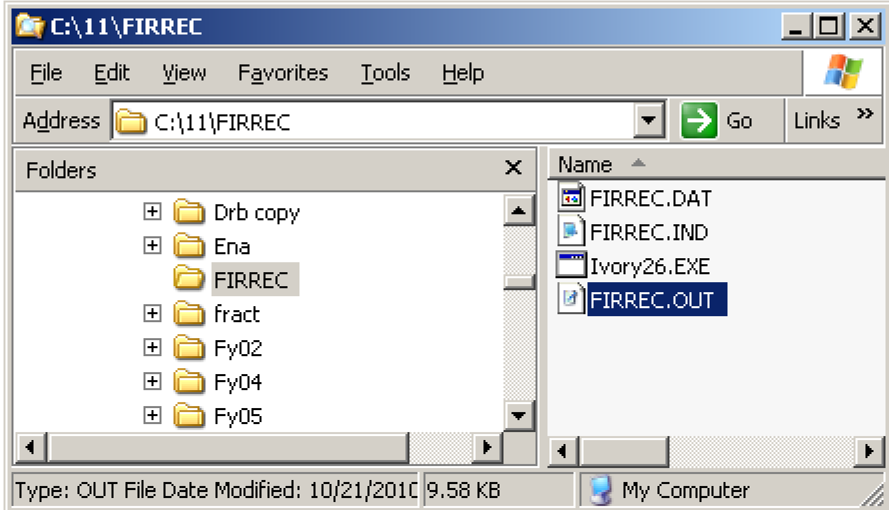
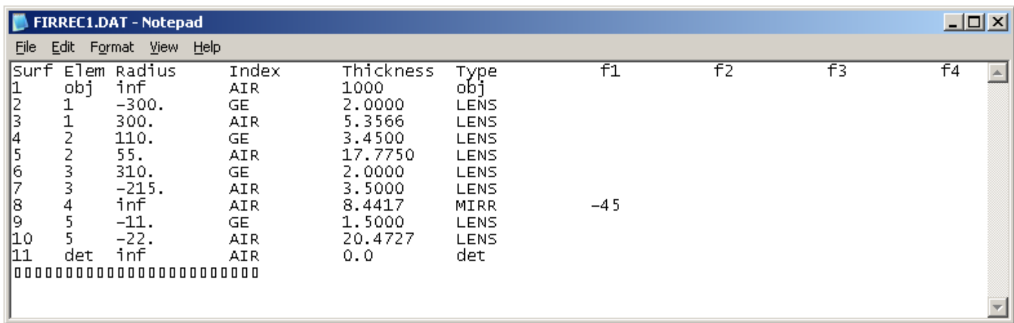


Figure 9.

Now, suppose you want to study the effects on the influence coefficients of different object distances. You can open FIRREC.DAT in Notepad and change the object distance from "inf" to say "1000" as shown in Figure 10. You save the new file as FIRREC1.DAT and you save a copy of FIRREC.IND as FIRREC1.IND as shown in Figure 11. You may now double click on IVORY26.EXE and enter "FIRREC1" at


FIRREC1.DAT - Notepad

File Edit Format View Help

Surf	Elem	Radius	Index	Thickness	Type	f1	f2	f3	f4
1	obj	inf	AIR	1000	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			
9	5	-11.	GE	1.5000	LENS				
10	5	-22.	AIR	20.4727	LENS				
11	det	inf	AIR	0.0	det				

Figure 10.

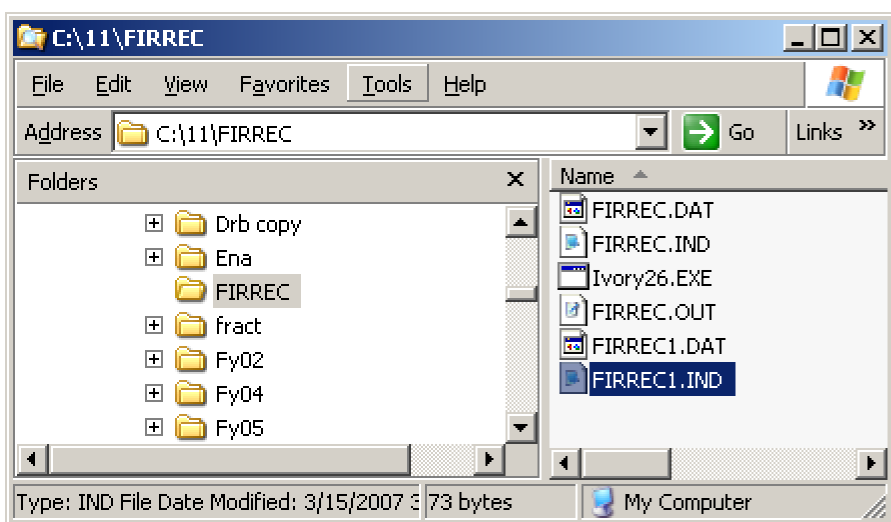


Figure 11.

the prompt to produce a new output file, FIRREC1.OUT, for the new configuration (Figure 12).

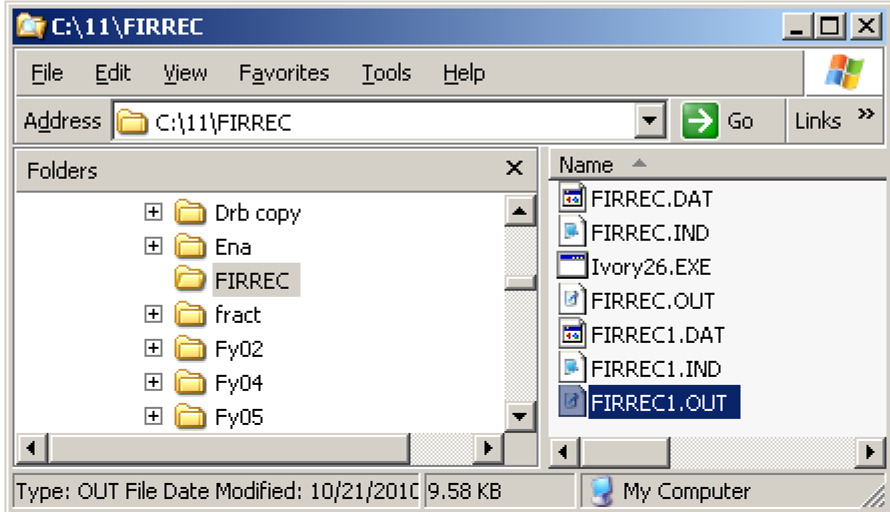
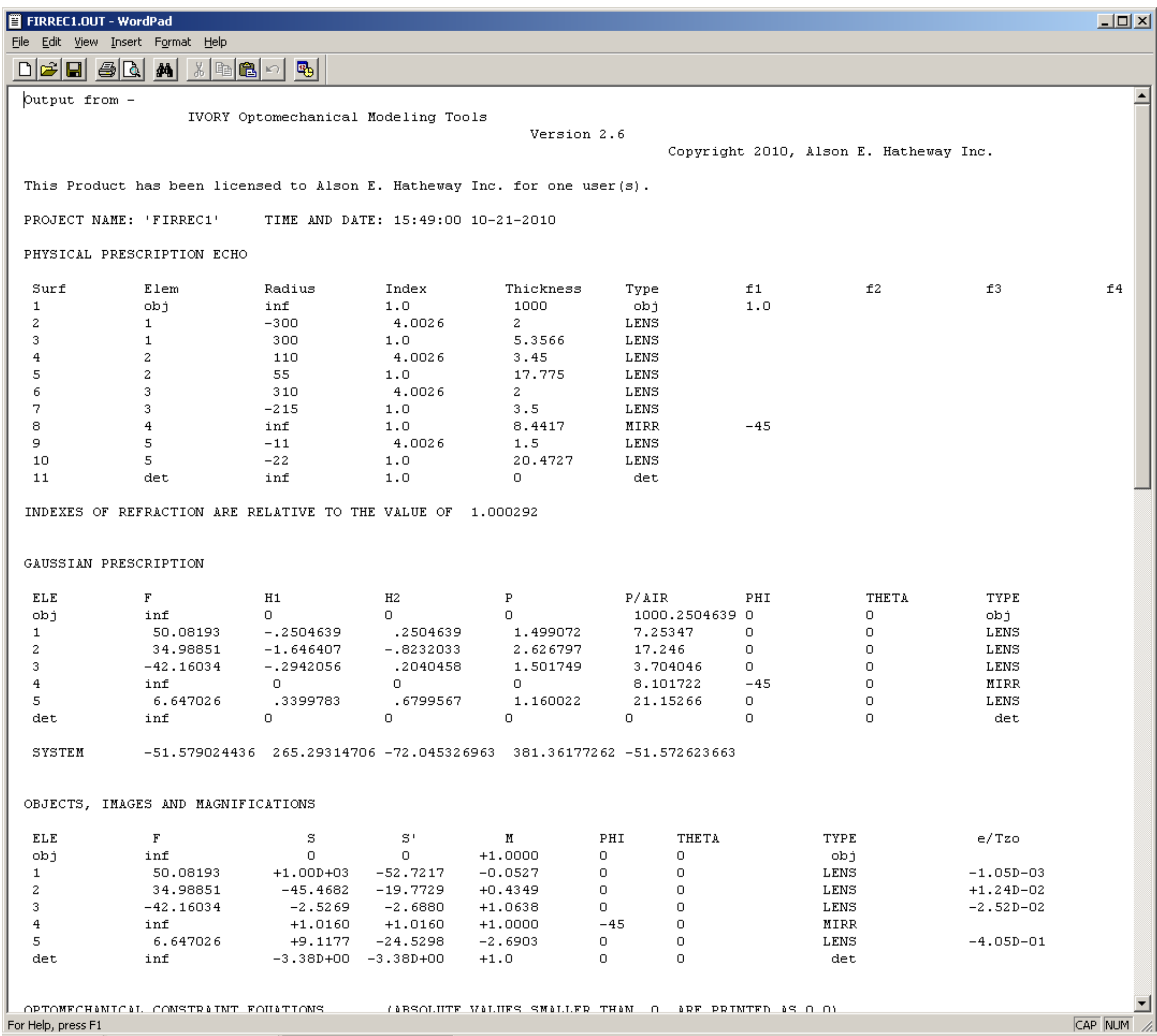


Figure 12.

Review of the new output file, FIRREC1.OUT (Figure 13), will disclose the effects of the changes in the object distance.



Output from -
IVORY Optomechanical Modeling Tools
Version 2.6
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PROJECT NAME: 'FIRREC1' TIME AND DATE: 15:49:00 10-21-2010

PHYSICAL PRESCRIPTION ECHO

Surf	Elem	Radius	Index	Thickness	Type	f1	f2	f3	f4
1	obj	inf	1.0	1000	obj	1.0			
2	1	-300	4.0026	2	LENS				
3	1	300	1.0	5.3566	LENS				
4	2	110	4.0026	3.45	LENS				
5	2	55	1.0	17.775	LENS				
6	3	310	4.0026	2	LENS				
7	3	-215	1.0	3.5	LENS				
8	4	inf	1.0	8.4417	MIRR	-45			
9	5	-11	4.0026	1.5	LENS				
10	5	-22	1.0	20.4727	LENS				
11	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	inf	0	0	0	1000.2504639	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	0	MIRR
5	6.647026	.3399783	.6799567	1.160022	21.15266	0	0	LENS
det	inf	0	0	0	0	0	0	det

SYSTEM -51.579024436 265.29314706 -72.045326963 381.36177262 -51.572623663

OBJECTS, IMAGES AND MAGNIFICATIONS

ELE	F	S	S'	M	PHI	THETA	TYPE	e/Tzo
obj	inf	0	0	+1.0000	0	0	obj	
1	50.08193	+1.00D+03	-52.7217	-0.0527	0	0	LENS	-1.05D-03
2	34.98851	-45.4682	-19.7729	+0.4349	0	0	LENS	+1.24D-02
3	-42.16034	-2.5269	-2.6880	+1.0638	0	0	LENS	-2.52D-02
4	inf	+1.0160	+1.0160	+1.0000	-45	0	MIRR	
5	6.647026	+9.1177	-24.5298	-2.6903	0	0	LENS	-4.05D-01
det	inf	-3.38D+00	-3.38D+00	+1.0	0	0	det	

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

Figure 13.

