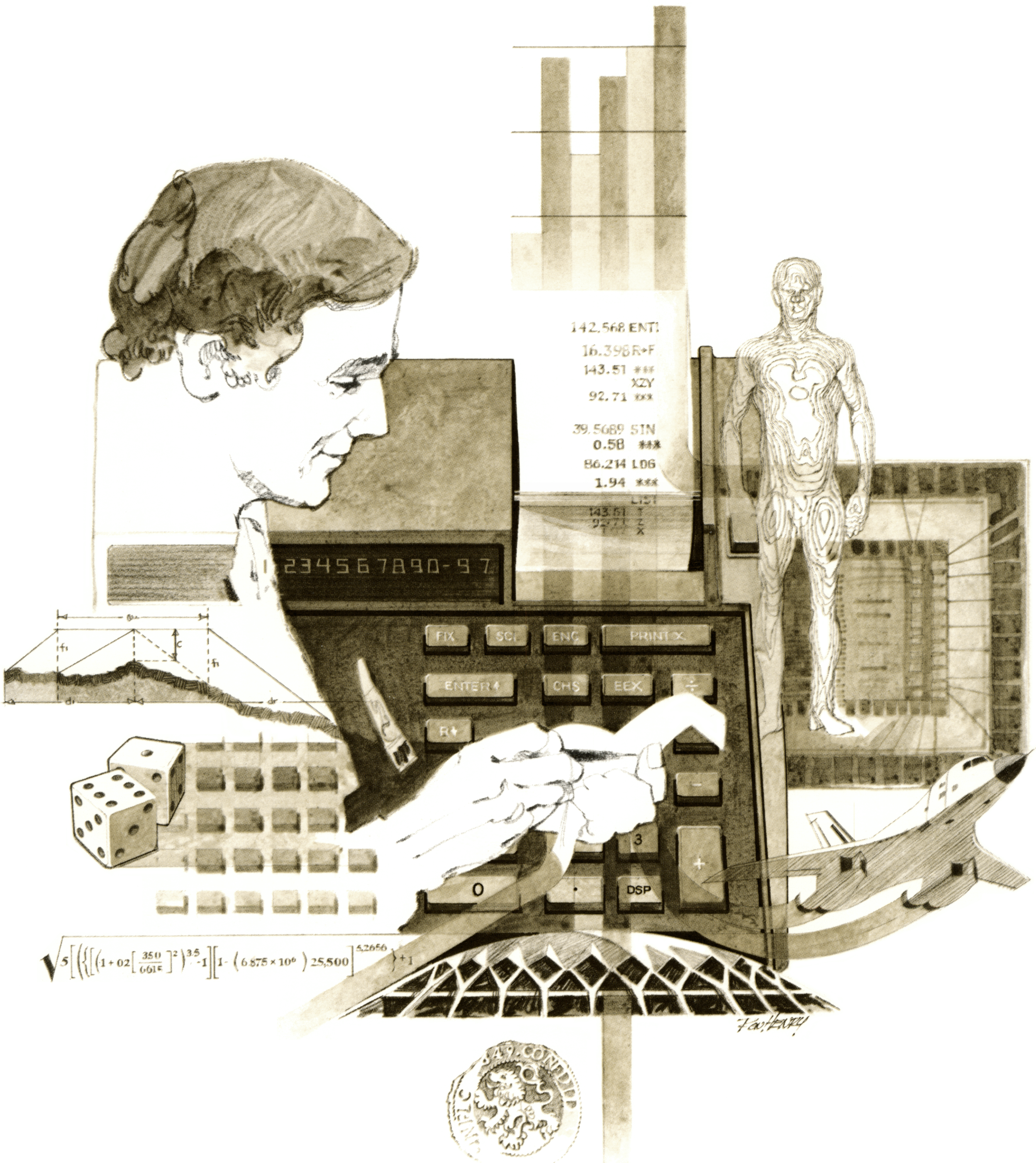
HEWLETT-PACKARD

HP-67/HP-97

Users' Library Solutions

Optics



INTRODUCTION

In an effort to provide continued value to it's customers, Hewlett-Packard is introducing a unique service for the HP fully programmable calculator user. This service is designed to save you time and programming effort. As users are aware, Programmable Calculators are capable of delivering tremendous problem solving potential in terms of power and flexibility, but the real genie in the bottle is program solutions. HP's introduction of the first handheld programmable calculator in 1974 immediately led to a request for program **solutions** — hence the beginning of the HP-65 Users' Library. In order to save HP calculator customers time, users wrote their own programs and sent them to the Library for the benefit of other program users. In a short period of time over 5,000 programs were accepted and made available. This overwhelming response indicated the value of the program library and a Users' Library was then established for the HP-67/97 users.

To extend the value of the Users' Library, Hewlett-Packard is introducing a unique service—a service designed to save you time and money. The Users' Library has collected the best programs in the most popular categories from the HP-67/97 and HP-65 Libraries. These programs have been packaged into a series of low-cost books, resulting in substantial savings for our valued HP-67/97 users.

We feel this new software service will extend the capabilities of our programmable calculators and provide a great benefit to our HP-67/97 users.

A WORD ABOUT PROGRAM USAGE

Each program contained herein is reproduced on the standard forms used by the Users' Library. Magnetic cards are not included. The Program Description I page gives a basic description of the program. The Program Description II page provides a sample problem and the keystrokes used to solve it. The User Instructions page contains a description of the keystrokes used to solve problems in general and the options which are available to the user. The Program Listing I and Program Listing II pages list the program steps necessary to operate the calculator. The comments, listed next to the steps, describe the reason for a step or group of steps. Other pertinent information about data register contents, uses of labels and flags and the initial calculator status mode is also found on these pages. Following the directions in your HP-67 or HP-97 **Owners' Handbook and Programming Guide,** "Loading a Program" (page 134, HP-67; page 119, HP-97), key in the program from the Program Listing I and Program Listing II pages. A number at the top of the Program Listing indicates on which calculator the program was written (HP-67 or HP-97). If the calculator indicated differs from the calculator you will be using, consult Appendix E of your **Owner's Handbook** for the corresponding keycodes and keystrokes converting HP-67 to HP-97 keycodes and vice versa. No program conversion is necessary. The HP-67 and HP-97 are totally compatible, but some differences do occur in the keycodes used to represent some of the functions.

A program loaded into the HP-67 or HP-97 is not permanent—once the calculator is turned off, the program will not be retained. You can, however, permanently save any program by recording it on a blank magnetic card, several of which were provided in the Standard Pac that was shipped with your calculator. Consult your **Owner's Handbook** for full instructions. A few points to remember:

> The Set Status section indicates the status of flags, angular mode, and display setting. After keying in your program, review the status section and set the conditions as indicated before using or permanently recording the program.
>
> REMEMBER! To save the program permanently, **clip** the corners of the magnetic card once you have recorded the program. This simple step will protect the magnetic card and keep the program from being inadvertently erased.

As a part of HP's continuing effort to provide value to our customers, we hope you will enjoy our newest concept.

TABLE OF CONTENTS

Program Description I

Program Title OPTICAL DESIGN I

Contributor's Name JOSEPH R. HOBART

Address 8723 BRADY AVENUE

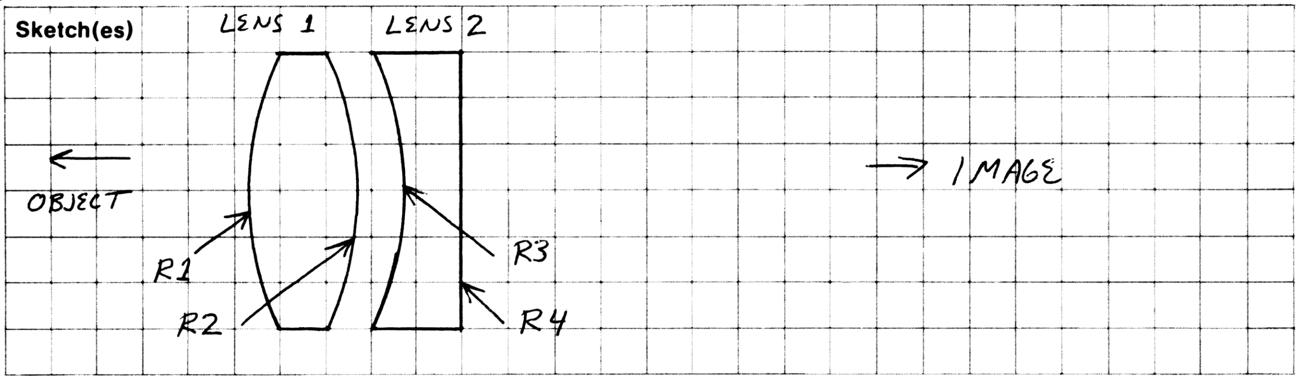
City SPRING VALLEY **State** CA **Zip Code** 92077

Program Description, Equations, Variables PROGRAM COMPUTES THE TWO SOLUTIONS OF AN ACHROMATIC DOUBLET USING THE ALGEBRAIC "G-SUM" METHOD TO ELIMINATE SPHERICAL ABERRATION AND COMA AT ONE WAVELENGTH. REQUIRED INPUTS ARE: REFRACTIVE INDEX (N) AND DISPERSION (δN) (DEFINED AS $N_F - N_C$) OF THE TWO GLASSES AND THE EFFECTIVE FOCAL LENGTH (EFL). PROGRAM USES TWO CARDS: FIRST CARD COMPUTES AND STORES THE VALUES OF THE "G" VALUES AND OVERALL LENS POWER; SECOND CARD COMPUTES TWO SETS OF RADII. LENS ONE IS CLOSER TO THE OBJECT; LENS TWO IS CLOSER TO THE IMAGE. POSITIVE RADII ARE CONVEX TOWARD THE OBJECT; NEGATIVE RADII ARE CONCAVE TOWARD THE OBJECT. EQUATIONS USED ARE HIGHLY DETAILED; USER IS REFERED TO A THOROUGH DISCUSSION IN REFERENCE 1 (DIFFICULT READING) OR A BRIEF DESCRIPTION IN REFERENCE 2. THE SOLUTION HAVING LONGER RADII IS PREFERABLE DUE TO LESS SERIOUS HIGHER ORDER ABERRATIONS AND EASIER FABRICATION.

Operating Limits and Warnings PROGRAM USES THIN LENS TECHNIQUES. SOLUTIONS FOR SLOW OPTICAL SYSTEMS ARE RELIABLE; SOLUTIONS FOR FAST OPTICAL SYSTEMS OR SYSTEMS USING SHARP LENS CURVATURES (SHORT RADII) MUST BE CHECKED BY TRIGONOMETRIC RAY TRACE TECHNIQUES. SHORT RADII ARE THOSE LESS THAN ABOUT ONE THIRD OF THE FOCAL LENGTH. FAST OPTICAL SYSTEMS ARE THOSE LESS THAN ABOUT F/10.

Program Description II

Sketch(es)



Sample Problem(s)

FIND THE RADII OF A TELESCOPE OBJECTIVE LENS USING LIGHT CROWN GLASS LEADING A DENSE FLINT GLASS WITH THE FOLLOWING PROPERTIES:

CROWN (BSC-2) $N_{5555} = 1.5193$; $\delta N = N_F - N_C = .00804$
FLINT (DF-4) $N_{5555} = 1.6509$; $\delta N = .01904$

THE EFFECTIVE FOCAL LENGTH IS TO BE 124 (INCHES)

(N_D IS USUALLY USED, BUT THIS IS TO BE A VISUAL OBJECTIVE AND 5555 Å IS THE CENTER OF THE RESPONSE OF THE EYE)

Solution(s) LOAD CARD A; KEYSTROKES:

A		→ 1.	D	→ 0		f A	→ 75.352 (R1)	
1.5193	R/S	→ 2.				f B	→ -50.710 (R2)	
1.6509	R/S	→ 0.	LOAD CARD B:			f ~~B~~C	→ -51.007 (R3)	
B		→ 1.	E	→ -.020		f D	→ -176.242 (R4)	
.00804	R/S	→ 2.	A	→ 21.846 (R1)		THIS SECOND SOLUTION		
.01904	R/S	→ 0.	B	→ 78.225 (R2)		GIVES EXTREEMLY LOW		
C		→ 1.	C	→ 22.824 (R3)		SPHERICAL ABERATION		
124	R/S	→ 0.	D	→ 17.318 (R4)		AND COMA WHEN CHECKED BY RAY TRACE.		

Reference(s)

(1) CONRADY, A.E., APPLIED OPTICS AND OPTICAL DESIGN, DOVER PUBLICATIONS, NEW YORK, 1957.
(2) GEE, A.E., "DESIGN OF TELESCOPES BY THE G-SUM METHOD." AMATEUR TELESCOPE MAKING BOOK THREE, SCIENTIFIC AMERICAN INC., KINGSPORT, 1953.