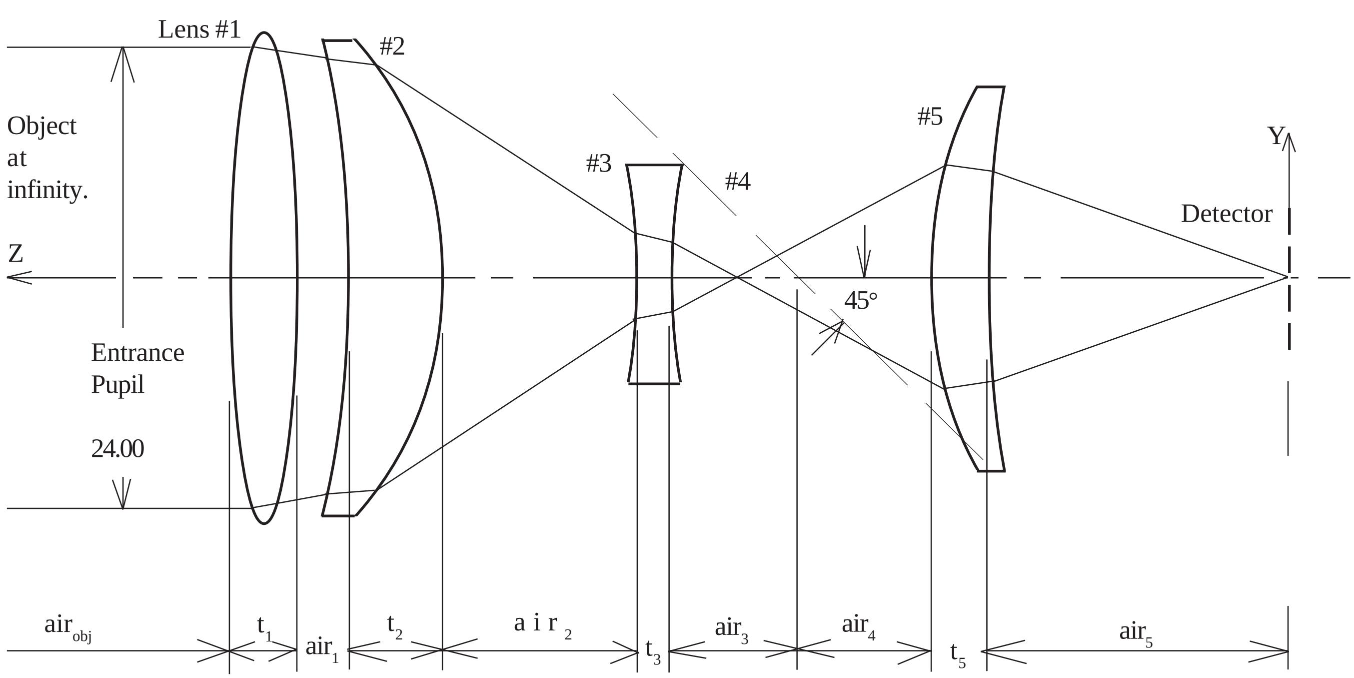
The user may copy IVORY26.EXE into as many directories as desired on the installation computer but the user may not run Ivory on more computers than permitted by the terms of the license agreement.

4.0 Overview of Ivory and its Operations

Ivory has two operating modes, PROJECT and SETUP.

4.1 PROJECT Operating Mode

This is Ivory’s basic operating mode in which it develops the OCE from the physical prescription data provided by the optical designer. These data are often available in the computer files used in the optical design activity and the files contain a lot more information than is necessary for the preparation of the OCE. The mechanical engineer will extract from the optical design files the data that defines the geometry of the optical system (thicknesses, radii, air spaces) and material properties (glass types and their real indexes of refraction). Since Ivory deals with the Gaussian properties only spherical (including flat) surfaces are used and aspheric terms in the physical prescription are ignored. An optical design for an infrared receiver with one fold mirror is shown below.



The physical prescription data for this lens as transcribed directly from a lens design code is shown here:

	Surface	Lens	Radius	Index	Thickness	ϕ
	1	obj.	inf.	1.0000	inf.	
	2	1	300.	4.0026	2.0000	
Physical	3	1	-300.	1.0000	5.3566	
	4	2	-110.	4.0026	3.4500	
Prescription	5	2	-55.	1.0000	17.7750	
	6	3	-310.	4.0026	2.0000	
Data	7	3	215.	1.0000	3.5	
	8	4	inf.	1.0000	-8.4417	45
	9	5	-11.	4.0026	-1.5000	
	10	5	-22	1.0000	-20.4727	
	11	det.	inf.	1.0000	0.0	

From these data the engineer prepares two files; one for the geometrical data and the other for the indexes of refraction data. The following sections show typical data files from the example project called "firrec." The geometric data is recorded in a file named *firrec.dat* and the index data is recorded in a file named *firrec.ind*. Project names are limited to eight characters.

4.1.1 Geometrical Data File

A typical geometric data file is shown in Table I (next page). Note the change in signs for the radii and the thickness to agree with OCE conventions based upon the element coordinate systems defined in the appendixes.

<u>Table I. Ivory's geometric data file for *firrec*</u>

Surf	Elem	Radius	Index	Thickness	Type	f1	f2	f3	f4
1	obj	inf	AIR	inf	obj	1.0			
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			
9	5	-11.	GE	1.5000	LENS				
10	5	-22.	AIR	20.4727	LENS				
11	det	inf	AIR	0.0	det				

The data file is formatted into ten vertical columns. The headings are shown in the Table. The widths of the first two columns are five characters each, the widths of the next three columns are eleven characters each, the width of the sixth column is five characters and the remaining four columns are each eleven characters wide. The first six columns are left-justified the final four are right justified.

Column 1, "Surf," 5 characters wide, left justified.
All the surfaces in the optical system are listed from the object, which is considered a surface, to the detector, also a surface. They are listed and numbered in the sequence in which the light from the object impinges on them.

Column 2, "Elem," 5 characters wide, left justified.
All of the elements are identified in the sequence in which the light impinges upon them. The first element is always the object and is entered in the table with the lower case abbreviation "obj." The final element is always the detector and is entered in the table with the lower case abbreviation "det." All of the other elements are numbered beginning with the number "1" and proceeding upward until all elements have been assigned a number. Cemented doublets and trip-

lets are considered to contain two and three elements respectively with a 0.0 thickness between them.

Column 3, “Radius,” 11 characters wide, left justified.
The radius (the reciprocal of the curvature, if that is how it is expressed in the physical prescription) of each surface is entered into this column from the physical prescription. Respect the sign convention for the particular type of optical element (this may be different than the sign assigned in the physical prescription listing). For the OCE sign conventions for elements see the Appendix for the element type concerned. For flat surfaces (infinite radius) enter the abbreviation “inf” in all lower case letters.

Column 4, “Index,” 11 characters wide, left justified.
An identifier, such as the glass type, is entered that corresponds to an entry in the material properties file. Ivory will retrieve the index of refraction from that file, repeat it in the physical prescription echo and use it to calculate the Gaussian properties of the elements. The identifier is case-sensitive and exactly the same form must be used in both files.

Column 5, “Thickness,” 11 characters, left justified.
The vertex thicknesses of all refractive materials (including air) are entered in this column. All real physical thicknesses are considered positive for the Ivory physical prescription. In lens design data files these thicknesses may be either positive or negative depending upon a number of other factors.

Column 6, “Type,” 5 characters, left justified.
A mnemonic is entered in this column to identify the type of element associated with each surface. The mnemonic must be capitalized (except for “obj” and “det”). The types of elements associated with each mnemonic are,

obj	object of the system
LENS	refractive lenses
MIRR	reflective mirror, flat or powered
WIND	flat refractive windows
PRIS	reflective prism
BSWI	beam splitter in transmission (as a window)
BSPR	beam splitter in reflection (as a prism)
PARA	general paraxial imaging element
det	detector of the system

Column 7, “f1,” 11 characters, right justified.
A scale factor may be entered here on the line for the object. This scale factor will be applied to all radii and thicknesses in the physical prescription. The default value is 1.0. The angle of incidence in degrees is entered here for flat fold mirrors, prisms, beams plitters (in reflection) and flat windows. The focal length is entered for paraxial elements. Observe the sign conventions for the appropriate elements.

Column 8, “f2,” 11 characters, right justified
The value of H1 is entered here for paraxial elements. The angle of rotation of the object (the previous element’s image) about its optical axis, Z_o, is entered for flat mirrors, prisms and beam splitters (in re-

flection). Observe the sign conventions for the appropriate elements.

Column 9, “f3,” 11 characters, right justified
The value of H2 is entered here for paraxial elements. Observe the sign conventions for the appropriate elements.

Column 10, “f4,” 11 characters, right justified
The value of p is entered here for paraxial elements. Observe the sign conventions for the appropriate elements.

The file is prepared as a text file. The file is then saved with the project name and the file extension *.DAT. In the sample project the file name is FIRREC.DAT.

4.1.2 Index Data File

A typical index data file is shown in Table II.

Table II. Ivory’s index data file for *firrec*

MATERIAL	INDEX
AIR	1.0000
GE	4.0026

This data file is formatted into two vertical columns. The headings are shown in the table. The width of the columns is eleven characters each and the entries are left justified in each column.

Column 1, “MATERIAL,” 11 characters, left justified.
This column contains an identifier for a material referenced in the “Index” column of the geometric data file. The identifier is case-sensitive and must be identical to the corresponding entry in the geometric data file.

Column 2, “INDEX,”11 characters, left justified.
This column contains the real index of refraction associated with the identifier referenced in the geometric data file. Relative indexes (the absolute index of the element’s material divided by the absolute index of the surrounding medium, usually air) are used throughout. Enter air with an index of unity (1.0).

The file is prepared as a text file. The file is then saved with the same project name as the geometric data file but with the file extension *.IND. In the sample project the file name is FIRREC.IND.

4.1.3 The Ivory Output File

The Ivory output is a text file organized into five sections. The first section is a “header” that identifies the software, the license holder, the date and time that the file was prepared and the user-assigned project name.

The second section is an echo of the user’s input data describing the physical prescription of the optical system. The data from both the *.DAT file of the geometry and the *.IND file of the refractive indexes are shown in this section. A quick review will indicate whether Ivory has properly interpreted the physical prescription data.

The third section presents the Gaussian (paraxial) imaging properties of the optical elements based upon the physical prescription data as echoed in the second section. Note that the air spaces here (P/AIR) are between principal points, not between vertexes. This section also presents the system’s Gaussian properties: F, H1, H2 and P.

The fourth section uses the paraxial imaging properties data from the third section to calculate the object distances and image distances for all of the elements in the system beginning at the system object. From these the magnification for each element is calculated. Note that the system's Gaussian image may not fall exactly on the detector unless the design is paraxially corrected by the optical designer. This section also prints the normalized deviation factions, e/Tzo, for all powered elements to assist the engineer to manage non-linearities (see 5.4).

The output for the first four sections of our example project, FIRREC, is shown below:

Output from -
IVORY Optomechanical Modeling Tools
Version 2.6
Copyright 2010, Alson E. Hatheway Inc.

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

PROJECT NAME: 'FIRREC' TIME AND DATE: 13:30:58 4-18-2010

PHYSICAL PRESCRIPTION ECHO

Surf	Elem	Radius	Index	Thickness	Type	f1	f2	f3	f4
1	obj	inf	1.0	inf	obj	1.0			
2	1	-300	4.0026	2	LENS				
3	1	300	1.0	5.3566	LENS				
4	2	110	4.0026	3.45	LENS				
5	2	55	1.0	17.775	LENS				
6	3	310	4.0026	2	LENS				
7	3	-215	1.0	3.5	LENS				
8	4	inf	1.0	8.4417	MIRR	-45			
9	5	-11	4.0026	1.5	LENS				
10	5	-22	1.0	20.4727	LENS				
11	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	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	0	MIRR
5	6.647026	.3399783	.6799567	1.160022	21.15266	0	0	LENS
det	0	0	0	0	0	0	0	det

SYSTEM -51.579024436 265.29314706 -72.045326963 381.36177262 -51.572623663

OBJECTS, IMAGES AND MAGNIFICATIONS

ELE	F	S	S'	M	PHI	THETA	TYPE	e/Tzo
obj	inf	0	0	+1.0000	0	0	obj	
1	50.08193	inf	-50.0819	0	0	0	LENS	+0.00D+00
2	34.98851	-42.8285	-19.2568	+0.4496	0	0	LENS	+1.29D-02
3	-42.16034	-2.0108	-2.1115	+1.0501	0	0	LENS	-2.49D-02
4	inf	+1.5926	+1.5926	+1.0000	-45	0	MIRR	
5	6.647026	+9.6943	-21.1463	-2.1813	0	0	LENS	-3.28D-01
det	inf	+6.38D-03	+6.38D-03	+1.0	0	0	det	

The final, and fifth, section of the output file is the Optomechanical Constraint Equations themselves. The equations are arranged vertically with the seven Gaussian image registration variables across the top and all of the element degrees of freedom down the left-hand side. On the far right-hand side are the focal length and principal thickness sensitivities for each of the elements.

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	+1.02990	0.0	0.0	0.0	0.0	0.0	0.0	+0.06277	Dt
Ty	0.0	-1.02990	0.0	0.0	0.0	0.0	0.0	-0.08326	DR1
Tz	0.0	0.0	+1.06069	0.0	0.0	0.0	-0.06534	+0.08326	DR2
Rx	0.0	-1.54389	0.0	-1.02990	0.0	0.0	0.0	-16.66907	Dn
Ry	-1.54389	0.0	0.0	0.0	+1.02990	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	-1.06069	0.0	0.0	0.0	+0.08531	0.0	
ELEMENT-1									
Tx	+1.26067	0.0	0.0	0.0	0.0	0.0	0.0	-0.45577	Dt
Ty	0.0	-1.26067	0.0	0.0	0.0	0.0	0.0	-0.28949	DR1
Tz	0.0	0.0	+4.18599	0.0	0.0	0.0	-0.32143	+1.24372	DR2
Rx	0.0	-6.01684	0.0	-1.26067	0.0	0.0	0.0	-11.78357	Dn
Ry	-6.01684	0.0	0.0	0.0	+1.26067	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	-1.58928	0.0	0.0	0.0	+0.13289	0.0	
ELEMENT-2									
Tx	-0.10925	0.0	0.0	0.0	0.0	0.0	0.0	+0.06007	Dt
Ty	0.0	+0.10925	0.0	0.0	0.0	0.0	0.0	-0.05592	DR1
Tz	0.0	0.0	-0.48854	0.0	0.0	0.0	+0.05860	+0.11602	DR2
Rx	0.0	-3.27579	0.0	+0.10925	0.0	0.0	0.0	+14.05127	Dn
Ry	-3.27579	0.0	0.0	0.0	-0.10925	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	-0.01193	0.0	0.0	0.0	+2.011E-03	0.0	
ELEMENT-3									
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	-3.08485	-6.72902	0.0	0.0	0.0	+0.46409	0.0	DR2
Rx	0.0	-6.94775	0.0	+4.36263	0.0	0.0	0.0	0.0	Dn
Ry	-4.91280	0.0	0.0	0.0	-3.08485	+1.41421	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									
Tx	+3.18131	0.0	0.0	0.0	0.0	0.0	0.0	-0.41124	Dt
Ty	0.0	+3.18131	0.0	0.0	0.0	0.0	0.0	-1.15247	DR1
Tz	0.0	0.0	-3.75813	0.0	0.0	0.0	+0.32816	+0.24606	DR2
Rx	0.0	+1.16002	0.0	+3.18131	0.0	0.0	0.0	-2.26508	Dn
Ry	-1.16002	0.0	0.0	0.0	+3.18131	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	-10.12076	0.0	0.0	0.0	+0.47861	0.0	
ELEMENT-5									
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 'FIRREC'.

4.2 SETUP Operating Mode

In the SETUP operating mode Ivory presents the user with other utilities that may be found helpful. These are accessed at the prompt for a project name by typing "SETUP" and pressing "Enter." The user will be offered six choices:

DATA INPUT (D)
ZERO THRESHOLD (Z)
UNIFIED OPTOMECHANICAL MODEL (U)
FOCAL LENGTH CALCULATIONS (F)
INDEX OF THE MEDIUM (M)
EXTENDED PRECISION FILES (E)

The user makes the choice by entering the appropriate code letter, indicated in parenthesis. Except for the first choice, DATA INPUT (D), the user may re-enter the SETUP mode to choose more than one option for a particular PROJECT run in Ivory.

Note that SETUP is a reserved project name in Ivory.

4.2.1 DATA INPUT (D)

In this utility the user is permitted to directly input the physical prescription data into Ivory and the program will automatically format and store the appropriate files. The user is prompted to input a project name for the files and then to prepare either a *.DAT geometric data file or a *.IND index of refraction file. The user is then prompted to input the appropriate information.

In the case of the geometric data file the user is taken surface-by-surface and column-by-column through the physical prescription. Ivory fills in all of the information for the “object” except for the thickness to the first vertex of the first element, which the user must supply and a desired scale factor in column f1. Ivory then goes to the second surface and requests input for each of the columns from the second to the tenth (Ivory automatically enters the surface number in the first column). After the last optical surface the user presses “Enter” at the request for the next surface and Ivory automatically enters the appropriate data for the detector, saves the file and closes it. The Command Prompt window is closed and the user is returned to Windows Explorer. The user may then review and edit the *.DAT file in any word processor.

To prepare an index of refraction file the user reopens Ivory by double-clicking on IVORY26.EXE, entering “SETUP” as the project, selecting DATA INPUT (D), entering the desire project name and entering “I” for the *IND type of file. Ivory will automatically enter “AIR” in the file with an index of refraction of 1.0. The user will then be prompted to enter the other glass types and their indexes of refraction. A blank entry for the next glass type will end the file preparation. Ivory will save the file under the desired project name and close the file. The Command Prompt window is closed and the user is returned to Windows Explorer. The user may then review and edit the *.IND file in any word processor.

4.2.2 ZERO THRESHOLD (Z)

The coefficients of the OCE printed in the *.OUT file are the result of a great many numerical calculations. The possible magnitudes of some of the intermediate numerical values make round-off and truncation errors inevitable in the resulting coefficients. Consequently, some coefficients that should be 0.0 may turn out to have small but finite values on the order of 10^{-10} to 10^{-25}. These computational artifacts are called "computational zeros." If a multitude of these computational zeros are reported in the OCE they may make it difficult to read and interpret the output file.

Ivory offers a utility to control the printing of computational zeros in the OCE. At the initial prompt for a project name the user enters "SETUP" and selects ZERO THRESHOLD (Z). The user will then be prompted to input a threshold value for the printing of small coefficient values. The user may input any value he wishes and all coefficients with absolute values (±) smaller than that threshold will be printed as 0.0 in the OCE (and in the *.NAS file if the UNIFIED OPTOMECHANICAL MODEL option is also selected for the run). The threshold may be set to a value as small as 0.0. The default value of the threshold is 0.0.

After the zero threshold is set the user is returned to the INPUT PROJECT NAME prompt. The user may then input the project name to be analyzed. This threshold value will be echoed in the header for the fifth section, "OPTOMECHANICAL CONSTRAINT EQUATIONS," of the output file.

The threshold value does not affect the computational process, only the printing of coefficients in the *.OUT and *.NAS files. The user may wish to try several different values for the threshold and review the results to assure that he is not suppressing useful information.

4.2.3 UNIFIED OPTOMECHANICAL MODEL (U)

It is often useful to incorporate the Optomechanical Constraint Equations (OCE) into a finite element model to allow the finite element code to calculate the registration errors at the detector. This is especially true in dynamic problems where many time steps or frequency increments may be involved in the analysis. If the user selects UNIFIED OPTOMECHANICAL MODEL (U) from the SETUP menu Ivory will prepare a separate file using the project name and the *.NAS file extension in the subsequent project run. This file echoes the optical path geometry, element geometry and the OCE coefficients in standard Nastran card format and can be directly copied into a Nastran finite element model to calculate the image motions. The user may view and edit the *.NAS file in any word processor.

The *.NAS file contains three sections: 1) the Case Control section contains the necessary calls for the MPC and SPC sets in the Bulk Data; 2) the necessary MPC data cards in the Bulk Data representing the Optomechanical Constraint Equations; 3) the geometric data including a GRID for the first principal points for each optical element (plus the object and detector), its positioning coordinate system (CORD2R) along the optical axis and its local element coordinate system (CORD2R) used in calculating displacements and registration errors in the OCE.

The MPC coefficients entered in the *.NAS file will honor any previously set zero threshold for the analysis (set the zero threshold before selecting the "U" option).

Ivory permits the engineer to specify the lowest number to be assigned to both the GRID and CORD2R cards in the NASTRAN model. While Ivory is preparing the model data the user will be asked (in the Command Prompt Window) to specify the lowest number to be used. The default value of 1 will be used if nothing is entered.

The GRID numbers will be assigned in the following order, beginning at the specified lowest number: first the first principal points of the optical elements will be assigned GRID numbers in ascending order (by element number); second the detector will be assigned a GRID number; third the object will be assigned a GRID number and finally the dependent degrees of freedom in the MPC set will be assigned two GRID numbers. The total number of GRID numbers assigned by Ivory will be equal to the number of optical elements plus the four noted above.

Every element plus the object and the detector gets two CORD2R cards assigned to it. One CORD2R card is for the element coordinate system and the other CORD2R card orients the element along the optical axis. So there are generally about twice as many CORD2R numbers used as GRID point numbers. The user should consider this when deciding the lowest number to be used.

The numbering of the CORD2R cards begins with the lowest number specified by the user, the same number as the lowest GRID point number.

The numbers assigned to the CORD2R cards for the element coordinate systems are the same as the numbers for the GRID points of the elements' first principal points. The numbers assigned to the CORD2R cards for orienting the elements along the optical axis are higher than those assigned to the element coordinate systems by the number of elements plus one (to provide for the detector). The object does not require an orienting coordinate system for subsequent elements.

All the geometry (GRIDs and CORD2Rs) are referenced to the detector, which is located at (0., 0., 0.) in the basic coordinate system. By appropriately defining the position and orientation of the detector the Nastran analyst may bring the optical model into congruence with his elastic model.

A sample *.NAS file is shown below:

```
NASTRAN MESH
CEND
TITLE=FIRREC'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  5 /123456 ARE ASSIGNED TO THE OPTICAL ELEMENTS IN ASCENDING ORDER.
$  6 /123456 ARE ASSIGNED TO THE SYSTEM DETECTOR.
$  7 /123456 ARE ASSIGNED TO THE SYSTEM OBJECT.
$  8 /123456 ARE ASSIGNED TO THE REGISTRATION VARIABLES TX, TY, TZ, RX, RY, RZ.
$  9 /1 IS ASSIGNED TO THE REGISTRATION VARIABLE DM/M.

GRID    8                0.      0.      0.
GRID    9                0.      0.      0.

MPC     1000    8       1       -1.     1       1        1.0299
                1       5       -1.543892       1        1.26067
                2       5       -6.016843       1       -.10925
                3       5       -3.275794       5       -4.9128
                5       1        3.181315       5       -1.16002
                6       1       -1.

MPC     1000    8       2       -1.     1       2       -1.0299
                1       4       -1.543892       2       -1.26067
                2       4       -6.016843       2        .10925
                3       4       -3.275794       3       -3.08485
                4       4       -6.947755       2        3.18131
                5       4        1.160026       2       -1.


MPC     1000    8       3       -1.     1       3        1.06069
                2       3        4.185993       3       -.48854
                4       3       -6.729025       3       -3.75813
                6       3       -1.

MPC     1000    8       4       -1.     1       4       -1.0299
                2       4       -1.260673       4        .10925
                4       4        4.362635       4        3.18131
                6       4       -1.

MPC     1000    8       5       -1.     1       5        1.0299
                2       5        1.260673       5       -.10925
                4       5       -3.084855       5        3.18131
                6       5       -1.

MPC     1000    8       6       -1.     4       5        1.41421
                6       6       -1.

MPC     1000    9       1       -1.     1       3       -.06534
                2       3       -.32143 3       3        .0586
                4       3        .46409 5       3        .32816


SPC     1000     9      23456

$ DETECTOR
$ PRINCIPAL POINT
```

```
GRID    6       6       0.      0.      0.      6
$ DETECTOR COORDINATE SYSTEM
CORD2R  6       0       0.      0.      0.      0.      0.      1.
        1.      0.      0.
$ INCIDENT OPTICAL AXIS COORDINATE SYSTEM
CORD2R  12      0       0.      0.      0.      0.      0.      1.
        1.      0.      0.

$ ELEMENT 5
$ FIRST PRINCIPAL POINT
GRID    5       12      0.      0.      22.312 5
$ ELEMENT COORDINATE SYSTEM
CORD2R  5       12      0.      0.      22.312  0.      0.      23.312
         1.      0.      22.312
$ INCIDENT OPTICAL AXIS COORDINATE SYSTEM
CORD2R  11      12      0.      0.      22.312  0.      0.      23.312
         1.      0.      22.312

$ ELEMENT 4
$ FIRST PRINCIPAL POINT
GRID    4       11      0.      0.      8.101  4
$ ELEMENT COORDINATE SYSTEM
CORD2R  4       11      0.      0.      8.101   0.      .707    7.394
        -1.      0.      8.101
$ INCIDENT OPTICAL AXIS COORDINATE SYSTEM
CORD2R  10      11      0.      0.      8.101   0.      1.      8.101
        -1.      0.      8.101

$ ELEMENT 3
$ FIRST PRINCIPAL POINT
GRID    3       10      0.      0.      5.205  3
$ ELEMENT COORDINATE SYSTEM
CORD2R  3       10      0.      0.      5.205   0.      0.      6.205
         1.      0.      5.205
$ INCIDENT OPTICAL AXIS COORDINATE SYSTEM
CORD2R  9       10      0.      0.      5.205   0.      0.      6.205
         1.      0.      5.205

$ ELEMENT 2
$ FIRST PRINCIPAL POINT
GRID    2       9       0.      0.      19.872 2
$ ELEMENT COORDINATE SYSTEM
CORD2R  2       9       0.      0.      19.872  0.      0.      20.872
         1.      0.      19.872
$ INCIDENT OPTICAL AXIS COORDINATE SYSTEM
CORD2R  8       9       0.      0.      19.872  0.      0.      20.872
         1.      0.      19.872

$ ELEMENT 1
$ FIRST PRINCIPAL POINT
GRID    1       8       0.      0.      8.752  1
$ ELEMENT COORDINATE SYSTEM
CORD2R  1       8       0.      0.      8.752   0.      0.      9.752
         1.      0.      8.752
$ INCIDENT OPTICAL AXIS COORDINATE SYSTEM
CORD2R  7       8       0.      0.      8.752   0.      0.      9.752
         1.      0.      8.752

$ OBJECT AT INFINITY AND NOT MODELED

$                  MODEL PREPARED BY IVORY(TM) OPTOMECHANICAL MODELING TOOLS
$                                      Version 2.6
$                                 FOR Alson E. Hatheway Inc.
$                             PROJECT NAME:  'FIRREC'
$                                  10-22-2010  15:26:15
$                        ALSON E. HATHEWAY INC., http://www.aehinc.com

ENDDATA
```