User Instructions

OPTICAL DESIGN 1A

LOAD N | LOAD δN | LOAD EFL | RUN

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	LOAD SIDES 1 AND 2 CARD A				0
2	LOAD REFRACTIVE INDEX (N)		A		→ 1
	ENTER DATA FOR LENS 1		R/S		→ 2
	ENTER DATA FOR LENS 2		R/S		→ 0
3	LOAD DISPERSION (δN)		B		→ 1
	ENTER δN FOR LENS 1		R/S		→ 2
	ENTER δN FOR LENS 2		R/S		→ 0
4	LOAD EFFECTIVE FOCAL LENGTH (EFL)		C		→ 1
	ENTER EFL		R/S		→ 0
5	RUN		D		→ 0
6	THE STORAGE REGISTERS HAVE BEEN	LOADED;			
	PROCEDE TO PART B				

Program Listing I

CARD A

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	f LBL A	31 25 11	LOAD N1 AND N2
	1	01	**67**
	R/S	84	
	STO E	33 15	
	2	02	
	R/S	84	
	h ST I	35 33	
	CLX	44	
	h RTN	35 22	
010	f LBL B	31 25 12	LOAD δN1 AND δN2
	1	01	
	R/S	84	
	STO A	33 11	
	2	02	
	R/S	84	
	STO B	33 12	
	CLX	44	
	h RTN	35 22	
	f LBL C	31 25 13	LOAD EFL
020	1	01	
	R/S	84	
	STO 8	33 08	
	CLX	44	
	h RTN	35 22	
	f LBL D	31 25 14	RUN
	RCL E	34 15	
	1	01	
	−	51	
	RCL A	34 11	
030	÷	81	
	STO C	33 13	
	h RC I	35 34	
	1	01	
	−	51	
	RCL B	34 12	
	÷	81	
	STO D	33 14	
	RCL C	34 13	
	RCL D	34 14	
040	−	51	
	RCL 8	34 08	
	x	71	
	RCL A	34 11	
	x	71	
	h 1/x	35 62	
	STO A	33 11	CA
	RCL D	34 14	
	RCL C	34 13	
	−	51	
050	RCL 8	34 08	
	x	71	
	RCL B	34 12	
	x	71	
	h 1/x	35 62	
	STO B	33 12	CB
	RCL E	34 15	

STEP	KEY ENTRY	KEY CODE	COMMENTS
	1	01	
	−	51	
	RCL A	34 11	
060	x	71	
	STO D	33 14	PA
	RCL E	34 15	
	f GSB 1	31 22 01	
	h RC I	35 34	
	f GSB 1	31 22 01	
	h RTN	35 22	
	f LBL 1	31 25 01	
	STO 9	33 09	
	1	01	
070	−	51	
	STO 8	33 08	
	RCL 9	34 09	
	g x^2	32 54	
	x	71	
	2	02	
	÷	81	
	STO Ø	33 00	G1
	RCL 9	34 09	
	2	02	
080	x	71	
	1	01	
	+	61	
	RCL 8	34 08	
	x	71	
	2	02	
	÷	81	
	STO 1	33 01	G2
	RCL 9	34 09	
	3	03	
090	x	71	
	1	01	
	+	61	
	RCL 8	34 08	
	x	71	
	2	02	
	÷	81	
	STO 2	33 02	G3
	RCL 9	34 09	
	2	02	
100	+	61	
	RCL 8	34 08	
	x	71	
	2	02	
	÷	81	
	RCL 9	34 09	
	÷	81	
	STO 3	33 03	G4
	RCL 9	34 09	
	g x^2	32 54	
110	1	01	
	−	51	
	2	02	

REGISTERS

0	1	2	3	4	5	6	7	8	9
$G1_a$	$G2_a$	$G3_a$	$G4_a$	$G5_a$	$G6_a$	$G7_a$	$G8_a$	$N_1 - 1$	N_1

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
$G1_b$	$G2_b$	$G3_b$	$G4_b$	$G5_b$	$G6_b$	$G7_b$	$G8_b$	EFL/N_2-1/A	N_2 / B

A	B	C	D	E	I
δN_1 / CA	δN_2 / CB	V_1 / Z	V_2 / Pa	N_1 / $C2_a$	N_2 / $C2_b$

CARD A **Program Listing II** CARD A

67

STEP	KEY ENTRY	KEY CODE	COMMENTS
	X	71	
	RCL 9	34 09	
	÷	81	
	STO 4	33 04	65
	RCL 9	34 09	
	3	03	
	x	71	
120	2	02	
	+	61	
	RCL 8	34 08	
	x	71	
	RCL 9	34 09	
	÷	81	
	2	02	
	÷	81	
	STO 5	33 05	66
	RCL 9	34 09	
130	2	02	
	x	71	
	1	01	
	+	61	
	RCL 8	34 08	
	x	71	
	RCL 9	34 09	
	÷	81	
	2	02	
	÷	81	
140	STO 6	33 06	67
	RCL 9	34 09	
	RCL 8	34 08	
	x	71	
	2	02	
	÷	81	
	STO 7	33 07	68
	f P⇌S	31 42	
	CLX	44	
	h RTN	35 22	
150			
160			
170			
180			
190			
200			
210			
220			

LABELS

A LOAD N	B LOAD S N	C LOAD EFL	D RUN	E
a	b	c	d	e
0	1 CALC G	2	3	4
5	6	7	8	9

FLAGS: 0, 1, 2, 3

SET STATUS

FLAGS	ON	OFF
0	☐	☒
1	☐	☒
2	☐	☒
3	☐	☒

TRIG: DEG ☒ GRAD ☐ RAD ☐

DISP: FIX ☒ SCI ☐ ENG ☐ n = Ø

User Instructions

OPTICAL DESIGN 1B

1					2
→ $R1_b$	$R2_b$	$R3_b$	$R4_b$		
→ $R1_a$	$R2_a$	$R3_a$	$R4_a$	RUN	

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1-6	SEE PART A				
7	LOAD SIDES 1 AND 2 CARD B				0.000
8	RUN		E		$C3_b$
9	COMPUTE RADII				
	$R1_a$		A		$R1_a$
	$R2_a$		B		$R2_a$
	$R3_a$		C		$R3_a$
	$R4_a$		D		$R4_a$
	$R1_b$		f	A	$R1_b$
	$R2_b$		f	B	$R2_b$
	$R3_b$		f	C	$R3_b$
	$R4_b$		f	D	$R4_b$
	ANY RADIUS MAY BE CALLED				
	IN ANY ORDER. SOLUTIONS A				
	AND B ARE SEPARATE; DO NOT				
	MIX SOME A PARTS WITH SOME				
	B PARTS IN YOUR DESIGN.				
	USING R/S AFTER RUN IS				
	COMPLETE WILL GIVE $R1_a$ TO				
	$R4_b$ IN ORDER LISTED ABOVE.				

CARD B

Program Listing I

CARD B

67

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	f LBL E	31 25 15	RUN
	RCL 6	34 06	
	RCL A	34 11	
	x	71	
	RCL D	34 14	
	x	71	
	RCL 7	34 07	
	RCL A	34 11	
	g x^2	32 54	
010	x	71	
	−	51	
	f P→S	31 42	
	RCL 6	34 06	
	RCL B	34 12	
	x	71	
	RCL D	34 14	
	x	71	
	+	61	
	RCL 7	34 07	
020	RCL B	34 12	
	g x^2	32 54	
	x	71	
	+	61	
	RCL 4	34 04	
	÷	81	
	RCL B	34 12	
	÷	81	
	4	04	
	x	71	
030	STO C	33 13	
	f P←S	31 42	
	RCL 3	34 03	
	RCL A	34 11	
	x	71	
	RCL 4	34 04	
	RCL A	34 11	
	x	71	
	g x^2	32 54	
	f P→S	31 42	
040	RCL 3	34 03	
	x	71	
	RCL B	34 12	
	x	71	
	RCL B	34 12	
	RCL 4	34 04	
	x	71	
	g x^2	32 54	
	÷	81	
	+	61	
050	STO 8	33 08	
	RCL 3	34 03	
	RCL 1	34 01	
	RCL B	34 12	
	g x^2	32 54	
	x	71	
	RCL B	34 12	

STEP	KEY ENTRY	KEY CODE	COMMENTS
	÷	81	
	f P←S	31 42	
	h x⇌y	35 52	
060	RCL C	34 13	
	x	71	
	2	02	
	x	71	
	−	51	
	RCL 4	34 04	
	x	71	
	RCL A	34 11	
	x	71	
	RCL 1	34 01	
070	RCL A	34 11	
	g x^2	32 54	
	x	71	
	f x⇌y	35 52	
	f P→S	31 42	
	RCL 4	34 04	
	÷	81	
	+	61	
	STO 9	33 09	
	RCL 0	34 00	
080	RCL B	34 12	
	g x^2	32 54	
	x	71	
	RCL 2	34 02	
	RCL B	34 12	
	x	71	
	RCL D	34 14	
	x	71	
	+	61	
	RCL 5	34 05	
090	RCL D	34 14	
	g x^2	32 54	
	x	71	
	+	61	
	RCL B	34 12	
	x	71	
	RCL 1	34 01	
	RCL B	34 12	
	x	71	
	RCL 4	34 04	
100	RCL D	34 14	
	x	71	
	+	61	
	RCL C	34 13	
	RCL 3	34 03	
	x	71	
	−	51	
	RCL C	34 13	
	x	71	
	RCL B	34 12	
110	x	71	
	−	51	
	f P←S	31 42	

REGISTERS

0	1	2	3	4	5	6	7	8	9
$G1_a$	$G2_a$	$G3_a$	$G4_a$	$G5_a$	$G6_a$	$G7_a$	$G8_a$	$N_1-1/C3_a$	$N_1/C3_b$

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
$G1_b$	$G2_b$	$G3_b$	$G4_b$	$G5_b$	$G6_b$	$G7_b$	$G8_b$	A	B

A	B	C	D	E	I
$\delta N_1/C_A$	$\delta N_2/C_B$	V_1/Z	V_2/P_A	$N_1/C2_a$	$N_2/C2_b$

 CARD B

Program Listing II

CARD B

67

STEP	KEY ENTRY	KEY CODE	COMMENTS
	RCL 0	34 00	
	RCL A	34 11	
	3	03	
	h y^x	35 63	
	x	71	
	+	61	
	RCL 2	34 02	
120	RCL A	34 11	
	g x^2	32 54	
	x	71	
	RCL D	34 14	
	x	71	
	−	51	
	RCL 5	34 05	
	RCL A	34 11	
	x	71	
	RCL D	34 14	
130	g x^2	32 54	
	x	71	
	+	61	
	f P→S	31 42	
	RCL 8	34 08	
	x	71	
	4	04	
	x	71	
	CHS	42	
	RCL 9	34 09	
140	g x^2	32 54	
	+	61	
	f $\sqrt{x}$	31 54	
	ENT↑	41	
	CHS	42	
	RCL 9	34 09	
	−	51	
	2	02	
	÷	81	
	RCL 8	34 08	
150	÷	81	
	STO E	33 15	
	h x⇄y	35 52	
	RCL 9	34 09	
	−	51	
	2	02	
	÷	81	
	RCL 8	34 08	
	÷	81	
	h ST I	35 33	
160	RCL 4	34 04	
	RCL B	34 12	
	x	71	
	h 1/x	35 62	
	f P←S	31 42	
	RCL 4	34 04	
	x	71	
	RCL A	34 11	
	x	71	

STEP	KEY ENTRY	KEY CODE	COMMENTS
	ENT↑	41	
170	ENT↑	41	
	RCL E	34 15	
	x	71	
	CHS	42	
	RCL C	34 13	
	+	61	
	STO 8	33 08	
	h R↓	35 53	
	h RC I	35 34	
	x	71	
180	CHS	42	
	RCL C	34 13	
	+	61	
	STO 9	33 09	
	R/S	84	
	f LBL A	31 25 11	
	RCL A	34 11	
	RCL E	34 15	
	+	61	
	h 1/x	35 62	
190	R/S	84	R1a
	f LBL B	31 25 12	
	RCL E	34 15	
	h 1/x	35 62	
	R/S	84	R2a
	f LBL C	31 25 13	
	RCL 8	34 08	
	h 1/x	35 62	
	R/S	84	R3a
	f LBL D	31 25 14	
200	RCL 8	34 08	
	RCL B	34 12	
	−	51	
	h 1/x	35 62	
	R/S	84	R4a
	g LBL a	32 25 11	
	RCL A	34 11	
	h RC I	35 34	
	+	61	
	h 1/x	35 62	
210	R/S	84	R1b
	g LBL b	32 25 12	
	h RC I	35 34	
	h 1/x	35 62	
	R/S	84	R2b
	g LBL c	32 25 13	
	RCL 9	34 09	
	h 1/x	35 62	
	R/S	84	R3b
	g LBL d	32 25 14	
220	RCL 9	34 09	
	RCL B	34 12	
	−	51	
	h 1/x	35 62	
	R/S	84	R4b

LABELS

A → R1a	B → R2a	C → R3a	D → R4a	E RUN
a → R1b	b → R2b	c → R3b	d → R4b	e
0	1	2	3	4
5	6	7	8	9

FLAGS

0
1
2
3

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n	3

Program Description I

Program Title OPTICAL DESIGN II

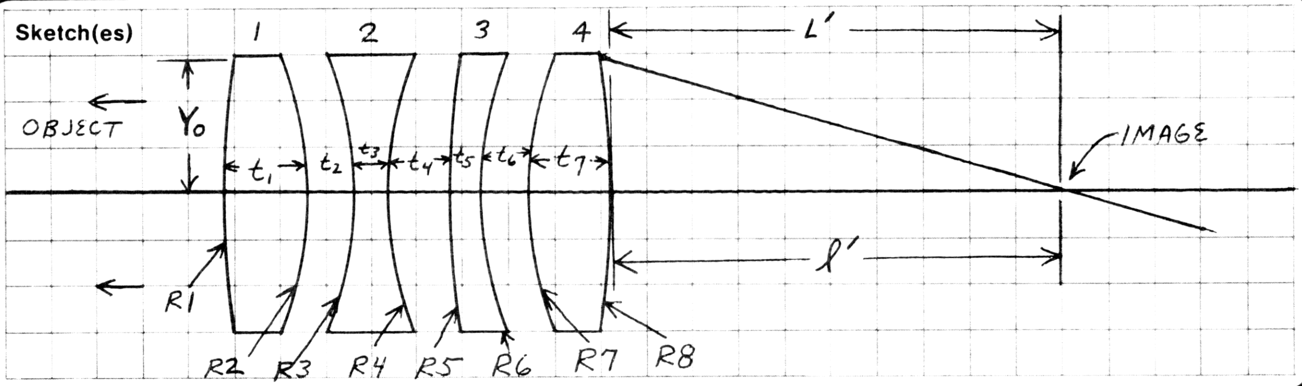
Contributor's Name JOSEPH R. HOBART
Address 8723 BRADY AVENUE
City SPRING VALLEY **State** CA **Zip Code** 92077

Program Description, Equations, Variables THIS PROGRAM USES TRIGONOMETRIC RAY TRACING TECHNIQUES TO COMPUTE THE INTERSECTION LENGTH FOR THE PARAXIAL RAYS (l') AND MARGINAL RAYS (L'), PRIMARY LONGITUDINAL SPHERICAL ABERRATION (LA'), OFFENCE AGAINST SINE CONDITION (OSC'), EFFECTIVE FOCAL LENGTH (efl), AND SYSTEM TOLERANCES FOR THE LA' AND OSC', FOR A ONE TO FOUR LENS OBJECTIVE. PARALLEL INCOM ING LIGHT IS ASSUMED. SIGN CONVENTIONS ARE AS PER CONRADY (REFERENCE 1): FOR A LENS SYSTEM WITH OBJECT TO THE LEFT (SEE SKETCH), LENSES AND SURFACE RADII ARE EACH NUMBERED CONSECUTIVELY FROM LEFT TO RIGHT; RADII ARE POSITIVE IF THEY EXTEND TOWARD THE IMAGE AND NEGATIVE IF THEY EXTEND TOWARD THE OBJECT (POSITIVE RADII ARE CONVEX TOWARD THE OBJECT); AND INTERSECTION LENGTHS ARE POSITIVE IF THEY EXTEND (CROSS THE OPTICAL AXIS) TOWARD THE IMAGE AND NEGATIVE IF TOWARD THE OBJECT. DATA IS ENTERED EN MASSE USING fA, INDIVIDUALLY MODIFIED USING fB, REFRACTIVE INDICES ALL MODIFIED USING fC, AND SEMI-APERTURE (Y_O) MODIFIED USING fD. fA AND fC DISPLAY REGISTER NUMBER AND LENS NUMBER RESPECTIVELY PRIOR TO DATA ENTRY. USER MUST DESIGNATE STORAGE REGISTER WHEN USING fB (SEE EXAMPLE). fD STORES NUMBER IN DISPLAY IN Y_O REGISTER. CEMENTED SURFACES ARE ENTERED AS TWO SEPARATE, IDENTICAL RADII WITH ZERO SPACING.