4.2.4 FOCAL LENGTH CALCULATIONS (F)

At the end of the GAUSSIAN PRESCRIPTION section Ivory reports the Gaussian properties (F, H 1, H2, P and P/AIR) of the entire optical system as a single imaging element. These system properties are calculated from the properties of the individual elements in the prescription using the doublet formulation (Smith, 1990, p43). This method first combines elements 1 and 2 as a doublet into an equivalent single lens 1-2. Then this lens 1-2 and lens 3 as a doublet are combined into lens 1-3. This process is repeated until all the elements in the system (of say n optical elements) are combined into a single element (identified as element 1-n). The properties of this final calculation are the SYSTEM properties that are normally printed in the output file at the bottom of the GAUSSIAN PRESCRIPTION section. If the user chooses the F option in SETUP all the intermediate properties will be printed out as shown below:

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	0	MIRR
5	6.647026	.3399783	.6799567	1.160022	21.15266	0	0	LENS
det	0	0	0	0	0	0	0	det

ELEMENTS	F	H1	H2	P	P/AIR	BA	BB
1—1	50.08193	-.2504639	.2504639	1.499072	7.25347		
1—2	22.518123085	-4.9186972788	2.4381432627	3.4497590584	20.507346562	17.849889706	-19.256776523
1—3	23.645879139	6.5829708358	21.738444401	15.426124134	25.238444601	35.147547253	-2.1114805376
1—4	23.645879139	6.5829708358	25.238444601	15.426124134	33.340166601	23.645879139	1.5925654623
1—5	-51.579024436	265.29314706	-72.045326963	381.36177262	-51.572623663	207.13115179	-21.146259226

The properties for ELEMENTS 1-5 are the same as those reported for the SYSTEM if the F option is not selected. In this latter case the BA and BB properties are not printed (see Figure 6).

4.2.5 INDEX OF THE MEDIUM (M)

The index of refraction data input to Ivory are relative values, i.e. the absolute index of refraction of the material divided by the absolute index of refraction of air at 20 degrees C and one atmosphere of pressure (the “reference” value). The absolute value of air’s index of refraction at these conditions is assumed to be 1.000292.

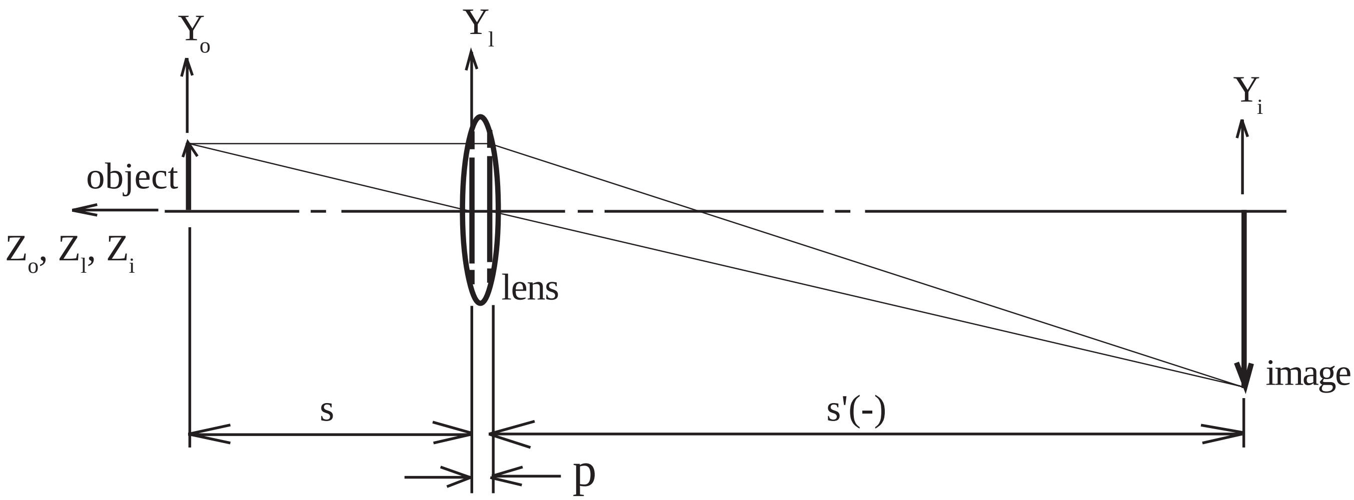
This utility allows the user to input a different “reference” value for the index of refraction for the medium around the elements. New “relative” values of the indexes of refraction are calculated for all the materials in the input data file and are reported in the project's output file. The requested reference value is also reported at the bottom of the PHYSICAL PRESCRIPTION ECHO in the project's output file.

4.2.6 EXTENDED PRECISION FILES (E)

The number of significant figures printed in the output file, and the Nastran model if the Unified Modeling option is selected, is limited by the format of the files. This option produces a separate file, *.COE, that prints out all of the influence coefficients in the OCE to full machine precision. If the Unified Modeling option has been selected it will also print out a separate file, *.GEO, of the Nastran geometry for the coordinate systems and the locations of the principal points in those coordinate systems.

5.0 Influence Functions in Optical Imaging

5.1 Optical Imaging

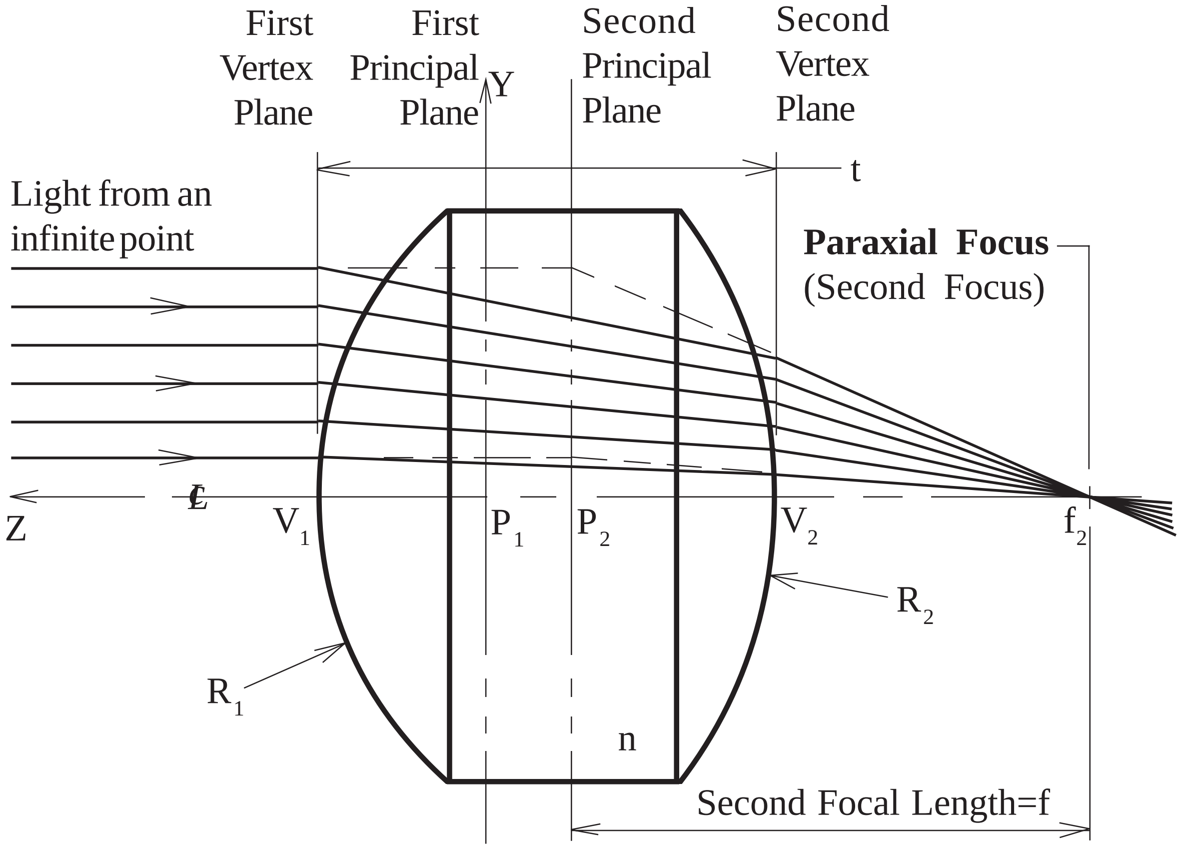


The position of the Gaussian image of a lens is given by Gauss' Law,

$$1/s - 1/s' = 1/f \tag{5.1}$$

where s is the object distance (from the lens to the object), s' is the image distance (from the image to the lens) and f is the focusing property of the lens (the focal length). Gauss' Law is congruent with the first order terms in the expansion of the ray aberration polynomial assuming appropriate cylindrical and dihedral symmetry conditions (Smith, 1990).

This formulation of the imaging law assumes a flat object plane being imaged onto a flat image plane. It also assumes that the positive direction along the optical axis is from the image to the object. Although this arangement seems to be natural for mechanical engineers it is opposite to the sense of frequently used lens design conventions.



For a refractive lens that is defined by two radii, R_1 and R_2, a thickness, t, and an index of refraction, n, its paraxial Gaussian imaging properties are defined by its focal length, f, the distance, H_1, from the first vertex, V_1, to the first principal point, P_1, the distance, H_2, from the second vertex, V_2, to the second principal point, P_2, and the principal thickness, p (the distance from the second principal point to the first principal point). The four physical prescription properties of a lens (R_1, R_2, t and n) and the four paraxial Gaussian properties of a lens (f, H_1, H_2 and p) are completely complementary descriptions of its imaging properties. These paraxial Gaussian properties of a lens may be determined from the physical prescription by the equations (Hatheway, *Optomechanics and the Tolerancing of Instruments*),

$$1/f = (n - 1)[1/R_2 - 1/R_1 + t(n - 1)/nR_1R_2] \quad 5.2$$

$$H_1 = Z(P_1) - Z(V_1) = -ft(n - 1)/nR_2 \quad 5.3$$

$$H_2 = Z(P_2) - Z(V_2) = -ft(n - 1)/nR_1 \quad 5.4$$

$$p = t[1 - f(n - 1)(1/R_2 - 1/R_1)/n]. \quad 5.5$$

Gaussian imaging properties may also be calculated for other zones of the lens than the paraxial zone (*ibid.*).

The sign conventions for the Optomechanical Constraint Equations (OCE) are based upon the coordinate systems for the individual optical elements. These conventions and coordinate systems may be different than those used by the lens designer. The object, the element and the image may each have different coordinate systems. For the refractive lens the element's coordinate system has its origin at the first principal point, P_1, and its Z axis is along the optical axis toward the source of light. The element's Y axis is up (assuming the optical axis is horizontal and the object is to the left in the view) and its X axis completes a right-handed coordinate system. The object's coordinate system has its origin on the optical axis in the object plane. The object's coordinate axes are parallel to the lens' coordinate axes. The image's coordinate system has its origin on the optical axis in the image plane and its coordinate axes are also parallel to the lens' coordinate axes. These conventions are shown graphically in Appendix B. The conventions for other types of optical elements are shown in the other appendixes.

Gauss' Law, equation 5.1, defines a linear transformation between points in the object's XY plane and points in the image's XY plane. The coefficient for this transformation is the magnification, M, and is equal to the image distance divided by the object distance,

$$M = s'/s. \qquad 5.6$$

The object distance is the distance (in the object coordinate system) from the first principal point, P_1, to the object. The image distance is the distance (in the image coordinate system) from the second principal point, P_2, to the image.

Gauss's Law, equation 5.1, also defines a non-linear relationship between the image distance and the object distance along the optical axis

$$s' = 1/(1/s - 1/f). \qquad 5.7$$

The above expressions, 5.1 through 5.7, allow us to calculate the position, orientation and size of an image if we know the position, orientation and size of the object and the position, orientation and imaging properties of the lens. In as much as the image of one lens is the object for the next one, these expressions also permit us to calculate the position, orientation and size of the image created by a system of any number of lenses.

All of the above is basic optical imaging and imaging systems would not be possible if the above were not true. A lens designer deals with all of this, plus a lot more (aberrations, color, coherence, materials, polarization, etc., etc...).

For the optomechanical engineer it is convenient to reformulate the above expressions to be able to express the *changes* in position, orientation and size of an image based upon the *changes* in position, orientation and size of the object and *changes* in position, orientation and focal length of each of the optical elements in the system. The optimal operating conditions have already been established by the lens designer and any deviations from his prescription will, most likely, result in misalignment of the system and loss of performance. The task of the optomechanical engineer is to limit these likely effects to acceptable levels. This requires the development of the *influence functions* that relate the *changes* in the image due to the *changes* in the object and the *changes* in the elements.