Operating Limits and Warnings ENSURE STRICT COMPLIANCE WITH SIGN CONVENTIONS. CLEAR PRIMARY AND SECONDARY REGISTERS PRIOR TO ENTERING DATA FOR A NEW SYSTEM; PROGRAM USES A ZERO IN DATA TO HALT EXECUTION OF A SYSTEM USING LESS THAN FOUR LENSES. TOLERANCES ARE BASED ON INCH UNITS; STEPS 208-211 ARE FOUR TIMES WAVELENGTH OF LIGHT IN INCHES AND MUST BE MODIFIED FOR OTHER UNITS. OSC' IS COMPUTED FOR ONE UNIT OFF AXIS, HOWEVER, OSC' IS A LINEAR FUNCTION DIRECTLY PROPORTIONAL TO OFF AXIS DISTANCE.

Program Description II

Sketch(es)



Sample Problem(s) (FROM REFERENCE 1 CH. 88) FIND THE ABERRATIONS OF A THREE LENS PHOTOVISUAL OBJECTIVE WITH PARAMETERS: LENS 1 Nc=1.51358, Nd=1.5160, Nf=1.52167; LENS 2 Nc=1.53447, Nd=1.5376, Nf=1.54516; LENS 3 Nc=1.57968, Nd=1.5833, Nf=1.59219; Y_O=.25;

R1= 2.3844	T1= .07
R2= -.8923	T2= .0325 (AIR)
R3= -.8524	T3= .02
R4= .92	T_4= 0 (CEMENTED)
R5= .92	T5= .05
R6= 4.7104	

SOLUTION. KEYSTROKES: (SEE WARNING ON PAGE ONE) OUTPUT

fA (TO TRACE IN D LIGHT)	0.0000
.25 R/S 1.5160 R/S 2.3844 R/S .07 R/S -.8923 R/S	

Solution(s)

.0325 R/S 1.5376 R/S -.8524 R/S .02 R/S .92 R/S	
0 R/S 1.5833 R/S .92 R/S .05 R/S 4.7104 R/S.	15.0000
A	8.6608 (l')
A	8.6621 (L')
B	-.0013 (LA')
C	.0004 (OSC')
D	9.0708 (efl)
E	.1184 (tol)
fE	.0004 (tol)

Reference(s)

(1) CONRADY, A.E., APPLIED OPTICS AND OPTICAL DESIGN PARTS 1 and 2, DOVER PUBLICATIONS, NEW YORK, 1957 and 1960.

(2) WYLD, J.H., " THE DESIGN OF REFRACTOR OBJECTIVES BY RAY TRACING", AMATEUR TELESCOPE MAKING BOOK THREE, SCIENTIFIC AMERICAN, INC. 1953.

Program Description II

Sketch(es)

Sample Problem(s)

SOLUTION (CONT):

fC (TO TRACE IN C LIGHT)	1.0000
1.51358 R/S 1.53447 R/s 1.57968 R/S	4.0000
A	8.6643 (1')
A	8.6656 (L')
B	-.0013 (LA')
C	.0004 (OSC')
D	9.0729 (efl)
E	.1185 (LA' tol)
fE	.0004 (OSC' tol)
fC (TO TRACE IN F LIGHT)	1.0000
1.52167 R/S 1.54516 R/S 1.59219	4.0000
A	8.6643 (1')

Solution(s)

A	8.6662 (L')
B	-.0019 (LA')
C	.0005 (OSC')
D	9.0778 (efl)
E	.1186 (LA' tol)
fE	.0004 (OSC' tol)

(IT TAKES ABOUT 47 SECONDS TO SOLVE FOR 1' IN A THREE LENS SYSTEM)

Reference(s) THE EQUATIONS AND TECHNIQUES USED IN THIS PROGRAM ARE HIGHLY DETAILED. USER IS REFERED TO A THOROUGH DISCUSSION IN REFERENCE (1) OR A BRIEF DESCRIPTION IN REFERENCE (2). THIS PROGRAM DOES NO DESIGN FUNCTION; IT ONLY CALCULATES THE ABERRATIONS OF A GIVEN DESIGN.

User Instructions

OPTICAL RAY TRACE			OPTICAL DESIGN II	
1 ENT DATA	MOD DATA	MOD N	MOD Y_O	OSC' tol 2
1',L'	LA'	OSC'	efl	LA' tol

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	LOAD SIDES 1 and2 (SEE WARNING PAGE ONE)				
2	LOAD DATA:		f	A	0.0000
	ENTER DATA FOR REGISTER NUMBER DISPLAYED IN				
	X REGISTER; REGISTER DESIGNATION IS AS				
	LISTED AT THE BOTTOM OF PAGE FIVE.		R/S		1.0000
	REPEAT AS NECESSARY.				
3	COMPUTE 1' (REQUIRES ~ 15 SECONDS PER LENS)		A		1'
4	COMPUTE L'		A		L'
5	COMPUTE LA'		B		LA'
6	COMPUTE OSC'		C		OSC'
7	COMPUTE efl		D		efl
8	COMPUTE SYSTEM RAYLEIGH TOLERANCE (LIMIT) FOR LA'		E		LA' tol
9	COMPUTE RAYLEIGH TOLERANCE FOR OSC'		f	E	OSC' tol
10	OPTIONAL DATA MODIFICATION:				
	TO MODIFY ONE PARAMETER		f	B	0.0000
	ENTER NEW DATA		ENT		DATA
	ENTER REGISTER NUMBER		R/S		0.0000
	REPEAT AS NECESSARY				
	TO MODIFY REFRACTIVE INDICES		f	C	1.0000
	ENTER INDEX FOR LENS 1		R/S		2.0000
	REPEAT FOR LENSES 2,3,4 AS NECESSARY**				
	TO MODIFY Y_O				
	ENTER NEW DATA		f	D	DATA
11	RETURN TO STEP THREE				
	** DO NOT ENTER IRRELEVANT DATA FOR LENSES NOT				
	USED. THE PROGRAM SEARCHES FOR ZERO TO EXIT				
	FROM A 1,2 OR 3 LENS SOLUTION.				
	STEPS FIVE THROUGH NINE MAY BE CALLED				
	IN ANY ORDER. CALLING STEPS 5,6 OR 7				
	IMMEDIATELY AFTER STEP TEN, HOWEVER,				
	WILL CAUSE THE PROGRAM TO SUBROUTINE				
	TO A AND RESOLVE FOR 1' AND L'.				

67 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS	STEP	KEY ENTRY	KEY CODE	COMMENTS
001	f LBL A	31 25 11	CALC ℓ'		f GSB 6	31 22 06	
	h CF 1	35 61 01			x	71	
	2	02			RCL (i)	34 24	R
	h ST I	35 33		060	x	71	
	CLX	44			RCL (i)	34 24	
	STO C	33 13			+	61	
	STO D	33 14			f ISZ	31 34	
	RCL 0	34 00	Y_0		STO A	33 11	
	STO B	33 12			2	02	
010	RCL 2	34 02	R1		0	00	
	÷	81			h RC I	35 34	
	GTO 3	22 03			−	51	
	f LBL 2	31 25 02			f x=0	31 51	
	RCL A	34 11	L	070	h SF 1	35 51 01	
	f GSB 0	31 22 00			f x≠0	31 61	TEST FOR LAST LENS
	f LBL 3	31 25 03			RCL (i)	34 24	t
	↑	41			CHS	42	
	↑	41			RCL A	34 11	L
	↑	41			+	61	
020	f DSZ	31 33			STO A	33 11	L'
	RCL (i)	34 24	N		1	01	
	STO E	33 15			RCL E	34 15	N
	÷	81			−	51	
	f GSB 6	31 22 06		080	RCL B	34 12	
	÷	81			x	71	
	f ISZ	31 34			RCL E	34 15	N
	RCL (i)	34 24	R		RCL D	34 14	u'
	x	71			x	71	
	RCL (i)	34 24			f DSZ	31 33	
030	+	61			RCL (i)	34 24	R
	f ISZ	31 34			x	71	
	RCL (i)	34 24	t		+	61	
	−	51			f GSB 7	31 22 07	
	STO A	33 11		090	h F? 1	35 71 01	
	RCL E	34 15	N		GTO 4	22 04	
	RCL E	34 15			f ISZ	31 34	
	1	01			f ISZ	31 34	
	−	51			RCL (i)	34 24	N
	RCL B	34 12	y'		f x≠0	31 61	CHECK FOR ZERO
040	x	71			GTO 2	22 02	
	RCL D	34 14	u		f LBL 4	31 25 04	
	f DSZ	31 33			RCL B	34 12	y'
	RCL (i)	34 24	R		RCL D	34 14	u'
	x	71		100	÷	81	
	+	61			h CF 0	35 61 00	
	h x⇄y	35 52			h RTN	35 22	ℓ' *
	÷	81			f LBL A	31 25 11	
	f GSB 7	31 22 07			RCL A	34 11	
	RCL A	34 11	L'		h RTN	35 22	L' *
050	f ISZ	31 34			f LBL B	31 25 12	CALC LA'
	f GSB 0	31 22 00			f GSB 9	31 22 09	
	↑	41			f GSB 4	31 22 04	
	↑	41			RCL A	34 11	L'
	↑	41		110	−	51	
	RCL E	34 15	N		h RTN	35 22	LA' *
	x	71			f LBL C	31 25 13	CALC OSC'

REGISTERS

0	1	2	3	4	5	6	7	8	9
Y_0	N1	R1	T1	R2	T2	N2	R3	T3	R4

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
T4	N3	R5	T5	R6	T6	N4	R7	T7	R8

A	B	C	D	E	I
L'	y'	U'	u'	N (i)	CONTROL

67 Program Listing II

STEP	KEY ENTRY	KEY CODE	COMMENTS	STEP	KEY ENTRY	KEY CODE	COMMENTS
	f GSB 9	31 22 09			CHS	42	
	1	01		170	RCL B	34 12	y'
	RCL B	34 12	y'		+	61	
	RCL C	34 13	U'		STO B	33 12	
	f SIN	31 62			h RTN	35 22	
	÷	81			f LBL 0	31 25 00	
	RCL A	34 11	L'		RCL (i)	34 24	
120	÷	81			—	51	
	—	51			RCL (i)	34 24	
	h RTN	35 22	OSC' *		÷	81	
	f LBL D	31 25 14	CALC efl		RCL C	34 13	
	f GSB 9	31 22 09		180	f SIN	31 62	
	RCL 0	34 00	Y_0		x	71	
	RCL D	34 14	u'		h RTN	35 22	
	÷	81			g LBL c	32 25 13	MOD N
	h RTN	35 22	efl *		h SF 0	35 51 00	
	g LBL a	32 25 11	LOAD DATA		1	01	
130	h SF 0	35 51 00			↑	41	
	0	00			f LBL 8	31 25 08	
	h ST I	35 33			h ST I	35 33	
	f LBL 5	31 25 05			h x⇄y	35 52	
	R/S	84		190	R/S	84	
	STO (i)	33 24			STO (i)	33 24	
	f ISZ	31 34			h R↓	35 53	
	h RC I	35 34			1	01	
	GTO 5	22 05			+	61	
	g LBL b	32 25 12	MOD DATA		h RC I	35 34	
140	0	00			5	05	
	R/S	84			+	61	
	h SF0	35 51 00			GTO 8	22 08	
	h ST I	35 33			f LBL 9	31 25 09	
	h R↓	35 53		200	h F?0	35 71 00	
	STO (i)	33 24			f GSB A	31 22 11	
	GTO f b	22 31 12			h RTN	35 22	
	f LBL 6	31 25 06			g LBL d	32 25 14	MOD Y_0
	g SIN^{-1}	32 62			h SF0	35 51 00	
	CHS	42			STO 0	33 00	
150	h x⇄y	35 52			h RTN	35 22	
	g SIN^{-1}	32 62			f LBL E	31 25 15	CALC LA' TOLERANCE
	+	61			9	09	MUST BE 4 X λ
	RCL C	34 13	U'		EEX	43	IN UNITS USED
	+	61		210	CHS	42	FOR OTHER DATA.
	STO C	33 13			5	05	THIS VALUE IS FOR
	f SIN	31 62			RCL C	34 13	INCH UNITS.
	÷	81			f SIN	31 62	
	RCL E	34 15	N		g x^2	32 54	
	h RTN	35 22			÷	81	
160	f LBL 7	31 25 07			h RTN	35 22	LA' TOL *
	RCL (i)	34 24	R		g LBL e	32 25 15	CALC OSC' TOLERANCE
	÷	81			f GSB E	31 22 15	
	STO D	33 14			8	08	
	f ISZ	31 34		220	÷	81	
	h F?1	35 71 01			RCL C	34 13	U'
	h RTN	35 22			f SIN	31 62	
	RCL (i)	34 24	t		x	71	
	x	71			h RTN	35 22	OSC' TOL *