5.2 Influence Functions

The influence functions for a lens must accommodate six degrees of freedom (DOFs) for the object (Tx_o, Ty_o, Tz_o, Rx_o, Ry_o and Rz_o) and seven degrees of freedom for the lens (Tx_l, Ty_l, Tz_l, Rx_l, Ry_l, Rz_l and Δf). The translation and rotation DOFs are in the local coordinate systems. The Δf represents a change in focal length that may be caused by changes in glass type, changes in index of refraction with temperature or variations in dimensions (as with tolerances) or a combination of all of these.

As mentioned above the points in the object plane map onto the points of the image plane with a coefficient equal to the magnification, M. Therefore, if we identify the DOFs of the image with the subscript “i” and the object with the subscript “o,”

$$Tx_i/Tx_o = M \qquad 5.8$$
$$Ty_i/Ty_o = M \qquad 5.9$$

and it follows that,

$$Rx_i/Rx_o = M \qquad 5.10$$
$$Ry_i/Ry_o = M. \qquad 5.11$$

Furthermore, if one rotates the object about its Z axis the image will also rotate the same amount about its Z axis so that,

$$Rz_i/Rz_o = 1.0. \quad 5.12$$

The subscripts refer to the image and object respectively. These five *influence functions* are linear expressions that describe the image's motions. They are fully defined by their *influence coefficients*, either M or 1.0 depending upon the expression.

As mentioned above the relationship along the optical (Z) axis is non-linear, equation 5.7, so when we have a small axial displacement of the object, Tz_o, the *influence function* becomes,

$$Tz_i/Tz_o = M^2/(1 - MTz_o/f). \quad 5.13$$

This is a non-linear function (Tz_o is on both sides). The relative magnitude of the non-linearity is described by the second term in the denominator, $-MTz_o/f$. If this term is acceptably small compared to 1 then the function may be represented, to acceptable accuracy, by its numerator, M^2. The term in the numerator of this function is called the *influence coefficient* for this function. The second term in the denominator is called the *deviation fraction* for this function and is represented symbolically by "e." The *deviation fraction* quantifies the deviation of a linear solution using the *influence coefficient*, M^2 in this case, from the true non-linear solution using the full *influence function*.

It will be convenient to define a generalized *influence function*, IF, such that

$$[IF] = C/(1+e) \quad 5.14$$

in which C represents the *influence coefficient* and e represents the *deviation fraction*. Most of the non-linearities in Gaussian imaging conveniently fit this functional form. It permits the linear and non-linear contributors to be separated and handled separately. This in turn simplifies the calculations of the image's position, orientation and size while assuring that the effects of non-linearities may be evaluated and accommodated appropriately.

Returning to the Z axis motion of the object, this will also cause a change in magnification of the lens and a corresponding change in size for the image. Let us define the change in size of the image as the change in magnification, ΔM, caused by the object's motion divided by the original magnification, M. The *influence function* then becomes

$$\Delta M/MTz_o = M/[f(1 + MTz_o/f)]. \qquad 5.15$$

The *influence coefficient* is M/f and the *deviation fraction* is MTz_o/f.

The influence functions for the motions of the lens itself may be developed in a fashion similar to that used for the object motions.

The lens displacements contain a seventh DOF, the change in focal length, Δf. The *influence coefficients* relating the lens design variables to the focal length are the first partial derivative of the lens' focal length to each of the lens design variables in the lens equation, Eq. 5.2. The *deviation fractions* for the lens design variables' influences on the focal length do not conveniently fit the functional form. It is recommended that non-linearities in the lens design variables be evaluated in a spreadsheet using the full lens equation.

A number of elements, such as the flat mirror, have no *deviation fractions* because they are completely linear.

5.3 The Optomechanical Constraint Equations (OCE)

The OCE are developed from the arrays of influence coefficients for the individual optical elements (Element Arrays). This is performed by taking each of the arrays for each of the elements in the system through all of the Object Arrays between them and the detector, including the detector. This process treats the image of each optical element as the object for the next optical element all the way through the system.

The result is seven equations, one for each of the registration variables (degrees of freedom), which are motions of the image with respect to the detector (Tx, Ty, Tz, Rx, Ry, Rz, ΔM/M). Each of the seven equations contains a term for each of the element displacement degrees of freedom (Tx_l, Ty_l, Tz_l, Rx_l, Ry_l, Rz_l, Δf, etc.) and for the object as well.

Since all the coordinate systems are right-handed the process passes a right handed image system from one element to a right handed object system for the next element. Establishing the orientation of any one element coordinate system therefore establishes the coordinate systems for all of the elements in the system.

5.4 Evaluating Effects of Non-linearities

As explained above, Gaussian imaging provides an exact linear mapping of an object plane onto an image plane. The OCE preserve that exact linear relationship between objects and images including all of the intermediate images in a system. Non-linearities occur only when the object or the elements are moved along the Z axis or when a focal length is changed. These non-linearities affect both the Z axis position of the image and the size of the image.

The deviation fractions determine the magnitude of the influence of these non-linearities. If the deviation fraction is small its effect on the calculated registration variable will be comparably small.

Example:
If a lens is working at a magnification of 2.3, has a focal length of 35 mm and may be subject to a tolerance or displacement in the Z direction of 25 microns the image motion is calculated to be

$$Tz_i = 25(1 - 2.3^2) = -107.25 \text{ microns}$$

and the deviation fraction, from the denominator of equation 5.13, is

$$e = -MTz_o/f = -(2.3)(.025)/35 = -0.00164.$$

That is, its image motion may be calculated to an accuracy of 0.164% (176 nm) for disturbances that are 25 microns in size. The sign indicates that the linear assumption leads to a smaller value (larger negative value) than the true non-linear value. Since the deviation fraction is proportional to the displacement the absolute value of the deviation (176 nm in this case) is proportional to the square of the displacement. If the lens motion is reduced to 12.5 microns the deviation will be 42 nm.

It is important to note at this point a distinction between optical design accuracies based upon, possibly, meter-sized dimensions of radii and/or air spaces and mechanical engineering accuracies based upon sub-millimeter displacements and deflections. The mechanical engineer's deflections are typically 3 to 6 orders of magnitude smaller than the principal dimensions of the optical elements determined by the optical designer. Therefore, the relative error expressed as a percent may be correspondingly larger for mechanical displacements than for optical dimensions in the physical prescription (witness the example above).

The deviation fractions provide the optomechanical engineer with a tool for assessing the impact of linear assumptions for non-linear behavior. The magnitudes of the deviation fractions depend upon the magnitudes of the displacements for the degrees of freedom of interest. Since the displacements are not available to Ivory, the deviation fractions themselves cannot be calculated in the output file. But a "normalized deviation fraction" may be defined as the deviation fraction, e, divided by the displacement, e/Tz_o, such that

$$e/Tz_o = M/f. \tag{5.16}$$

This value may be calculated from the data in Ivory and is printed in the fourth section of the output file "OBJECTS, IMAGES AND MAGNIFICATIONS." The normalized deviation fraction provides the engineer a tool to manage the non-linearities in the image's behavior.

6.0 Optomechanical Modeling Topics

6.1 Angles of Incidence and Rotation

Folded optical instruments are accommodated by specifying angles of incidence and rotation for flat mirrors, prisms and beam splitters (acting as prisms). The angles are defined by the orientation of the object with respect to the element. The angle of incidence, Φ, is positive if the sense of the object's Z axis is rotated in the sense of the object's Y axis into the its Z axis (right handed). The angle of rotation, Θ, is positive if the object is rotated about its own Z axis in the sense of the object's X axis into its Y axis (right handed).

6.2 The Internal Collimation Singularity

If the physical prescription data causes collimated light conditions in the optical path (indicated by infinitely distant images) Ivory will not complete the OCE and will present an error message in the Command Prompt window. This is caused by the fact that the collimating element will have an infinite magnification,

M = infinite

and the infinite magnification value will cause an overflow condition in the mathematical processor. There are two possible work-arounds for this computational problem.

The first is to adjust the air space preceding the collimating element just enough to break up the condition of collimation. This can usually be accomplished without materially affecting the accuracy of the coefficients in the OCE. The user may verify the accuracy of the coefficients by trying several different small adjustments to the air space.

The second is to combine both the collimating lens and the de-collimating lens into a doublet. The paraxial properties of the doublet may be determined by submitting the doublet to Ivory as a separate prescription. These paraxial properties may be substituted via the PARA element, see Appendix I, for the two elements in the physical prescription data. This method eliminates the use of the magnification, M, of the collimating element in the calculations. It can also be used to verify the accuracy of the other coefficients calculated by the first method.

6.3 Local Coordinate Systems

Each optical element has its own local coordinate system. Its origin is at the first principal point of the element. Its X-Y plane is in the plane of the first principal point and the positive Z axis is on the side of the incident light. This is a right-handed coordinate system.

The object and the image also have local coordinate systems that are aligned to the element coordinate system. Their Z axes are along the optical axis and positive toward the light. Their Y axes lie in the plane of incidence at the element and are positive on the same side of the optical axis as the element's Y axis. Their X axes complete right-handed coordinate systems.

6.4 Sign Conventions

1. Index of Refraction, n:

The material property of a lens that contributes to its focusing property.

The index of refraction of a vacuum is 1.0; all other materials having larger indexes.

2. Surfaces, S_1, S_2:

The geometric features (assumed to be spherical) of a lens that contribute to its focusing property. They are subscripted in the sequence that light passes through them.

3. Centers of Curvature, C_1, C_2:

The points in space that are the centers of the spherical surfaces. The centers of curvature derive their subscripts from their associated surfaces.

4. Optical Axis:

The straight line defined by the centers of curvature of the spherical surfaces.

5. Vertices, V_1, V_2:

The points of intersection of the optical axis and the spherical surfaces. The vertices derive their subscripts from the associated surfaces.

6. Radii of Curvature, R_1, R_2:

The distances from vertices to their centers of curvature. The radii of curvature derive their subscripts from the associated surfaces. Note that the sense (+ or -) of each radius of curvature is the same as the sense (+ or -) of the Z axis value at the radius' center of curvature.

7. Thickness, t:

The distance between two surfaces in an optical prescription. The physical thickness is always positive.

8. Focal points, f_1, f_2:

Points on the optical axis at which infinite points (also on the optical axis) are imaged. All lenses have two focal points: the first is associated with an object point that is infinitely far away along the negative Z axis and the second is associated with an object point that is infinitely far away along the positive Z axis.

9. Principal Points, P_1, P_2:

Points on the optical axis at which the focusing property of the surfaces of a lens may be assumed to be concentrated. All refractive elements have two principal points.

The Z axis distance from a vertex to the associated principal point may be calculated from:

$$H_1 = Z_{P1} - Z_{V1} = -ft(n-1)/nR_2$$
$$H_2 = Z_{P2} - Z_{V2} = -ft(n-1)/nR_1$$

Reflective elements have only one principal point located at the element's vertex.

10. Principal Thickness, p:

The distance from the second principal point to the first principle point.

The principal thickness is usually positive but if

$$-1 > t/(R_2 - R_1) > -n/(n-1)$$

then p will be negative and P_1 and P_2 will be in reversed order.

11. Focal Length, f:

The distance from the first principal point to the first focal point. Positive lenses have positive focal lengths and negative lenses have negative focal lengths. The equation for the focal length is,

$$1/f = (n - 1)[1/R_2 - 1/R_1 + t(n - 1)/nR_1R_2] .$$

12. A Doublet's First Focus, Ba:

In a doublet, the distance from the first element's first principal point to the doublet's first focal point.

13. A Doublet's Second Focus, Bb:

In a doublet, the distance from the second element's second principal point to the doublet's second focal point.

6.5 Model Validation

1. Ivory's Gaussian system focal length should be the same as the paraxial focal length calculated by the lens design code.

2. Ivory's Gaussian system focal length should be close to the effective focal length determined by the lens design code if the optical

design is paraxially well corrected (this is a measure of quality of the paraxial correction).

3. If the system's object is at infinity the image's initial focus error at the detector (the S' value at the detector in the OBJECTS, IMAGES AND MAGNIFICATIONS section of the output file) should be equal to the difference between the lens design code's effective focal length and its paraxial focal length.

4. If the system's object is at infinity (and therefore not included in the model) and the model is rotated one radian about X or Y (in object coordinates) the image's motion on the detector will be equal to Ivory's paraxial focal length. The sense (+ or -) of the motion depends upon the coordinate transformations between the object and the detector but the two will be of opposite sense. If the model is rotated one radian about Z (in object coordinates) the image rotation at the detector will be ±1, the sense depending upon the coordinate transformations between the object and the detector. These results will be true in both Nastran and Excel.

5. If the system's object included in the model (at any distance except infinity) and the model (including the object) is rotated about X, Y or Z image's motion on the detector will be zero. These results will be true in both Nastran and Excel.

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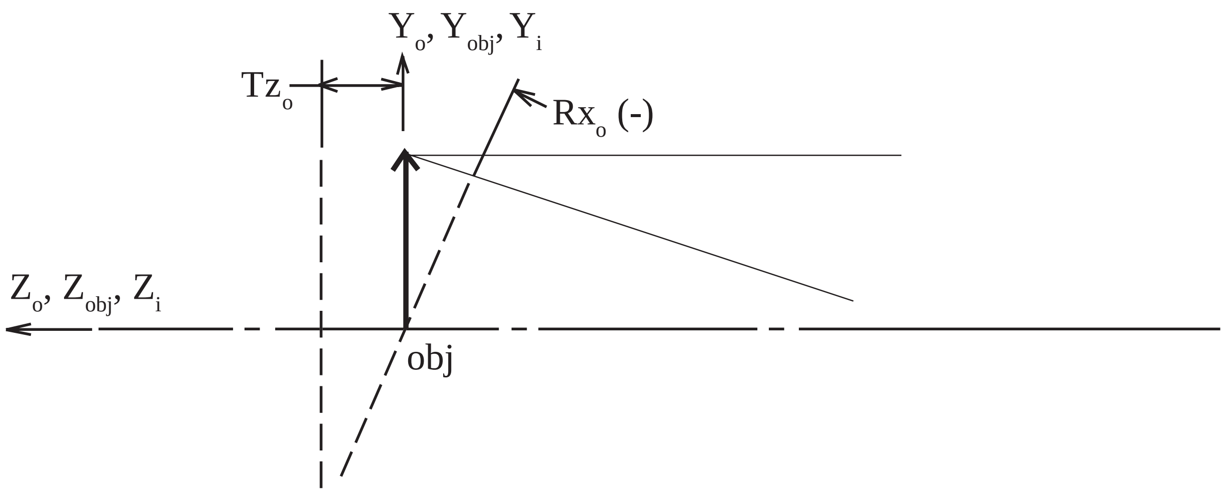
APPENDIX A
The Object's Coordinate System



The object's three coordinate system are congruent.

The object's coordinate systems have their origins at the point where the object crosses the optical axis, their positive Z axes are opposite the light from the object to the first optical element and their Y axes are up. The X axes complete right-handed coordinate systems.

Although the system object has its own line in the physical prescription, its properties are usually treated as the object of the first optical element in the system

APPENDIX A
The Object's Prescription Conventions

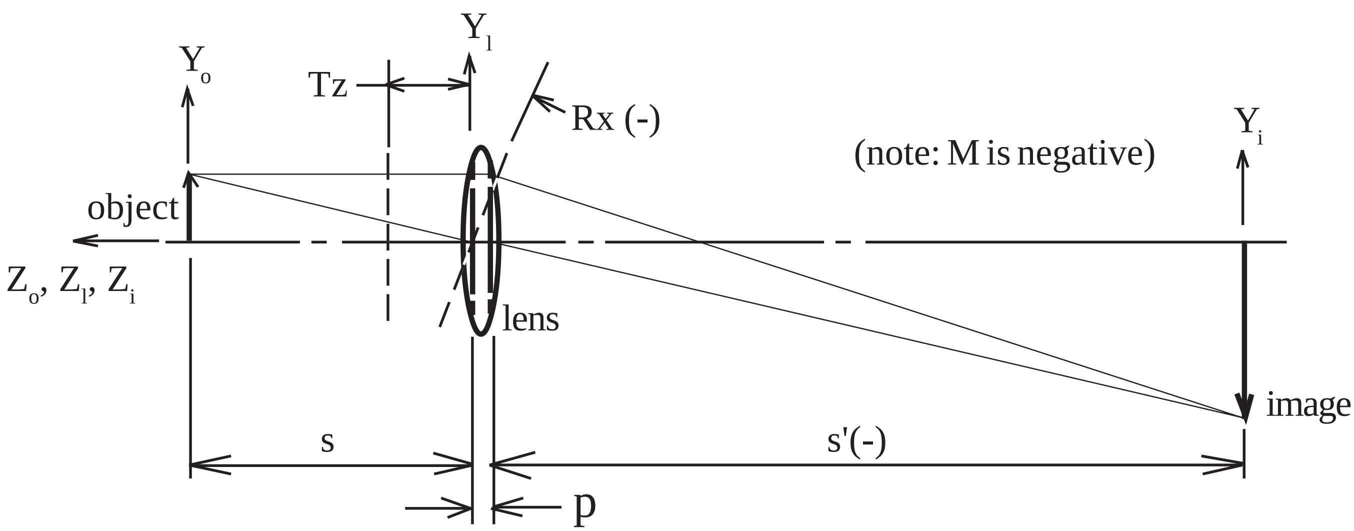
Physical prescription properties:

Surf	1
Elem	"obj"
Radius:	"inf"
Index	"AIR"
Thickness	t: positive
TYPE:	"obj", all lower case
f1	scale factor: default = 1.0
f2	
f3	
f4	

Example (surface 1/element "obj"):

```
Surf Elem Radius     Index      Thickness  Type          f1         f2         f3         f4
1    obj  inf        AIR        inf        obj          1.0
...
6    3    310.       GE         2.0000     LENS
7    3    -215.      AIR        3.5000     LENS
...
11   det  inf        AIR        0.0        det
```

APPENDIX B
The Lens' Coordinate Systems



A lens uses three coordinate systems: one for the object, one for the lens and one for the image.

The object coordinate system has its origin at the point where the object crosses the optical axis, its positive Z axis is against the light leaving the object and its Y axis is up.

The lens coordinate system has its origin at its first principal point, its positive Z axis is pointed against the incident light and its Y axis is up.

The image coordinate system has its origin at the point where the image crosses the optical axis, its positive Z axis is against the imaging light and its Y axis is up.

The X axes complete right-handed coordinate systems.

APPENDIX B
The Lens' Prescription Conventions

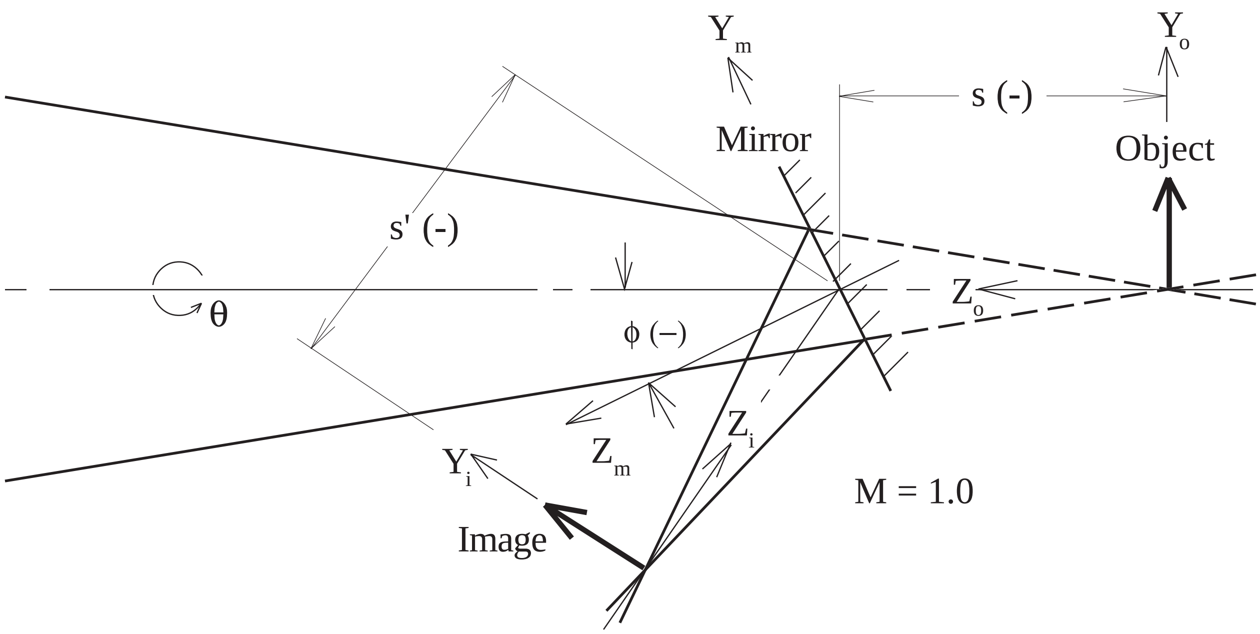
Physical prescription properties:

Surf	positive integer in sequence
Elem	positive integer in sequence
Radius:	R_1: positive if concave, "inf" if flat
	R_2: positive if convex, "inf" if flat
Index	n: mnemonic to agree with MATERIAL column of *.IND file.
Thickness	t: positive
TYPE:	"LENS", all upper case
f1	
f2	
f3	
f4	

Example (surfaces 6 and 7/element 3):

```
Surf Elem Radius     Index      Thickness  Type          f1         f2         f3         f4
1    obj  inf        AIR        inf        obj
...
6    3    310.       GE         2.0000     LENS
7    3    -215.      AIR        3.5000     LENS
...
11   det  inf        AIR        0.0        det
```

APPENDIX C
The Fold Mirror's Coordinate Systems



The fold mirror uses three coordinate systems: one for the object, one for the fold mirror and one for the image.

A fold mirror often changes the direction of the optical axis. As a result these coordinate systems may be neither parallel nor congruent.

The object coordinate system has its origin at the point where the object crosses the incident optical axis (or its projection as shown above), its positive Z axis is opposite the direction of the light leaving the object and its Y axis is up.

The mirror coordinate system has its origin at the point where the optical axis intercepts the mirror, its positive Z axis is normal to the mirror on the incident side and the Y axis is up.

APPENDIX C
The Fold Mirror's Coordinate Systems

The image coordinate system has its origin at the point where the image crosses the reflected optical axis, its positive Z axis is against the imaging light and the Y axis is an image of the object’s Y axis.

The X axes complete right-handed coordinate systems.

The angle of incidence, Φ, is positive if the sense of the object’s Z axis is rotated (with respect to the mirror) in the sense of the mirror’s Y axis into the mirror’s Z axis (right handed).

The angle of rotation, Θ, is positive if the object is rotated about its own Z axis in the sense of the object’s X axis into its Y axis (right handed).

APPENDIX C
The Fold Mirror's Prescription Conventions

A fold mirror contains one flat surface and one index of refraction. A flat mirror may not be the first element in the system if the object is at infinity.

Physical prescription properties:

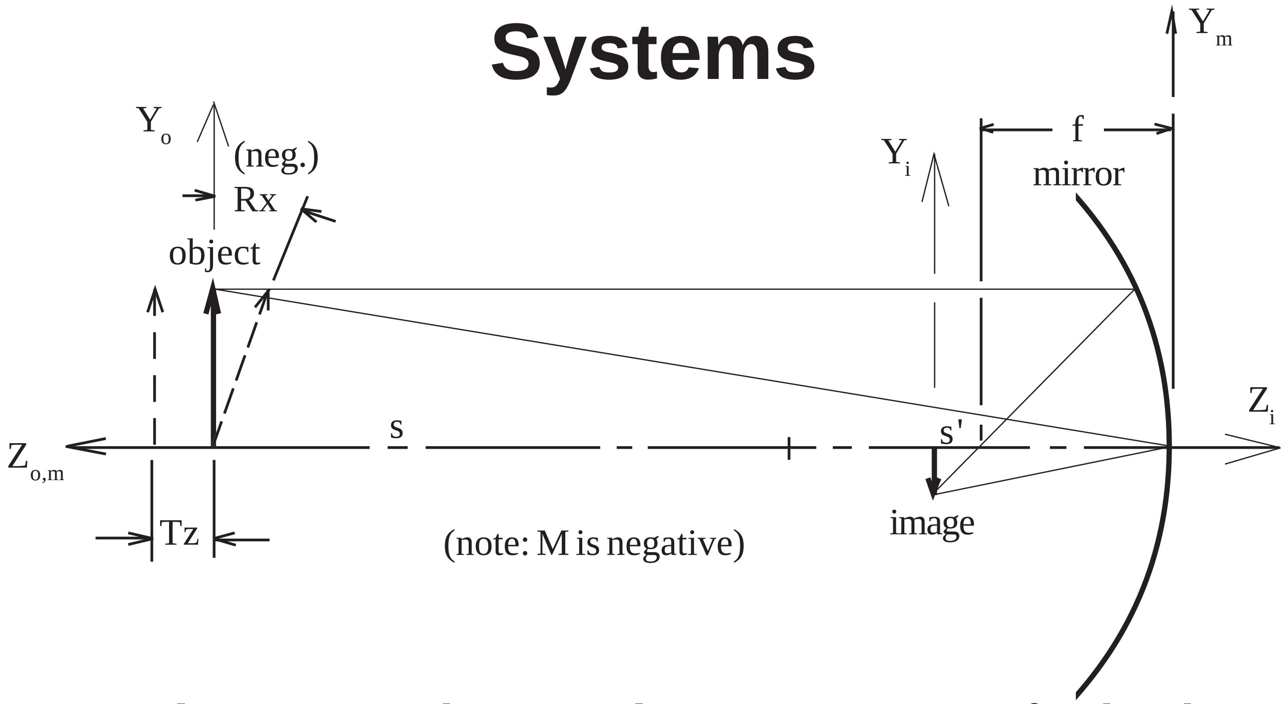
Surf	positive integer in sequence
Elem	positive integer in sequence
Radius	“inf” all lower case
Index	“AIR”
Thickness	t: positive
TYPE	“MIRR” all upper case
f1	ϕ: angle in degrees
f2	θ: angle in degrees
f3	
f4	

Examples (surface 4/element 3):

```
Surf Elem Radius     Index      Thickness  Type         f1         f2         f3         f4
1    obj  inf        AIR        inf        obj
...
4    3    inf        AIR        7.5        MIRR        -35         90

...
42   det  inf        AIR        0.0        det
```

APPENDIX D
The Powered Mirror's Coordinate Systems



A powered mirror uses three coordinate systems: one for the object, one for the mirror and one for the image.