LABELS

A ℓ'/L'	B LA'	C OSC'	D efl	E LA' tol
a LOAD DATA	b MOD DATA	c MOD N	d MOD Y0	e OSC' tol
0 SUBROUTINE	1	2 CONTINUE	3 CONTINUE	4 CALC ℓ'
5 CONTINUE	6 SUBROUTINE	7 SUBROUTINE	8 CONTINUE	9 INTERLOCK

FLAGS

0	INTERLOCK
1	EXIT
2	
3	

SET STATUS

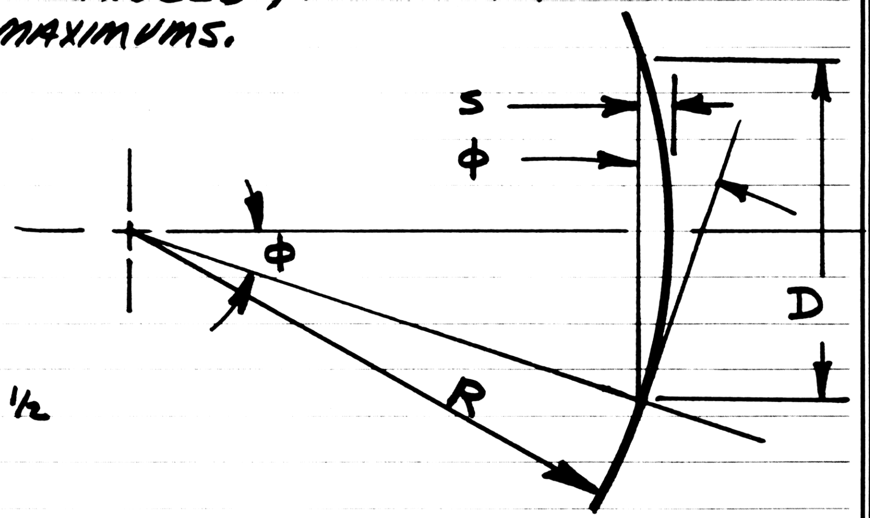
FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n	4

Program Description I

Program Title LENS CALCULATIONS – SAG, ANGLE, MIN/MAX

Contributor's Name L. D. TUCHSCHERER
Address 5880 CATHEDRAL OAKS RD.
City GOLETA State CA Zip Code 93017

Program Description, Equations, Variables GIVEN ANY TWO OF THREE (RADIUS OF CURVATURE, DIAMETER, SAG) PROGRAM COMPUTES OTHER ONE AND ANGLE OF TANGENCY. WITH INPUTS TOLERANCED, PROGRAM CALCULATES MINIMUMS AND MAXIMUMS.



$$R = \frac{D^2 + 4s^2}{8s}$$

$$D = 2\left(2Rs - s^2\right)^{1/2}$$

$$s = R - \tfrac{1}{2}\left(4R^2 - D^2\right)^{1/2}$$

$$\phi = \tan^{-1}\left(\frac{D}{2(R-s)}\right)$$

Operating Limits and Warnings

THE FOLLOWING MUST BE TRUE:

$$s \leq R$$

$$D \leq 2R$$

Program Description II

Sketch(es)

SEE PAGE 1.

Sample Problem(s)

GIVEN: R = 5 ± .7
D = 7 ± 1.0

DETERMINE: S_{NOM}.
S_{MAX}.
S_{MIN}.
ϕ_{NOM}.
ϕ_{MAX}.
ϕ_{MIN}.

Solution(s)

KEY	DISPLAY
[A]	0.000
5 [B]	5.000
.7 [f] [B]	0.700
7 [C]	7.000
1 [f] [C]	1.000
[D]	1.429 = S_{NOM}
[f] [D]	2.722 = S_{MAX}
[f] [D]	0.853 = S_{MIN}
[E]	44.2537 = ϕ_{NOM}
[f] [E]	68.2816 = ϕ_{MAX}
[f] [E]	31.4525 = ϕ_{MIN}

NOTE! ϕ = DD.MMSS

Reference(s) HANDBOOK OF MATH TABLES AND FORMULAS, R.S. BURINGTON, McGRAW HILL, N.Y., 1962, pp 11-12 para 37 FIG 2

User Instructions

LENS CALC - SAG, ANGLE, MIN/MAX				
f →	± / MAX MIN	± / MAX MIN	± / MAX MIN	MAX/MIN
START	R	D	S	φ

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	ENTER PROGRAM — TWO SIDES				
2	INITIALIZE		A		0.000
3	FOR MAX/MIN CALCULATIONS -				
	GO TO STEP 7. OTHERWISE	R	B		R
	CONTINUE BY ENTERING NOMINAL	OR D	C		D
	VALUES — TWO OF THREE →	OR S	D		S
4	COMPUTE THE UNKNOWN		B		R
			OR C		D
			OR D		S
5	COMPUTE NOMINAL ANGLE IF DESIRED		E		φ*
6	FOR NEW PROB. OR TOLERANCES GO TO 2				
7	ENTER TWO OF THREE NOMINAL	R_{nom}	B		R
	VALUES EACH FOLLOWED BY ITS	± TOL.	f	b	± TOL.
	TOLERANCE	OR D_{nom}	C		D
		± TOL.	f	c	± TOL
		OR S_{nom}	D		S
		± TOL.	f	d	± TOL
8	COMPUTE THE UNKNOWN NOMINAL		B		R_{nom}
	AND ITS MAX AND MIN VALUES		f	b	R_{max}
	IF DESIRED		f	b	R_{min}
		OR	C		D_{nom}
			f	c	D_{max}
			f	c	D_{min}
		OR	D		S_{nom}
			f	d	S_{max}
			f	d	S_{min}
9	COMPUTE NOMINAL ANGLE IF		E		$φ_{nom}$*
	DESIRED AND ITS MAX AND MIN		f	e	$φ_{max}$*
	IF DESIRED		f	e	$φ_{min}$*
10	FOR NEW PROB. GO TO STEP 2				
	* OUTPUT φ = DD.MMSS				

67 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
A	f LBL A	31 25 11	
	f CLR REG	31 43	
	CLX	44	INITILIZE
	DSP 3	23 03	
	h RTN	35 22	
B	f LBL B	31 25 12	Rnom
	h F? 3	35 71 03	?
	GTO 0	22 00	CALC STO · / GTO 0 STO
	RCL 1	34 01	
	g x²	32 54	
	RCL 4	34 04	
	g x²	32 54	
	4	04	Rnom = f (Dnom Snom)
	x	71	
	+	61	
	RCL 4	34 04	
	8	08	
	x	71	
	÷	81	
	STO 7	33 07	
	h RTN	35 22	
b	g LBL f b	32 25 12	CALC Rmax + STO
	RCL 3	34 03	
	g x²	32 54	
	RCL 6	34 06	
	g x²	32 54	
	4	04	Rmax = f (Dmin, Smin)
	x	71	
	+	61	
	RCL 6	34 06	
	8	08	
	x	71	
	÷	81	
	STO 8	33 08	
	h RTN	35 22	
b	g LBL f b	32 25 12	CALC Rmin + STO
	RCL 2	34 02	
	g x²	32 54	
	RCL 5	34 05	
	g x²	32 54	
	4	04	Rmin = f (Dmax, Smax)
	x	71	
	+	61	
	RCL 5	34 05	
	8	08	
	x	71	
	÷	81	
	STO 9	33 09	
	h RTN	35 22	
0	f LBL 0	31 25 00	STO Rnom
	STO 7	33 07	
	h RTN	35 22	
b	g LBL f b	32 25 12	R± —
	STO C	33 13	
	RCL 7	34 07	CALC + STO
	+	61	
	STO 8	33 08	Rmax
	RCL 7	34 07	
	RCL C	34 13	
	−	51	
	STO 9	33 09	Rmin
	RCL C	34 13	
	h CF 3	35 61 03	
	h RTN	35 22	
C	f LBL C	31 25 13	Dnom
	h F? 3	35 71 03	?
	GTO 1	22 01	CALC + STO / GTO 1 STO
	RCL 7	34 07	
	RCL 4	34 04	
	x	71	
	2	02	
	x	71	
	RCL 4	34 04	Dnom = f (Rnom, Snom)
	g x²	32 54	
	−	51	
	f √x	31 54	
	2	02	
	x	71	
	STO 1	33 01	
	h RTN	35 22	
c	g LBL f c	32 25 13	CALC Dmax + STO
	RCL 9	34 09	
	RCL 5	34 05	
	x	71	
	2	02	
	x	71	Dmax = f (Rmin, Smax)
	RCL 5	34 05	
	g x²	32 54	
	−	51	
	f √x	31 54	
	2	02	
	x	71	
	STO 2	33 02	
	h RTN	35 22	
c	g LBL f c	32 25 13	CALC Dmin + STO
	RCL 8	34 08	
	RCL 6	34 06	
	x	71	
	2	02	Dmin = f (Rmax, Smin)
	x	71	
	RCL 6	34 06	
	g x²	32 54	
	−	51	
	f √x	31 54	
	2	02	
	x	71	
	STO 3	33 03	
	h RTN	35 22	
1	f LBL 1	31 25 01	STO Dnom
	STO 1	33 01	
	h RTN	35 22	
c	g LBL f c	32 25 13	

REGISTERS

0	1	2	3	4	5	6	7	8	9
—	Dnom	Dmax	Dmin	Snom	Smax	Smin	Rnom	Rmax	Rmin

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
—	—	—	—	—	—	—	—	—	—

A	B	C	D	E	I
D (± TOL)	S (± TOL)	R (± TOL)	—	—	—

67 Program Listing II

STEP	KEY ENTRY	KEY CODE	COMMENTS
	STO A	3311	D± —
	RCL 1	3401	
	+	61	CALC + STO
	STO 2	3302	
	RCL 1	3401	DMAX
	RCL A	3411	
	−	51	
120	STO 3	3303	
	RCL A	3411	DMIN
	h CF 3	35 61 03	
	h RTN	3522	
D	f LBL D	31 25 14	SNOM
	h F? 3	35 71 03	?
	GTO 2	22 02	
	RCL 7	3407	CALC STO / GTO 2 + STO
	g x^2	3254	
	4	04	
130	×	71	
	RCL 1	3401	
	g x^2	3254	
	−	51	
	f $\sqrt{x}$	3154	$S_{NOM} = f(D_{NOM}, R_{NOM})$
	2	02	
	÷	81	
	CHS	42	
	RCL 7	3407	
	+	61	
140	STO 4	3304	
	h RTN	3522	
d	g LBL f d	32 25 14	CALC SMAX + STO
	RCL 9	3409	
	g x^2	3254	
	4	04	
	×	71	
	RCL 2	3402	$S_{MAX} = f(R_{MIN}, D_{MAX})$
	g x^2	3254	
	−	51	
150	f $\sqrt{x}$	3154	
	2	02	
	÷	81	
	CHS	42	
	RCL 9	3409	
	+	61	
	STO 5	3305	
	h RTN	3522	
d	g LBL f d	32 25 14	CALC SMIN + STO
	RCL 8	3408	
160	g x^2	3254	
	4	04	
	×	71	$S_{MIN} = f(R_{MAX}, D_{MIN})$
	RCL 3	3403	
	g x^2	3254	
	−	51	
	f $\sqrt{x}$	3154	
	2	02	
	÷	81	

STEP	KEY ENTRY	KEY CODE	COMMENTS
	CHS	42	
170	RCL 8	3408	
	+	61	
	STO 6	3306	
	h RTN	3522	
2	f LBL 2	31 25 02	
	STO 4	3304	STO SNOM
	h RTN	3522	
d	g LBL f d	32 25 14	CALC + STO
	STO B	3312	
	RCL 4	3404	
180	+	61	
	STO 5	3305	SMAX
	RCL 4	3404	
	RCL B	3412	
	−	51	
	STO 6	3306	
	RCL 6	3412	SMIN
	h CF 3	3561	
	h RTN	3522	
E	f LBL E	31 25 15	CALC ϕ_{NOM}
190	RCL 1	3401	
	2	02	
	÷	81	
	RCL 7	3407	
	RCL 4	3404	
	−	51	$\phi_{NOM} = f(R_{NOM}, D_{NOM}, S_{NOM})$
	÷	81	
	g TAN⁻¹	3264	
	DSP 4	2304	
	g →HMS	3274	
200	h RTN	3522	
e	g LBL f e	32 25 15	CALC ϕ_{MAX}
	RCL 2	3402	
	2	02	
	÷	81	
	RCL 9	3409	$\phi_{MAX} = f(D_{MAX}, R_{MIN}, S_{MAX})$
	RCL 5	3405	
	−	51	
	÷	81	
	g TAN⁻¹	3264	
210	f →HMS	3274	
	h RTN	3522	
e	g LBL f e	32 25 15	CALC ϕ_{MIN}
	RCL 3	3403	
	2	02	
	÷	81	
	RCL 8	3408	
	RCL 6	3406	$\phi_{MIN} = f(D_{MIN}, R_{MAX}, S_{MIN})$
	−	57	
	÷	81	
220	g TAN⁻¹	3264	
	f →HMS	3274	
	h RTN	3522	

LABELS

A START	B R	C D	D S	E ϕ
a —	b ±/ MAX MIN	c ±/ MAX MIN	d ±/ MAX MIN	e MAX/MIN
0 USED	1 USED	2 USED	3 —	4 –
5 –	6 —	7 —	8 —	9 —

FLAGS

0	—
1	—
2	—
3	USED

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n	3

Program Description I

Program Title RAY TRACER- SPHERICAL, PARABOLOIDAL AND FLAT SURFACES

Contributor's Name ALAN STEIN

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City DALY CITY **State** CA **Zip Code** 94014

Program Description, Equations, Variables This program traces light rays in two-dimensions through spherical, flat or paraboloidal cross sections of lens surfaces. Theray may be in the form of a slope (or the corresponding angle) and the y-intercept, the surface intercept, or an arbitrary point of the ray, (x,y). All forms are converted to slope-y-intercept (a,b) form(see sketch).