The object coordinate system has its origin at the point where the object crosses the optical axis, its positive Z axis is against the light from the object and its Y axis is up.

The powered mirror coordinate system has its origin at its principal point, its positive Z axis is normal to the surface at the vertex and on the incident side of the mirror and its Y axis is up.

The image coordinate system has its origin at the point where the image crosses the reflected optical axis, its positive Z axis is against the imaging light and its Y axis is up.

The X axes complete right-handed coordinate systems.

APPENDIX D
The Powered Mirror's Prescription Conventions

A powered mirror contains one curved surface and one index of refraction.

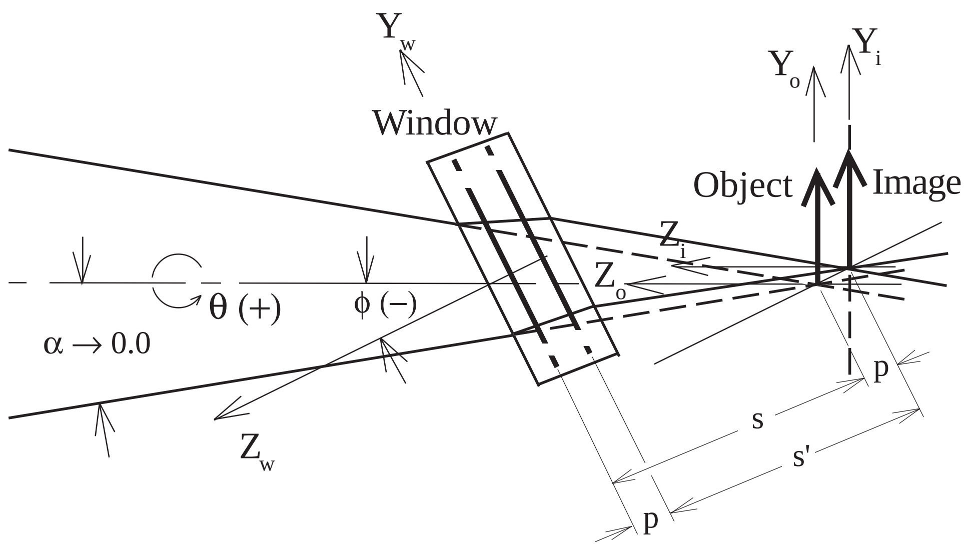
Physical prescription properties:

Surf	positive integer in sequence
Elem	positive integer in sequence
Radius	R: positive if concave
Index	“AIR”
Thickness	t: positive
TYPE	“MIRR” all upper case
f1	
f2	
f3	
f4	

Examples (surface 3/element 2):

Surf	Elem	Radius	Index	Thickness	Type	f1	f2	f3	f4
1	obj	inf	AIR	inf	obj				
...									
3	**2**	**-18.3991**	**AIR**	**10.3468**	**MIRR**				
...									
42	det	inf	AIR	0.0	det				

APPENDIX E
The Window's Coordinate Systems



A window uses three coordinate systems: one for the object, one for the window and one for the image.

The object coordinate system has its origin at the point where the object crosses the optical axis, its positive Z axis is against the light from the object and its Y axis is up.

The window coordinate system has its origin at its first principal point, its positive Z axis is normal to the first surface at the vertex and on the incident side of the window and its Y axis is up. In theory the locations of a window's principal points is indefinite. In Ivory they are assumed to be centered in the window's thickness.

The image coordinate system has its origin at the point where the image crosses the transmitted optical axis, its positive Z axis is against the imaging light and its Y axis is up.

The X axes complete right-handed coordinate systems.

APPENDIX E
The Window’s Coordinate Systems

The angle of incidence, Φ, is positive if the sense of the object’s Z axis is rotated (with respect to the window) in the sense of the window’s Y axis into the window’s Z axis (right handed).

The angle of rotation, Θ, is positive if the object is rotated about its own Z axis in the sense of the object’s X axis into its Y axis (right handed).

APPENDIX E
The Window's Prescription Conventions

A window contains two flat surfaces and one index of refraction.

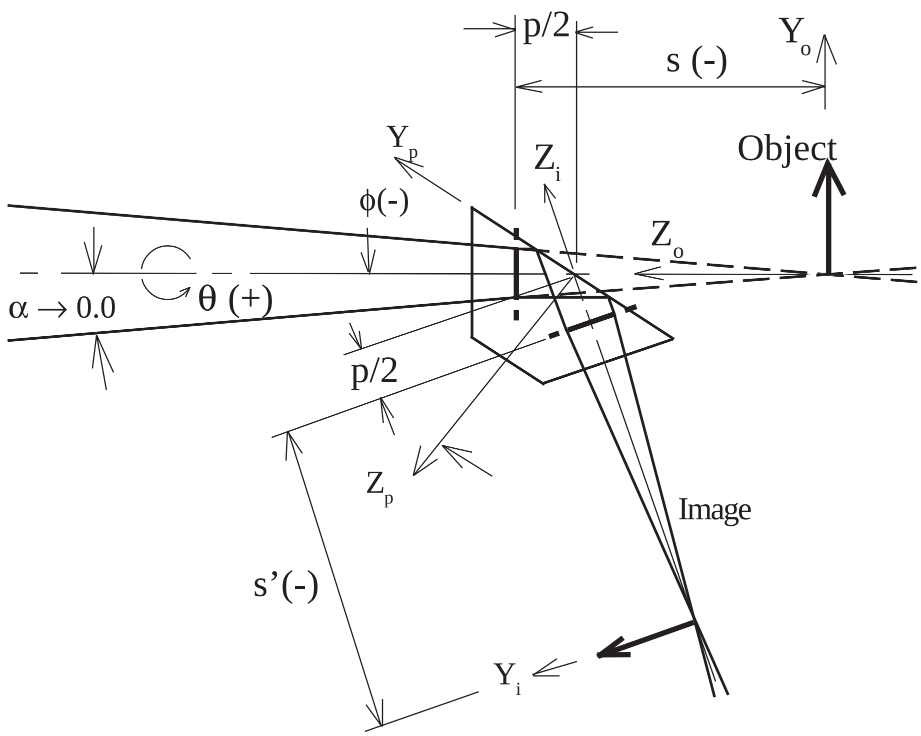
Physical prescription properties:

Surf	positive integer in sequence
Elem	positive integer in sequence
Radius	R_1: "inf" all lower case
	$R_{2:}$ "inf" all lower case
Index	n: mnemonic to agree with MATERIAL column of *.IND file.
Thickness	t: positive
TYPE	"WIND" all upper case
f1	ϕ: angle in degrees
f2	θ: angle in degrees
f3	
f4	

Examples (surfaces 10 and 11/element 6):

```
Surf Elem Radius     Index      Thickness  Type          f1         f2         f3         f4
1    obj  inf        AIR        inf        obj
...
10   6    inf        og515      .25        WIND       12.5
11   6    inf        AIR        .3         WIND
...
42   det  inf        AIR        0.0        det
```

APPENDIX F
The Prism's Coordinate Systems



The prism uses three coordinate systems: one for the object, one for the fold mirror and one for the image.

A prism changes the direction of the optical axis. As a result these coordinate systems are neither parallel nor congruent. The angle of incidence at the refractive surfaces is 0.0°. The angle of incidence at the reflective surface may be either positive or negative (shown).

The object coordinate system has its origin at the point where the object crosses the incident optical axis (or its projection as shown above), its positive Z axis is opposite the direction of the light leaving the object and its Y axis is up.

APPENDIX F
The Prism's Coordinate Systems

The prism coordinate system has its origin at the point where the optical axis intercepts the prism's reflective surface, its positive Z axis is normal to the reflective surface on the incident side and is against the incident light. The Y axis is up.

The image coordinate system has its origin at the point where the image crosses the reflected optical axis, its positive Z axis is against the incident light and the Y axis is an image of the object's Y axis.

The X axes complete right-handed coordinate systems.

The angle of incidence, Φ, is positive if the sense of the object's Z axis is rotated (with respect to the prism) in the sense of the prism's Y axis into the prism's Z axis (right handed).

The angle of rotation, Θ, is positive if the object is rotated about its own Z axis in the sense of the object's X axis into its Y axis (right handed).

APPENDIX F
The Prism's Prescription Conventions

A prism contains three surfaces and one index of refraction. The angle of incidence is at the second (reflective) surface. The other surfaces are normal to the local optical axes.

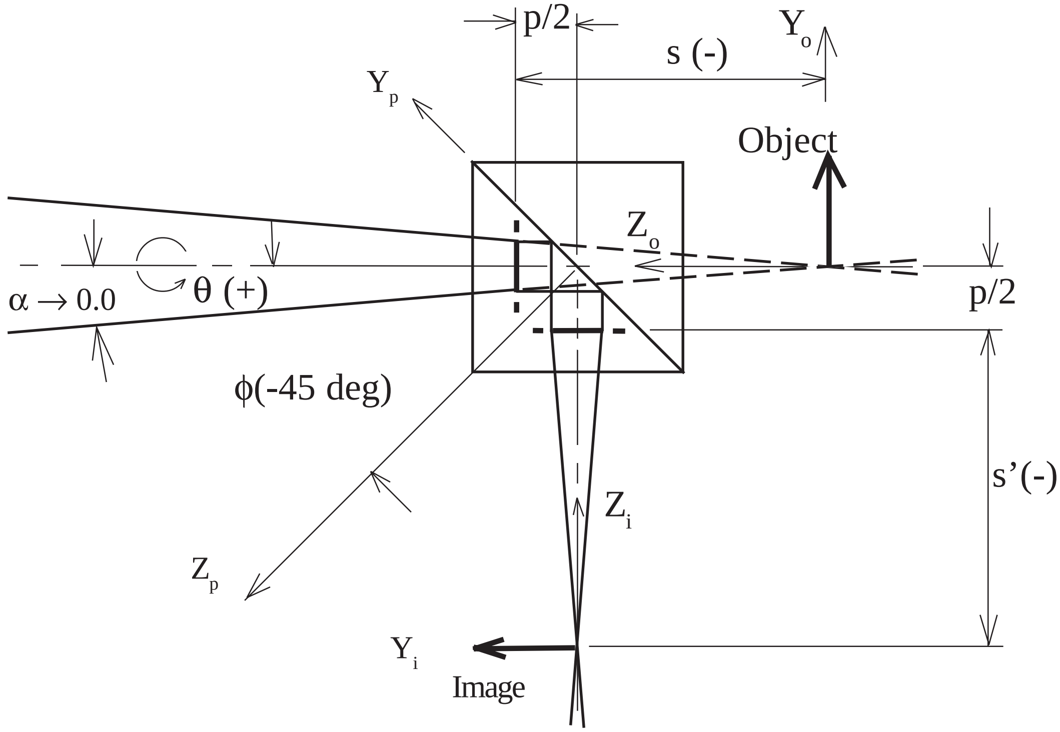
Physical prescription properties:

Surf	positive integers (3) in sequence
Elem	positive integer in sequence
Radius	R_1: "inf" all lower case
	R_2: "inf" all lower case
	R_3: "inf" all lower case
Index	n: mnemonic to agree with MATERIAL column of *.IND file.
Thickness	t: positive
TYPE	"PRIS" all upper case
f1	ϕ: angle in degrees
f2	θ: angle in degrees
f3	
f4	

Example (surfaces 10, 11 and 12/element 6):

```
Surf Elem Radius     Index      Thickness  Type          f1         f2         f3         f4
1    obj  inf        AIR        inf        obj
...
10   6    inf        sili       2.15       PRIS
11   6    inf        sili       2.35       PRIS         -55         90
12   6    inf        AIR        .1         PRIS
...
42   det  inf        AIR        0.0        det
```

APPENDIX G
The Beam Splitter's Coordinate Systems (in Reflection)



The beam splitter (as a prism) uses three coordinate systems: one for the object, one for the fold mirror and one for the image.

A beam splitter (as a prism) changes the direction of the optical axis. As a result these coordinate systems are neither parallel nor congruent. The beam splitter is assumed to be a cube. The angles of incidence at the refractive surfaces are 0°. The angle of incidence at the reflective surface is either positive or negative 45° (shown).

The object coordinate system has its origin at the point where the object crosses the incident optical axis (or its projection as shown above), its positive Z axis is opposite the direction of the light leaving the object and its Y axis is up.

APPENDIX G
The Beam Splitter’s Coordinate Systems (in Reflection)

The beam splitter (as a prism) coordinate system has its origin at the point where the optical axis intercepts the beam splitter’s (as a prism) reflective surface, its positive Z axis is normal to the reflective surface on the incident side and the Y axis is up.