The flat surface is defined by $x = f_a*y + f_b$. Inputs are (fa,fb). The sphere is defined by radius of curvature(R) and intercept of surface with x -axis. If R is positive, the left intercept of ray and surface is found. If R is negative the right intereept is found. The parabola is also defined by R and d, where d is still the x-intercept. R is the distance from d at which $y= \pm 1$ (i.e. the parabola is defined as $x= Ry^2+d$).

r_i is the ratio of the exit over incident refractive indices at the boundary.

The program computes the lens-ray intercept (x_i, y_i) and displays this as an option. The slope and y-intercept of the refracted ray, (a',b') are computed from Snell's law and stored in R_a and R_b for future reference. All computations are analytic.

Note that the program always selects the parabola-ray intercept closest to the x-axis intersection(d).

equations: ray-- y=ax+b; sphere-- $x= \mathrm{SQRT}(R^2-y^2)*(-\mathrm{sgn}(R))+(R+d)$
flat-- $x = f_a y+f_b$: parabola -- $x= Ry^2+d$.
Snells law: $\sin(\theta') = \sin(\theta)/r_i$ where $r_i = r_{exit}/r_{incident}$

Operating Limits and Warnings NOTE: f_a and f_b are the reciprocal of the slope and the x-intercept, respectively.

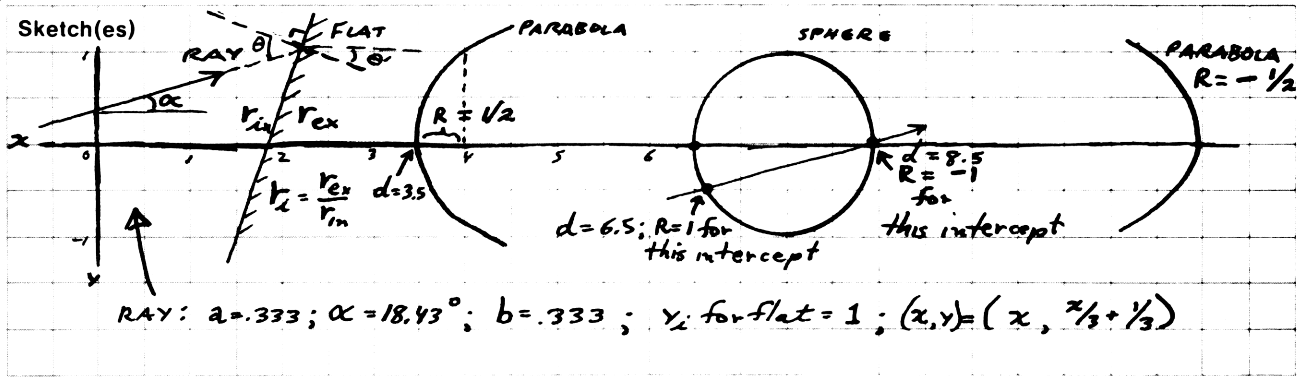
LIMITS: $\alpha \neq 90^\circ$
$r_i > 0$
$R \neq 0$

ERROR MESSAGE WILL BE DISPLAYED:

1) if ray and lens are chosen so that no intersection exists
or
2) CONDITIONS ARE SUCH THAT TOTAL INTERNAL REFLECTION OCCURS AT INTERSECTION.

Program Description II

Sketch(es)



Sample Problem(s)

1) A flat with slope^{-1} of -1/2 and -intercept of 4, r_i=2, is intersected by a ray with slope = 1 and y-intercept = -2. Find the point of intersection and the refracted ray.

2) For a spherical surface of radius=2 and right x-intercept of 6, find the point of intersection with a ray coming in at 45° and passing through the point (1,-2). If the refractive index is 2, find the refracted ray.

3) Given a parabola with R=1 and d=3, find the intersection with a ray of slope .3333333 and lens-y-intercept of -.43649. Find the refracted ray if r_i=2.

Solution(s)

1) .5, CHS, ent, 4, B, 2, C, fB, 1 , ent, 2, CHS, D, (x_i,y_i) = (3.33333,1.33333); fC, a'=.71758, b'=-1.05860.

2) 2, CHS, ent, 6, A, fB, 45, ent, 1, ent, 2, CHS, fD, (x_i,y_i)= (4.82288, 1.82288); 2, C, fC, a'=1.45625, b'=-5.20042.

3) 1, ent, 3, fA, fB, 2, C, .3333333, ent, .43649, CHS, E, x_i,y_i)= (3.19052, -.43649); fC, a'=.57740, b'= -2.27869

Reference(s)

author's HP-65 programs for ray tracing through spherical and paraboloidal surfaces.

User Instructions

RAY TRACE-- SPHERES,PARABOLOIDS AND FLATS

parabola	see int?	find a'b'	$\to\alpha,(x,y)$	$\to\alpha, y_i$
$\to$R, d	$\to f_a, f_b$	$\to r_i$	$\to$a,b	$\to a, y_i$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	LOAD SIDES ONE AND TWO OF CARD	-----	--	--	-----
2	Load positive radius and x-intercept for left-side of sphere	R	ENT		
		d	A		
	OR				
2	Load negative radius and x-intercept for right-side of sphere	R	ENT		
		d	A		
	OR				
2	Load R and x-intercept(d) for parabola	R	ENT		
		d	f	A	
	OR				
2	Load inverse slope (f_a) and x-intercept (f_b) for flat	f_a	ENT		
		f_b	B		
	OPTIONAL: DISPLAY (x_i, y_i)	-----	f	B	
3	Load refractive ratio (r_i)	r_i	C		
4	Load slope(a) and y-intercept of ray,	a	ENT		
	find a', b' (optional: find (x_i,y_i))	b	D		y:a';x:b'
	(optional results)	-----	----	----	($y:y_i$; $x:x_i$)
	OR				
4	load angle(α) and point (x,y) of ray	α	ENT		
		x	ENT		
	find a',b' (optional, find (x_i,y_i))	y	f	D	as above
	OR				
4	Load slope and y-coordinate of lens intersection(y_i).	a	ENT		
	find a',b' (optional, find (x_i,y_i))	y_i	E		as above
	OR				
4	Load angle(α) and y_i. Outputs as in other choices.	α	ENT		
		y_i	f	E	as above
	OPTIONAL: FIND a', b' after display of (x_i,y_i)	----	f	C	y:a';x:b'
	FOR NEW CASE, GO TO STEP 2.				

ray trace: s,p & f

67 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBL a	32 25 11	SET FLAGS FOR
	SF 0	35 51 00	PARABOLIC CASE
	CF 1	35 61 01	
	GTO 3	22 03	
	*LBL B	31 25 12	SET FLAGS FOR
	CF 0	35 61 00	FLAT CASE
	SF 1	35 51 01	
	GTO 3	22 03	
	*LBL A	31 25 11	SET FLAGS FOR
010	CF 1	35 61 01	SPHERE CASE
	CF 0	35 61 00	---------------
	*LBL 3	31 25 03	
	STO 6	33 06	store d, f_b
	R↓	35 53	
	STO 5	33 05	store R, f_a
	R/S	84	
	*LBL b	32 25 12	SET FLAG TO
	SF 2	35 51 02	DISPLAY (x_i, y_i)
	R/S	84	
020	*LBL C	31 25 13	
	STO 0	33 00	STORE r_i
	R/S	84	
	*LBL e	32 25 15	CONVERT α, y_i
	x↔y	35 52	
	tan	31 64	tan(α)=a
	x↔y	35 52	-------------
	*LBL E	31 25 15	LOAD a, y_i
	x↔y	35 52	
	STO 1	33 01	store a
030	x↔y	35 52	
	F? 0	35 71 00	if either flag is
	GTO 2	22 02	on, lens is not
	F?1	35 71 01	a sphere.
	GTO 2	22 02	
	STO 4	33 04	store y_i
	x^2	32 54	y^2
	RCL 5	34 05	R
	x^2	32 54	R^2
	x↔y	35 52	
040	GSB 9	31 22 09	$x=\pm\sqrt{(R^2-y^2)}$
	CHS	42	
	RCL 5	34 05	R
	+	61	
	RCL 6	34 06	d
	+	61	correct x by R+d
	GTO 4	22 04	display(?) inter
	*LBL d	32 25 14	CONVERT α,(x,y)
	R↓	35 53	
	x↔y	35 52	a= atan(α)
050	tan	31 64	a*x
	x	71	
	LST x	35 82	x
	x↔y	35 52	
	R↑	35 54	y
	x↔y	35 52	
	-	51	b= y-ax

STEP	KEY ENTRY	KEY CODE	COMMENTS
	*LBL D	31 25 14	LOAD a,b
	x↔y	35 52	
	x ≠ 0?	31 61	if a = 0, then
060	GTO 5	22 05	case is same as
	x↔y	35 52	a, y_i, so go to
	GTO E	22 15	E.
	*LBL 5	31 25 05	------------
	STO 1	33 01	store a
	x↔y	35 52	
	STO 2	33 02	store b
	F?0	35 71 00	if flag 0, then
	GTO 0	22 00	paraboloid lens
	F?1	35 71 01	if flag 1, then
070	GTO 1	22 01	flat lans.
	x	71	ab
	RCL 5	34 05	R
	RCL 6	34 06	d
	+	61	R+d
	STO 9	33 09	store temporar.
	x↔y	35 52	
	-	51	R+d-ab
	RCL 1	34 01	a
	x^2	32 54	a^2
080	1	01	
	+	61	$1+a^2$
	STO 8	33 08	temporary store
	/	81	$m=(R+d-ab)/(1+a^2)$
	RCL 9	34 09	R+d
	RCL 5	34 05	R
	+	61	2R+d
	RCL 6	34 06	
	x	71	d(2R+d)
	RCL 2	34 02	b
090	x^2	32 54	b^2
	+	61	b^2+d^2+2Rd
	RCL 8	34 08	$1+a^2$
	/	81	$n=b^2+d^2+2Rd/1+a^2$
	x↔y	35 52	m
	ENT	41	
	ENT	41	
	x	71	m^2
	R↑	35 54	n
	GSB 9	31 22 09	$x=\pm\sqrt{(m^2-n)}$
100	-	51	$x_i=m-x$
	*LBL 4	31 25 04	------------
	ENT	41	store and display
	STO 3	33 03	(x_i, y_i)
	RCL 1	34 01	a
	x	71	ax_i
	RCL 2	34 02	
	+	61	$ax_i+b=y_i$
	STO 4	33 04	
	x↔y	35 52	display results
110	F?2	35 71 02	if F2 is set.
	R/S	84	FIND a', b'
	*LBL c	32 25 13	

REGISTERS

0	1	2	3	4	5	6	7	8	9
r_i	a	b	x_i	y_i	R, f_a	d, f_b	---	used	used

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I
a'	b'				

ray trace: s, p & f

67 Program Listing II

STEP	KEY ENTRY	KEY CODE	COMMENTS
	RCL 1	34 01	a
	atan	32 64	α
	F?0	35 71 00	if flag 1 is set
	GTO 7	22 07	then para.lens
	F?1	35 71 01	if flag 2 is set
	GTO 7	22 07	then flat lens
	RCL 4	34 04	y_i
120	RCL 5	34 05	R
	/	81	y_i/R
	asin	32 62	Ø =angle of per-
	GTO 6	22 06	pendicular
	*LBL 7	31 25 07	parabola case?
	RCL 5	34 05	R
	F?0	35 71 00	GTO 8 for
	GSB 8	31 22 08	parabola case
	atan	32 64	Ø=perpendicular.
	*LBL 6	31 25 06	------------
130	STO 8	33 08	FIND a',b'
	+	61	α+Ø gives angle
	sin	31 62	of incidence
	RCL 0	34 00	r_i
	/	81	sin(θ')=sin(θ)/r_i
	asin	32 62	θ'
	RCL 8	34 08	-Ø
	-	51	α'
	tan	31 64	a'
	ENT	41	
140	STO A	33 11	store for future
	RCL 3	34 03	x_i
	x	71	ax_i
	RCL 4	34 04	y_i
	x↔y	35 52	
	-	51	$b'=y_i-a'x_i$
	STO B	33 12	store
	R/S	84	
	*LBL 0	31 25 00	FIND PARABOLIC
	RCL 1	34 01	INTERSECTION
150	1/x	35 62	1/a
	STO 8	33 08	
	x^2	32 54	$1/a^2$
	RCL 2	34 02	b
	RCL 1	34 01	a
	/	81	b/a
	RCL 6	34 06	d
	+	61	d+b/a
	RCL 5	34 05	R
	x	71	R(d+b/a)
160	4	04	4
	x	71	
	-	51	$m=1/a^2-4R(d+b/a)$
	SQRT	31 54	$\sqrt{m}$
	RCL 1	34 01	a
	ABS	35 64	
	LST x	35 82	sgn(a)
	/	81	select appropriate
	CHS	42	intersection

STEP	KEY ENTRY	KEY CODE	COMMENTS
	x	71	± SQRT(m)
170	RCL 8	34 08	1/a
	+	61	1/a+SQRT(m)=n
	RCL 5	34 05	R
	/	81	
	2	02	
	/	81	y_i=n/2R
	GTO 2	22 02	
	*LBL 1	31 25 01	FIND FLAT INTER.
	RCL 2	34 02	b
	RCL 1	34 01	a
180	RCL 6	34 06	f_b
	x	71	af_b+b
	+	61	
	1	01	
	RCL 1	34 01	a
	RCL 5	34 05	f_a
	x	71	
	-	51	$1-af_a$
	/	81	$y_i=af_b+b/1-af_a$
	ENT	41	
190	*LBL 2	31 25 02	---------------
	STO 4	33 04	store and display
	RCL 4	34 04	(x_i, y_i)
	F?0	35 71 00	y_i^2 for parabola
	x^2	32 54	
	RCL 5	34 05	R or f_a
	x	71	
	RCL 6	34 06	d or f_b
	+	61	x_i
	STO 3	33 03	
200	F?2	35 71 02	display if flag
	R/S	84	2 is on.
	GTO c	22 31 13	find a',b'.
	*LBL 8	31 25 08	R
	RCL 4	34 04	y_i
	x	71	
	2	02	
	x	71	$2Ry_i$
	RTN	35 22	
	*LBL 9	31 25 09	
210	-	51	y-x
	SQRT	31 54	SQRT(y-x)
	RCL 5	34 05	R
	ABS	35 64	
	LST x	35 82	
	/	81	sgnR
	x	71	±SQRT(y-x)
	RTN	35 22	
	#		
	#		
220	#		
	#		
	#		
	#		
	#		

LABELS

A →R,d	B →f_a,f_b	C →r_i	D →a,b	E →a,y_i
a parabola	b see int?	c find a'b'	d →α,(x,y)	e →α,y_i
0 para.int	1 flat int.	2 display	3 storeRd	4 display
5 find int	6 a',b'	7 flat	8 parabola	9 used

FLAGS

0	flat
1	parabola
2	display
3	-----

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n	5

Program Description I

Program Title General lens tracer

Contributor's Name Alan Stein
Address 298 Vista Grande
City Daly City **State** Ca **Zip Code** 94014

Program Description, Equations, Variables (see sketch 1) This program traces a light ray in two dimensions, through an arbitrary lens surface whose cross-section is f(y)=x. f(y) may be up to 30 steps long and is stored under LBL fe by the user. y is in the x-register and the user has registers C,D, &E available for storage of y or arbitrary constants. The only limits on f(y) are that it must be single valued and exist for y=0 to y=a*f(0)+b. (fig 2)

The following variables are either supplied by the user or computed:

R_0-- r_i(user)=$n_{exit}/n_{incident}$

R1--a(user)=slope of incident ray. The user may provide α, the corresponding angle instead.