The image coordinate system has its origin at the point where the image crosses the reflected optical axis, its positive Z axis is against the light forming the image and the Y axis is an image of the object’s Y axis.

The X axes complete right-handed coordinate systems.

The angle of incidence, Φ, is positive if the sense of the object’s Z axis is rotated (with respect to the beam splitter) in the sense of the beam splitter’s Y axis into the the beam splitter’s Z axis (right handed).

The angle of rotation, Θ, is positive if the object is rotated about its own Z axis in the sense of the object’s X axis into its Y axis (right handed).

APPENDIX G
The Beam Splitter's Prescription Conventions (in Reflection)

A beam splitter (as a prism) contains three surfaces and one index of refraction. The angle of incidence is either + or - 45° at the second (reflective) surface. The other surfaces are normal to the optical axis. It may also be modeled as a prism, "PRIS."

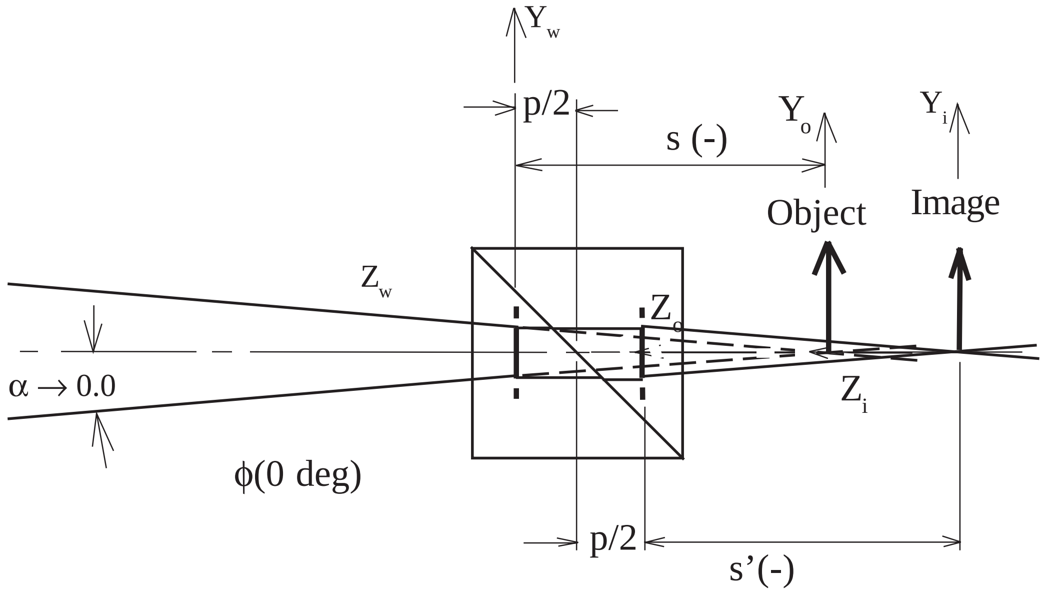
Physical prescription properties:

Surf	positive integers (3) in sequence
Elem	positive integer in sequence
Radius	R_1: "inf" all lower case
	R_2: "inf" all lower case
	R_3: "inf" all lower case
Index	n: mnemonic to agree with MATERIAL column of *.IND file.
Thickness	t: positive
Type	"BSPR" all upper case
f1	ϕ: angle in degrees, ±45 only
f2	θ: angle in degrees
f3	
f4	

Example (surfaces 7, 8 and 9/element 5):

```
Surf Elem Radius     Index      Thickness  Type          f1         f2         f3         f4
1    obj  inf        AIR        inf        obj
...
7    5    inf        caf2       1.55       BSPR
8    5    inf        caf2       1.55       BSPR          45         -30
9    5    inf        AIR        .1         BSPR
...
42   det  inf        AIR        0.0        det
```

APPENDIX H
The Beam Splitter’s Coordinate Systems (in Transmission)



The beam splitter (as a window) uses three coordinate systems: one for the object, one for the beam splitter and one for the image.

A beam splitter (as a window) transmits the incident light as a window. As a result the coordinate systems are all parallel. The beam splitter is assumed to be a cube. The angles of incidence at the refractive surfaces are 0°. The reflective surface is ignored.

The object coordinate system has its origin at the point where the object crosses the incident optical axis (or its projection as shown above), its positive Z axis is opposite the direction of the light leaving the object and its Y axis is up.

The beam splitter (as a window) coordinate system has its origin at

APPENDIX H
The Beam Splitter's Coordinate Systems (in Transmission)

the beam splitter's (as a window) first principal point, its positive Z axis is normal to the incident surface on the incident side and the Y axis is up.

The image coordinate system has its origin at the point where the image crosses the transmitted optical axis, its positive Z axis is against the light forming the image and the Y axis is up.

The X axes complete right-handed coordinate systems.

APPENDIX H
The Beam Splitter's Prescription Conventions (in Transmission)

A beam splitter (as a window) contains three surfaces and one index of refraction. The angle of incidence is 0° at the first and third surfaces. The second surface is ignored. It may also be modeled as a window, "WIND."

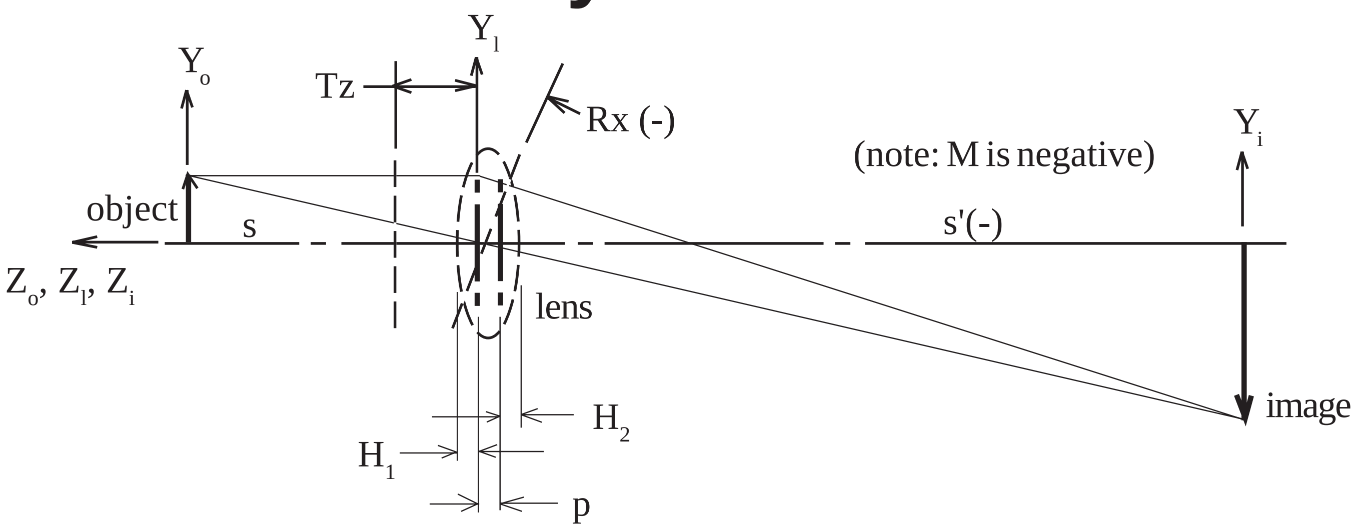
Physical prescription properties:

Surf	positive integers (3) in sequence
Elem	positive integer in sequence
Radius	R_1: "inf" all lower case
	R_2: "inf" all lower case
	R_3: "inf" all lower case
Index	n: mnemonic to agree with MATERIAL column of *.IND file.
Thickness	t: positive
Type	"BSWI" all upper case
f1	
f2	
f3	
f4	

Example (surfaces 7, 8 and 9/element 5):

```
Surf Elem Radius     Index      Thickness  Type          f1          f2          f3          f4
1    obj  inf        AIR        inf        obj
...
7    5    inf        caf2       1.55       BSWI
8    5    inf        caf2       1.55       BSWI
9    5    inf        AIR        .1         BSWI
...
42   det  inf        AIR        0.0        det
```

APPENDIX I
The Paraxial Element's Coordinate Systems



A paraxial element uses three coordinate systems: one for the object, one for the lens and one for the image.

The object coordinate system has its origin at the point where the object crosses the optical axis, its positive Z axis is opposite the direction of the light leaving the object and its Y axis is up.

The paraxial element coordinate system has its origin at the first principal point, its positive Z axis is pointed against the incident light and its Y axis is up.

The image coordinate system has its origin at the point where the image crosses the optical axis, its positive Z axis is against the imaging light and its Y axis is up.

The X axes complete right-handed coordinate systems.

APPENDIX I
The Paraxial Element's Prescription Conventions

A paraxial element has four properties; the focal length (f), the position of the first principal plane (H_1), the position of the second principal plane (H_2) and the principal thickness (p). The index of refraction data is not used so a "nul" entry is required in the .ind file.

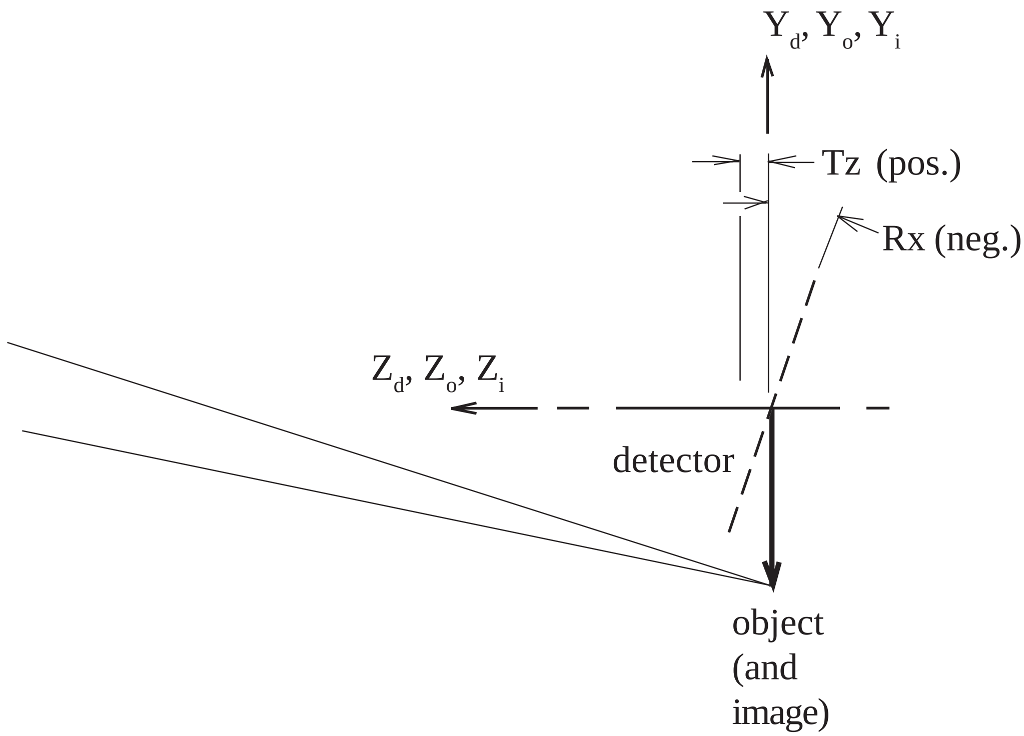
Physical prescription properties:

Surf	positive integer
Elem	positive integer
Radius	no entry
Index	n: "nul," and enter the index also as "nul" in the *.IND file
Thickness	t: positive, the next physical thickness in the prescription
Type	"PARA" all upper case
f1	f: the focal length
f2	H_1: the position of the first principal point
f3	H_2: the position of the second principal point
f4	p: the principal thickness (may have a negative value)

Example (surface 4/element 2):

```
Surf Elem Radius     Index      Thickness  Type          f1         f2         f3         f4
1    obj  inf        AIR        18.385     obj
...
4    2               nul        7.3234     PARA      20.700       -2.3         .4        1.6
...
7    det  inf        AIR                   ima
```

APPENDIX J
The Detector's Coordinate Systems



A detector has three coordinate systems: one for the object, one for the detector and one for the image. The three are congruent, assuming the detector is placed at the paraxial image.

The role of a detector is to transfer its object (the system image) into another medium such as electronic signals, silver halide grain changes or neurological responses in the brain. Consequently, the “image” of the detector is not an optical image but rather the perceived representation of the behavior (signal) created by its object.

The origin is at the point where the image crosses the optical axis, its positive Z axis is against the light forming the image and the Y axis is up. The X axes complete right-handed coordinate systems.

APPENDIX J
The Detector's Prescription Conventions

A detector contains one flat surface and one index of refraction.

Physical prescription properties:

Surf	positive final integer in the sequence
Elem	“det” all lower case
Radius	“inf” all lower case
Index	n: “AIR”
Thickness	t: “0.0”
TYPE	“det” all lower case
f1	
f2	
f3	
f4	

Examples (surface 11):

```
Surf Elem Radius     Index      Thickness  Type          f1          f2          f3          f4
1    obj  inf        AIR        inf        obj
...
11   det  inf        AIR        0.0        det
```