R_2-- b(user)=y-intercept of the incident ray. Alternately, the user may provide the value of y desired at the intersection, y_1; or an arbitrary point $(x_0 y_0)$ the ray passes through.

(R_3, R_4) --(x_1, y_1)= the intersection of ray and curve f(y).

R_5-- y_0=previous approximation to y_1(computed)

R_6-- g_0= f(y)- $(y_0$-b)/a (computed). This is a measure of the error in the estimated value of y_1;i.e. if g=0, then $y_1=y_0$.

R_7-- f'=df/dy.(computed). (R_a, R_b)-- (a',b') the parameters of the exiting ray.

(fig #3) The intersection is found computing the approximate slope of g(y) and generating a new y_1 from this. When $g<10^{-6}$, the routine exits. The slope at this point is found by computing df/dy for smaller intervals of y until the change from one cycle to the next is $< 10^{-6}$ or until the error starts to increase.

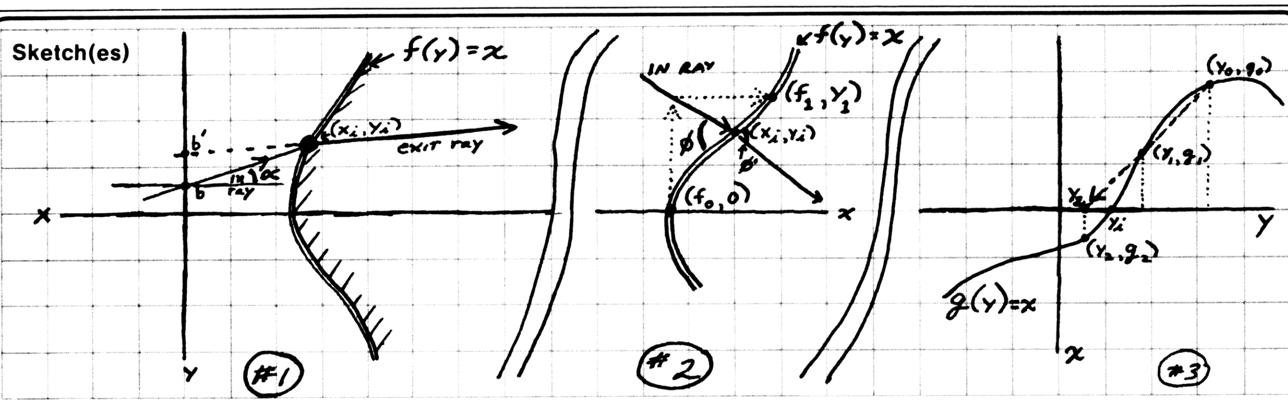
Operating Limits and Warnings

ERROR OCCURS IF NO INTERSECTION CAN BE COMPUTED OR IF REFRACTION AT THAT POINT IS IMPOSSIBLE.

This program is much slower and much less accurate than the analytic ray tracers and should be used only with surfaces which cannot be analyzed by these other programs.

Program Description II

Sketch(es)



Sample Problem(s)

Given a lens surface of revolution whose cross-section is $x = f(y) = y^2+3$, and a ray of slope= 1/3 and y-intercept= -1.5, find the intersection of ray and surface. If the refractive ratio is 2, find a' and b' for the refracted ray.

Solution(s) GTO, f, E, (switch to W/Prgm), ENT, x, 3, +, (switch to Run), A, 3, 1/x, -1.5, C , (x_i, y_i)= (3.190525,-.436492); 2, B, E, a'=.577399 b'= -2.278697.

Correct values to six places are (x_i, y_i)=(3.190525,-.436492); a'= .577399 b'=-2.278697. The numerical programs differ from the analytic answer in the ninth place of a' and b'.

Reference(s) programs by author for HP-65 and 67 to compute general lens trace and parabolic lens trace

User Instructions

GENERAL LENS TRACER

→a,($x_o y_o$)	→α,($x_o y_o$)	→α,b	→α,y_i	f(y)
see int?	→r_i	→a,b	→a,y_i	find a'b'

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	load both sides of card				
2	Enter lens cross-section	-----	GTO	f	
			E	w/prgm	
	(enter keystrokes of lens equation-- y is in the x-register and the user may use R_C,R_D,R_E,R_I and the secondary registers for computations,constant storage)				
3	return to run mode	----			
	OPTIONAL: to see intersection--	____	A		
4	store refractive ratio				
	(OPTIONAL-- this step may be executed after intersection is computed, if "see int" option has been taken)	r_i	B		
5	ENTER INCIDENT RAY IN ANY OF FOLLOWING				
	FORMS: slope, y-intercept	a	ENT		
		b	C		
	or slope,lens-intercept(y_i)	a	ENT		
		y_i	D		
	or point-slope form	a	ENT		
		x_o	ENT		
		y_o	f	A	
	or point-incident angle(atan a)	angle(α)	ENT		
		x_o	ENT		
		y_o	f	B	
	or angle-y-intercept	α	ENT		
		b	f	C	
	or angle- lens(y_i) intercept	α	ENT		
		y_i	f	D	
	OUTPUT OF STEP FIVE WILL BE (x_i,y_i) or				$x=y_i$, $y=x_i$
	a',b' depending on otpion chosen--				or
	a' and x_i will be in y register; b' and				x=b', y=a'
	y_i will be in x-register. NOTE THAT a', b'				
	ARE ALSO STORED IN R_A AND R_B. FOR FUTURE USE.				
	OPTIONAL: find a',b' if "see int" option				
	has been taken:	-----	E		x=b',y=a'

67 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	* LBL A	31 25 11	set F2 to see
	SF 2	35 51 02	intersection
	R/S	84	
	* LBL B	31 25 12	store r_1 in R_0
	STO 0	33 00	
	R/S	84	
	* LBL b	32 25 12	set F1 for angle
	SF 1	35 51 01	instead of slope
	* LBL a	32 25 11	
010	R↓	35 53	convert point-
	x<->y	35 52	slope form to
	F?1	35 71 01	slope-intercept
	tan	31 64	form
	CF 1	35 61 01	find tan(alpha)
	x	71	ax_0
	LST x	35 82	a
	x<->y	35 52	ax_0
	R↑	35 54	y_0
	x<->y	35 52	
020	-	51	$b=y_0-ax_0$
	GTO C	22 13	
	* LBL c	32 25 13	set F1 for angle
	SF 1	35 51 01	
	* LBL C	31 25 13	(slope-inter.form)
	STO 2	33 02	R_2 is b
	STO 4	33 04	R_4 is b
	x<->y	35 52	a,alpha
	F?1	35 71 01	
	tan	31 64	a is tan(alpha)
030	CF 1	35 61 01	
	STO 1	33 01	R_1 is a
	x=0?	31 51	if 0, then go to
	GTO 0	22 00	case for y_1 given.
	0	00	0
	GSB e	32 22 15	$x_0 = f(0)$
	RCL 1	34 01	a
	x	71	ax_0
	RCL 2	34 02	b
	+	61	$y_1 = ax_0+b$
040	STO 4	33 04	R_4 is y_1
	STO 5	33 05	Initialize y_0(old)
	GSB 2	31 22 02	find g_1
	STO 6	33 06	R_6 is g_0(old)
	RCL 5	34 05	y_0
	EEX	43	
	CHS	42	10^{-2}
	2	02	
	+	61	$y_1 = y_0 + .01$
	STO 4	33 04	
050	* LBL 1	31 25 01	find $(x,y)_1$ (inter)
	x<->y	35 52	g_0
	ABS	35 64	abs(g_0)
	EEX	43	
	CHS	42	10^{-6}
	6	06	
	-	51	error=abs(g_0)-10^{-6}

STEP	KEY ENTRY	KEY CODE	COMMENTS
	x<0?	31 71	if error<10^{-6}
	GTO 0	22 00	then exit.
	R↓	35 53	y_1
060	GSB 2	31 22 02	g_1
	ENTER	41	
	ENTER	41	
	RCL 6	34 06	g_0
	x<->y	35 52	g_1
	STO 6	33 06	replace g_0
	-	51	d(g)
	RCL 5	34 05	y_0
	RCL 4	34 04	y_1
	STO 5	33 05	replace y_0
070	-	51	d(y)
	/	81	dg/dy
	/	81	g_1*dy/dg
	RCL 4	34 04	y_1
	x<->y	35 52	
	-	51	$y_{new}=y_1-g_1$*dy/dg
	STO 4	33 04	replace y_1
	GTO 1	22 01	iterate new y_1
	* LBL d	32 25 14	set F1 for alpha
	SF 1	35 51 01	
080	* LBL D	31 25 14	find intersection
	STO 4	33 04	given a(alpha)
	x<->y	35 52	and y_1
	F? 1	35 71 01	
	tan	31 64	find tan(alpha)
	CF 1	35 61 01	
	STO 1	33 01	R_1 is a
	* LBL 0	31 25 00	-------------
	x<->y	35 52	y_1
	GSB e	32 22 15	find x_1 from y_1
090	STO 3	33 03	R_3 is x_1
	RCL 4	34 04	y_1
	x<->y	35 52	
	F? 2	35 71 02	display results
	R/S	84	if F2 is on
	* LBL E	31 25 15	find f'=df/dy
	RCL 4	34 04	y_1
	EEX	43	
	2	02	100
	STO 7	33 07	f' init.
100	STO 9	33 09	
	STO + 9	33 61 09	200=df'
	1/x	35 62	.01=dy_{init}
	STO 8	33 08	R_8 is dy
	* LBL 3	31 25 03	------------
	3	03	reduce dy
	STO / 8	33 81 08	
	RCL 4	34 04	y_1
	RCL 8	34 08	
	+	61	y_1+dy
110	GSB e	32 22 15	f(+)
	STO A	33 11	temporary store
	RCL 4	34 04	y_1

REGISTERS

0	1	2	3	4	5	6	7	8	9
r_1	a	b	x_1	y_1	y_0	g_0	f'_1	dy	df'
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I
a'	b'				

67 Program Listing II

STEP	KEY ENTRY	KEY CODE	COMMENTS
	RCL 8	34 08	dy
	-	51	y-dy
	GSB e	32 22 15	f(-)
	RCL A	34 11	f(+)
	-	51	2df
	RCL 8	34 08	dy
	ENTER	41	
120	+	61	2dy
	/	81	df/dy=f'
	RCL 7	34 07	old f'
	x<->y	35 52	
	STO 7	33 07	replace with new
	-	51	df'
	ABS	35 64	
	EEX	43	
	CHS	42	10^{-6}
	6	06	is change in f'
130	x>y?	32 81	$<10^{-6}$?, Then exit
	GTO 4	22 04	from routine
	R↓	35 53	
	RCL 9	34 09	old df'
	x<->y	35 52	
	STO 9	33 09	replace with new
	x< y?	32 71	is df' increasing?
	GTO 3	22 03	if so, exit.
	* LBL 4	31 25 04	----------------
	RCL 1	34 01	a — FIND a' FROM a AND f'
140	RCL 7	34 07	f'
	-	51	a-f'
	1	01	1
	LST x	35 82	f'
	RCL 1	34 01	a
	x	71	af'
	+	61	1+af'
	/	81	a-f'/1+af'= tan Ø
	ENTER	41	
	x^2	32 54	tan^2
150	1	01	1
	+	61	$1+tan^2$
	SQRT	31 54	
	RCL 0	34 00	r_i
	x	71	$r_i*\sqrt{(1+tan^2)}$
	/	81	sin Ø/r_i=sin Ø'
	ENTER	41	
	x^2	32 54	sin^2
	1	01	1
	x<->y	35 52	
160	-	51	$1-sin^2$
	SQRT	31 54	
	/	81	tanØ'=sin/$\sqrt{(1-sin^2}$
	STO 9	33 09	
	RCL 7	34 07	f'
	+	61	tan+f'
	1	01	1
	RCL 9	34 09	tan
	RCL 7	34 07	f'
	x	71	f'tan
170	-	51	1-f'tan
	/	81	a'
	STO A	33 11	R_a is a'
	RCL 4	34 04	y_i
	GSB e	32 22 15	x_i
	RCL A	34 11	a'
	x	71	a'x_i
	RCL 4	34 04	
	x<->y	35 52	
	-	51	b' is y_i-a'x_i
180	STO B	33 12	R_B is b'
	RCL A	34 11	set up display
	x<->y	35 52	
	R/S	84	end of routine
	* LBL 2	31 25 02	Find g(y)
	GSB e	32 22 15	f(y)
	RCL 4	34 04	y_i
	RCL 2	34 02	b
	-	51	y_i-b
	RCL 1	34 01	a
190	/	81	(y_i-b)/a
	-	51	g(y)= f(y)-(y_i-b)/a
	RTN	35 22	
	* LBL e	32 25 15	STORE f(y) HERE
	RTN	35 22	:
	-		:
	-		:
	-		:
	-		:
	-		30 program steps
200	-		reserved for
	-		user entry
	-		of f(y)
	-		:
	-		:
	-		:
	-		:
	-		:
	-		:
	-		:
210	-		:
	-		:
	-		:
	-		:
	-		:
	-		:
	-		:
	-		:
	-		:
	-		:
220	-		:
	-		:
	-		:
	-		:
	-		:

LABELS

A see inter.	B r_i	C a,b	D a,y_i	E find a'b'
a a,$(x,y)_b$	b ,$(x,y)_o$	c ,b	d ,y_i	e f(y)
0 find x_i	1 find y_i	2 find g	3 find f'	4 Snellslaw
5 -----	6 -----	7 -----	8 -----	9 -----

FLAGS

0	------
1	alpha a
2	display
3	-------

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n	6

Program Description I

Program Title RAY TRACE

Contributor's Name HERMAN R. DITTMER
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City SEATTLE **State** WASH **Zip Code** 98118

Program Description, Equations, Variables THIS IS ONE OF SEVERAL PROGRAMS WHICH CALCULATE THE ABERRATIONS OF OPTICAL SYSTEMS BY TRIGNOMETRIC RAY TRACING. THE EQUATIONS USED ARE DERIVED FROM OR TAKEN FROM <u>MODERN OPTICAL ENGINEERING</u> BY WARREN J. SMITH LCCC#58690 McGRAW HILL. THIS PROGRAM TRACES MERIDINAL AND PARAXIAL RAYS THRU ANY NUMBER OF SPHERICAL SURFACES. OUTPUT INCLUDES FINAL RAY SLOPE AND VERTEX DISTANCE NORMAL TO THE RAY AT THE FINAL SURFACE, RAY HEIGHT AT ANY DISTANCE, AND THE INTERCEPT DISTANCE WITH THE OPTICAL AXIS. THE SPHERICAL ABERRATION AND OFFENSE AGAINST THE SINE CONDITION ARE CALCULATED. A SUB-ROUTINE WILL SELECTIVELY "BEND" ANY ELEMENT(S) AND INSERT THE NEW DATA FOR RECALCULATION AND EVALUATION OF THE CHANGE.

THE MERIDINAL & PARAXIAL TRACES ARE THE BASIS FOR THE CALCULATION OF OTHER ABERRATIONS

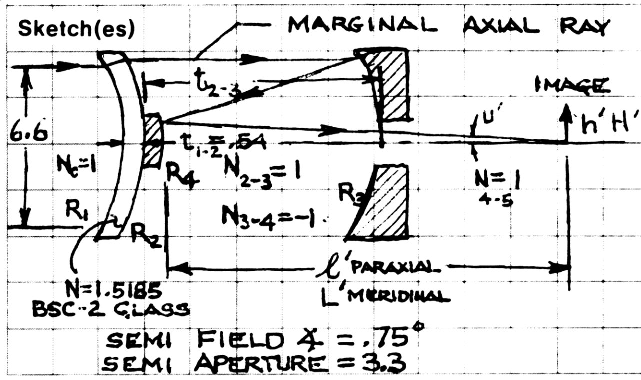
$$LA' = L' - \ell' \qquad \text{SPHERICAL ABERRATION}$$

$$OSC' = \frac{\sin U}{u} \cdot \frac{u'}{\sin U'} \cdot \frac{\ell' - \ell'_{PR}}{L' - \ell'_{PR}} - 1 \qquad \text{OFFENSE AGAINST SINE CONDITION}$$

Operating Limits and Warnings EXTENDED TRACES THRU MORE THAN 4 SURFACES REQUIRE ENTRY OF EXTENDED DATA. FOLLOWING DISPLAY OF "19" — PRESS "9 MERGE" — ENTER THE DATA CARD — PRESS (R/S) TO RESTART THE PROGRAM. CARD TO BE ENTERED IS DETERMINED BY MONITORING PROGRESS AS SHOWN BY SURFACE NUMBER DISPLAYED AS EACH SURFACE IS COMPLETED.

Program Description II

Sketch(es)



R = RADIUS OF SURFACE
N = INDEX OF REFRACTION
t = THICKNESS OR SPACING

Sample Problem(s) MAKSUTOV CASSEGRAIN TELESCOPE

	A	B	C	D	E
→ KEYED INPUTS	Q	SIN U	ℓ' FOR H, h'; ℓ'_{PR} FOR LA', OSC'	y	u

N_0 = 1
R_1 = −8.000 AIR/GLASS
N_{1-2} = 1.5185 t_{1-2} = .54 NOTE: ALL RADII ARE NEG.
R_2 = −8.314 GLASS/AIR AS CENTERS ARE TO LEFT.
N_{2-3} = 1 t = 13.51 t_{3-4} IS NEG AS LIGHT PATH WAS
R_3 = −35.820 MIRROR REVERSED AT R_3 (MIRROR)
N = −1 t = −12.71 N_{3-4} IS ALSO NEG. MIRROR R_4
R_4 = −15.200 MIRROR CHANGES t_{4-5} (0) AND N_{4-5} TO
N = 1 t = 0 POSITIVE AGAIN (t=0 AT LAST SURFACE)
REG "0" KEEPS TRACK OF SURFACE #'S & DISPLAYS
AT END OF EACH SURFACE. (DATA MAY BE READ DURING PAUSE)
CALCULATE: LA'_M MARGINAL SPHERICAL ABERRATION
AND OSC' OFFENSE AGAINST SINE CONDITION

STANDARD DATA CARD FORMAT

REG #	1ST CARD	2ND CARD	REG #	1ST CARD	2ND CARD
0	1	5 etc	10	t_{1-2}	t_{5-6}
1	↑ #1 CARD 1ST 4 SURFACES	↑ #2 CARD NEXT 4 SURFACES	11	R_2	R_6
2			12	N_{2-3}	N_{6-7}
3			13	t_{2-3}	t_{6-7}
4			14	R_3	R_7
5			15	N_{3-4}	N_{7-8}
6	↑	↑	16	t_{3-4}	t_{7-8}
7	N_0	N_{4-5}	17	R_4	R_8
8	R_1	R_5	18	N_{4-5}	N_{8-9}
9	N_{1-2}	N_{5-6}	19	t_{4-5}	t_{8-9}
I	8	8	NOTE: MAKE t=0 AT LAST SURFACE		

Solution(s) 1ST CALCULATE ℓ'_{PR} THE INTERCEPT OF THE PRINCIPAL RAY WITH THE OPTICAL AXIS FROM THE LAST SURFACE. THIS REQUIRES A PARAXIAL TRACE (E). INPUT DATA CARD (SAME CARD IS USED FOR ALL TRACES) KEY y=0 STO D, KEY u=−.75° IN RADIANS (−.01308997) STO E. PRESS (E) ℓ'_{PR} = −6.89449495, INPUT DATA CARD, STO ℓ'_{PR} IN C – KEY Q & y = 3.3 (SEMI-APERTURE) STO A & STO D. STO SIN U & u = 0 IN B AND IN E. – PRESS (C) READ LA'_M = .00102257 PRESS (R/S) READ OSC' = .00003020 NOTE: L' IN REG #3 AND ℓ' IN REG #2. LA'_M IS IN REG #5, OSC' IS IN REG #6, Q IS IN A, SIN U' IN B, y IN D & u' IN E.

Reference(s) WARREN J. SMITH – MODERN OPTICAL ENGINEERING 1ST ED 1966
McGRAW HILL, INC. CHAPTER 10

User Instructions

MERID. BEND. LA'OSC' PARAXIAL

1 LA', OSC' MERIDINAL/PARAXIAL 2

Q (Q) | SIN U (SIN U') | S' OR ℓ' | y (y') | u (u')

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	LOAD PROGRAM (BOTH SIDES)				
2	LOAD DATA CARD (BOTH SIDES)				
3	DECIDE CALCULATION TO BE MADE				
	MERIDINAL TRACE		A		
	LENS ELEMENT BENDING		B		
	CALCULATE LA' AND OSC'		C		
	PARAXIAL TRACE		E		
4	MAKE INPUTS FOR CALCULATION TO BE MADE				
	(A) - MERIDINAL TRACE				
	1 INPUT DATA CARD	BOTH SIDES			
	2 KEY Q (RAY VERTEX DISTANCE AT	Q	STO	A	
	1ST SURFACE)				NOTE: * FINAL Q IS
	3 KEY SIN U (RAY SLOPE ENTERING 1ST	SIN U	STO	B	STORED IN A FINAL SIN U'
	SURFACE) (SLOPES ARE OPPOSITE USUAL MATH USE - SEE REF TEXT				STORED IN B
	4 IF H' (RAY HEIGHT) REQ'D, KEY AXIAL		STO	C	
	DISTANCE S' FROM LAST SURFACE ** S' = ℓ' FOR FINAL	IMAGE HEIGHT			
	5 PRESS (A) * SEE NOTE FOR OTHER			A	L' DISPLAY AND R3
	6 PRESS (R/S) DATA CALCULATED AND STORED			R/S	H' DISPLAY ** AND R4
	(B) - LENS BENDING				
	1 INPUT DATA CARD	BOTH SIDES			
	2 KEY ΔC BENDING REQ'D (C = 1/RADIUS)	ΔC	STO	I	
	3 KEY REG # OF RADIUS TO BE CHANGED RN	REG # OF RADIUS RN			
	4 PRESS (B) PAUSES ON RN' & STORES IN		B		RN' IN REG # N
	REG # RN - DISPLAYS REG # OF NEXT SURFACE	REG # OF RN+1			
	5 PRESS (B) PAUSES ON RN+1' etc - -		B		RN+1' IN REG # N+1
	(C) - CALCULATE LA' & OSC' (AXIAL RAY)				
	1. CALC ℓ'PR SEE (E) PARAXIAL TRACE OF PRINCIPAL RAY				
	2. INPUT DATA CARD	BOTH SIDES			
	3. STO ℓ'PR IN C		STO	C	
	4 STEPS 2 & 3 MERIDINAL TRACE (A)	Q SIN U	STO STO	A B	
	5 KEY y RAY HEIGHT ENTERING 1ST SURFACE		STO	D	
	6 KEY u RAY SLOPE IN RADIANS	=0 IF OBJECT AT ∞	STO	E	
	7 PRESS (C) READ LA'		C		
	8 PRESS (R/S) READ OSC'		R/S		
	(E) - PARAXIAL TRACE	y	STO	D	
	SAME AS FOR (A) EXCEPT STO y IN D	u	STO	E	
	AND u IN E PRESS (E) READ ℓ' THEN	START	E		ℓ' DISPLAY & R2
	(R/S) READ h' (IF S' IN C)		R/S		h' DISPLAY ** & R4
NOTE	SEE OPERATING LIMITS PG 2 FOR USE OF EXTENDED	DATA CARDS			y IN D u IN E

67 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
001 *	LBL A	31 25 11	MERIDINAL TRACE
	RCL A	34 11	
	(i)	34 24	
	÷	81	
	RCL B	34 12	
	−	51	
	STO 6	33 06	SIN I
	RCL 7	34 07	
	ISZ	31 34	
010	(i)	34 24	
	STO 7	33 07	
	÷	81	
	×	71	
	STO 5	33 05	SIN I′
	SIN^{-1}	32 62	
	CHS	42	
	RCL 6	34 06	
	SIN^{-1}	32 62	
	+	61	
020	RCL B	34 12	
	SIN^{-1}	32 62	
	+	61	
	SIN	31 62	
	RCL B	34 12	
	x⇌y	35 52	
	STO B	32 12	SIN U′
	SIN^{-1}	33 ~~32~~ ~~62~~ 12	
	COS	31 63	
	RCL 5	34 05	
030	SIN^{-1}	32 62	
	COS	31 63	
	+	61	
	RCL A	34 11	
	×	71	
	x⇌y	35 52	
	SIN^{-1}	32 ~~36~~ 62	
	COS	31 63	
	RCL 6	34 06	
	SIN^{-1}	32 62	
040	COS	31 63	
	+	61	
	÷	81	
	STO 5	33 05	Q′
	RCL B	34 12	
	÷	81	
	STO 3	33 03	L′
	RCL 5	34 05	
	RCL B	34 12	
	ISZ	31 34	
050	(i)	34 24	
	×	71	
	−	51	
	STO A	33 11	Q_2
	GSB 0	31 22 00	
	x=0	31 51	t=0?
	GTO 2	22 02	
	GTO 3	22 03	
*	LBL 2	31 25 02	
	F1?	35 71 01	
060	GTO e	22 31 15	
	RCL C	34 13	
	RCL 3	34 03	
	R/S	84	DISPLAY L′
	x⇌y	35 52	
	RCL B	34 12	
	×	71	
	RCL 5	34 05	
	x⇌y	35 52	
	−	51	
070	RCL B	34 12	
	SIN^{-1}	32 ~~36~~ 62	
	COS	31 63	
	÷	81	
	STO 4	33 04	H′
	R/S	84	DISPLAY H′
*	LBL 3	31 25 03	
	1	01	
	9	09	
	RC I	35 34	
080	ISZ	31 34	
	x=y	32 ~~36~~ ~~61~~ 61	
	GTO A	22 11	
	F1?	35 71 01	
	GTO 4	22 04	
	GSB 6	31 22 06	
	GTO A	22 11	
	LBL 6	31 25 06	
	1	01	
	9	09	
090	ST I	35 33	
	R/S	84	9 MERGE - LOAD NEXT DATA CARD
	8	08	
	ST I	35 33	
	RTN	35 22	
*	LBL 4	31 25 04	
	4	04	
	STO −0	33 51 00	
	8	08	
	ST I	35 33	
100	RCL 1	34 01	
	STO 7	33 07	
	GTO E	22 15	
*	LBL C	31 25 13	
	SF 1	35 51 01	
	RCL 0	34 00	
	STO 2	33 02	
	RCL 7	34 07	
	STO 1	33 01	
	GTO A	22 11	
110 *	LBL 0	31 25 00	
	RCL 0	34 00	
	PAUSE	35 72	SURFACE NUMBER

REGISTERS

0	1	2	3	4	5	6	7	8	9
SURF. COUNTER	USED	USED	USED	USED	USED	USED	N_0	R_1	N_{1-2}

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
t_{1-2}	R_2	N_{2-3}	t_{2-3}	R_3	N_{3-4}	t_{3-4}	R_4	N_{4-5}	t_{4-5}

A	B	C	D	E	I
$Q_1 \rightarrow Q_K$	$SIN U \rightarrow SIN U'_K$	S′ OR ℓ′	$y \rightarrow y_K$	$u \rightarrow u'_K$	USED

67 Program Listing II

STEP		KEY ENTRY	KEY CODE	COMMENTS
		1	01	
		STO + 0	33 61 00	
		(i)	34 24	
		RTN	35 22	
	*	LBL E	31 25 15	PARAXIAL TRACE
		RCL D	34 14	
		(i)	34 24	
120		÷	81	
		ISZ	31 34	
		(i)	34 24	
		RCL 7	34 07	
		−	51	
		×	71	
		(i)	34 24	
		÷	81	
		RCL 7	34 07	
		RCL E	34 15	
130		×	71	
		(i)	34 24	
		STO 7	33 07	
		÷	81	
		+	61	
		STO E	33 15	u′
		ISZ	31 34	
		(i)	34 24	
		×	71	
		RCL D	34 14	
140		x⇄y	35 52	
		−	51	
		STO D	33 14	y
		RCL E	34 15	
		÷	81	
		STO 2	33 02	l′
		GSB 0	31 22 00	
		x=0	31 51	t=0?
		GTO 1	22 01	
		GTO 5	22 05	
150	*	LBL 1	31 25 01	
		F1?	35 71 01	
		GTO c	22 31 13	
		RCL C	34 13	
		RCL 2	34 02	
		R/S	84	DISPLAY l′
		x⇄y	35 52	
		RCL E	34 15	
		×	71	
		RCL D	34 14	
160		x⇄y	35 52	
		−	51	
		STO 4	33 04	
		R/S	84	DISPLAY h′
	*	LBL c	32 25 13	
		CF 1	35 61 01	
		RCL 3	34 03	
		RCL 2	34 02	
		−	51	

STEP		KEY ENTRY	KEY CODE	COMMENTS
		STO 5	33 05	
170		R/S	84	DISPLAY LA′
		RCL E	34 15	
		RCL B	34 12	
		÷	81	
		RCL 2	34 02	
		RCL C	34 13	
		−	51	
		×	71	
		RCL 3	34 03	
		RCL C	34 13	
180		−	51	
		÷	81	
		1	01	
		−	51	
		STO 6	33 06	
		R/S	84	DISPLAY OSC′
	*	LBL 5	31 25 05	
		1	01	
		9	09	
		RC I	35 34	
190		ISZ	31 34	
		x≠y	32 61	
		GTO E	22 15	
		F1?	35 71 01	
		GTO a	22 31 11	
		GSB 6	31 22 06	
		GTO E	22 15	
		LBL e	32 25 15	
		RCL 1	34 01	
		STO 7	33 07	
200		RCL 2	34 02	
		STO 0	33 00	
		8	08	
		ST I	35 33	
		GTO E	22 15	
		LBL a	32 25 11	
		GSB 6	31 22 06	
		RCL 0	34 00	
		STO 2	33 02	
		RCL 7	34 07	
210		STO 1	33 01	
		GTO A	22 11	
	*	LBL B	31 25 12	LENS BENDING
		ST I	35 33	
		(i)	34 24	
		1/x	35 62	
		RCL 1	34 01	
		+	61	
		1/x	35 62	
		STO (i)	33 24	
220		PAUSE	35 72	DISPLAY R_n'
		RC I	35 34	
		3	03	
		+	61	
		R/S	84	

LABELS

A MERIDINAL	B LENS BENDER	C LA′ OSC′	D	E PARAXIAL
a	b	c CLOSING	d	e X-FER TO PARAXIAL
0 COUNTER	1 CLOSING	2 CLOSING	3 DATA?	4 X-FER TO PARAXIAL
5 DATA?	6	7	8	9

FLAGS

0	
1	LA′ OSC′ ?
2	
3	

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☑	DEG	☑	FIX	☑
1	☐	☑	GRAD	☐	SCI	☐
2	☐	☑	RAD	☐	ENG	☐
3	☐	☑			n	8

Program Description I

Program Title First Order Raytracing by Matrix Methods

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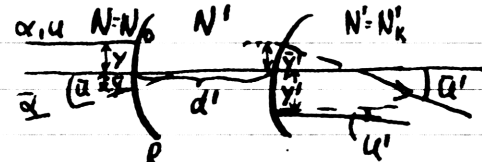
Program Description, Equations, Variables



Refraction (Power) Matrix: $K = \frac{N' - N}{R}$; $P = \begin{pmatrix} 1 & -K \\ 0 & 1 \end{pmatrix}$; $|P| = 1$

Transfer (Thickness) Matrix: $D' = \frac{d'}{N'}$; $\Theta = \begin{pmatrix} 1 & 0 \\ D' & 1 \end{pmatrix}$; $|\Theta| = 1$

Ray Matrix: Marginal Ray: $y, \alpha = u \cdot N_0$
(Incoming Rays) Principal Ray: $\bar{y}, \bar{\alpha} = \bar{u} \cdot N_0$ $M = \begin{pmatrix} y & \alpha \\ \bar{y} & \bar{\alpha} \end{pmatrix}$

Ray Matrix: $M' = \begin{pmatrix} y' & \alpha' \\ \bar{y}' & \bar{\alpha}' \end{pmatrix} = MA$ $A = P_1 \Theta_1 P_2 \Theta_2 \ldots P_K$
(Outgoing Rays)

Inverted Matrix: $A^{-1} = \begin{pmatrix} a_4 & -a_3 \\ -a_2 & a_1 \end{pmatrix}$; $A = \begin{pmatrix} a_1 & a_3 \\ a_2 & a_4 \end{pmatrix}$; $AA^{-1} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

Multiplication: $E = AB = \begin{pmatrix} a_1 & a_3 \\ a_2 & a_4 \end{pmatrix} \begin{pmatrix} b_1 & b_3 \\ b_2 & b_4 \end{pmatrix} = \begin{pmatrix} a_1 b_1 + a_3 b_2 & a_1 b_3 + a_3 b_4 \\ a_2 b_1 + a_4 b_2 & a_2 b_3 + a_4 b_4 \end{pmatrix} = \begin{pmatrix} e_1 & e_3 \\ e_2 & e_4 \end{pmatrix}$

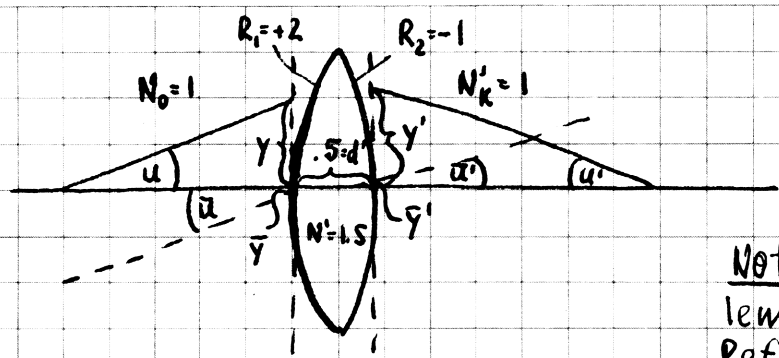
Angular Magnification: $\longrightarrow m'_A = \frac{\bar{u}'}{\bar{u}} = \frac{\bar{\alpha}'}{N'_K} \cdot \frac{N_0}{\bar{\alpha}}$

Operating Limits and Warnings

1. Make sure to press R/S after entering Lens parameters K, D' via [C] and [D]. ~~and~~
2. After matrix multiplication Xfer E Matrix to either A or B Matrix location for further processing
3. Enter N'_K via [f][D] to obtain outgoing ray data via [f][E]

Program Description II

Sketch(es)



Note: Sample Problem taken from Ref b (Brouwer) p.38

Sample Problem(s) $u = \bar{u} = .2$, $y = .353$, $\bar{y} = 0$, $N_0 = 1$, $N' = 1.5$, $N'_K = 1$

$R_1 = +2$ $R_2 = -1$: $K_1 = \frac{1.5-1}{2} = +.25$, $D' = \frac{.5}{1.5} = +1/3$ $K_2 = \frac{1-1.5}{-1} = +.5$

$y' = ?$; $u' = ?$; $\bar{y}' = ?$; $\bar{u}' = ?$ $m'_A = ?$

Solution(s)

Keystrokes:		
1) 1.5↑1↑2 [C]	→ 0.250	K_1
R/S → 1.000; [A]	→ "1.000", 1.000 "|P1|",	P_{14}
2) .5↑1.5 [D]	→ .333	D'
R/S → 1.000; [B]	→ "1.000", 1.000 "|Θ1|",	Θ_{14}
3) [E]	→ "1.000", 1.000 "|E|",	e_4
[A]	→ "1.000", 1.000 "|A|",	a_4
4) 1↑1.5↑1 CHS [C]	→ 0.500	K_2
R/S → 1.000; [B]	→ "1.000", 1.000 "|P2|",	P_{24}
5) [E]	→ "1.000", ~~1.000~~ 0.833 "|E|",	e_4
6) [B]	→ "1.000", ~~1.000~~ 0.833 "|E|",	e_4
7) [f][E] (or [f][B])	→ "1.000", 0.917, "|E|"	e_1 (Lens Matrix)
	0.333,	e_2 (Lens Matrix)
	−0.708,	e_3 (Lens Matrix)
	0.833	e_4 (Lens Matrix)
8) .353↑.2↑1↑1 [f][D]	→ 0.000	
0↑.2 R/S	→ 0.200	
9) [A]	→ "0.071", 0.200	
10) [f][A]	→ "0.071", 0.353,	(Ray Matrix)
	0.000, 0.200, 0.200	(Ray Matrix)
11.) [E]	→ "0.071", 0.167 "|E|",	$\bar{u}'$
12.) [f][E]	→ "0.071", ~~0.167~~ 0.390 "|E|",	y'
	0.067	$\bar{y}'$
	−0.083	$N'_K u'$
	0.167	$N'_K \bar{u}'$
13) R/S	0.390	y'
	0.067	$\bar{y}'$
	−0.083	u'
	0.167	$\bar{u}'$
14) R/S	0.833	m'_A

Reference(s)

a) E. Delano: Course in Geometrical Optics, St. John Fisher Coll., Rochester, N.Y.

b) W. Brouwer: Matrix Methods in Optical Instrument Design 1964, W.A. Benjamin Inc. p.38

User Instructions

First Order Raytracing

1					2
	Recall A Matrix	Recall B Matrix	Invert Stk Mat.	$y \uparrow u \uparrow N_0 \uparrow N_k \to M$ $\bar{y} \uparrow \bar{u}$ R/S	Recall E Mat.
	$a_1 \uparrow a_2 \uparrow a_3 \uparrow a_4$	$b_1 \uparrow b_2 \uparrow b_3 \uparrow b_4$	$N' \uparrow N \uparrow R \to K$ R/S	$d' \uparrow N' \to D'$ R/S	Mult. A B

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Load side 1 and side 2				
2	Input Refractive Index to right of Surface	N'	ENTER↑		N'
3	Input Refractive Index to left of Surface	N	ENTER↑		N
4	Input Surface Radius	R	C		K
5	Form Refraction Matrix in Stack (Opt.: Enter K)	(K)	R/S		1.000
6	Assign (Refraction Matrix) to Matrix A for Multipl		A		"1.000", 1.000
7	Recall "A" Matrix		f	A	"|A|" a_1, a_2, a_3, a_4
8	Input Distance	d'	ENTER↑		d'
9	Input Refractive Index of Transfer Space	N'	D		D'
10	Form Transfer Matrix in Stack (Opt.: Enter D')	(D')	R/S		"1.000", 1.000
11	Assign to Matrix B for Multiplication		B		
12	Recall "B" Matrix		f	B	"|B|", b_1, b_2, b_3, b_4
13	Compute Matrix E = AB		E		"|E|", e_4
14	Recall "E" Matrix		f	E	"|E|", e_1, e_2, e_3, e_4
15	For more Refraction Matrices, assign to Matrix A		A		"|A|", a_4
	and repeat Steps 2, 3, 4, 5, 11, 13				
16	For more Transfer Matrices, assign to Matrix A		A		"|A|", a_4
	and repeat Steps 8, 9, 10, 11, 13				
17	For obtaining output ray, assign to Matrix B		B		"|B|", b_4
18	~~Comput~~ Input Marg. Ray Height	y	ENTER↑		y
19	Input Marg. Ray Angle	u	ENTER↑		u
20	Input Object Space Refractive Index	N_0	ENTER↑		N_0
21	Input Image Space Refractive Index, Form M	N_k'	f	D	"|M|", 0.000
22	Opt.: Add 2nd Ray (Princ Ray) Height	$\bar{y}$	ENTER↑		$\bar{y}$
23	" ~~For~~ Input 2nd Ray (Princ. Ray) Angle	$\bar{u}$	R/S		"|M|", M_4
24	Repeat Step 11		B		"|B|", b_4
25	Repeat Step 13		E		"|E|", e_4
26	Recall Outgoing Ray Matrix		f	E	"|M|", $y', \bar{y}', N_k u', N_k \bar{u}'$
			R/S		"|M|", $y', \bar{y}', u', \bar{u}'$
			R/S		m_A' (angul mag.)
27	Invert Matrix in Stack		f	C	"|C|", c_4
	(Obtain Inverse, correct error, change design param)				

67 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBL B	31 25 12	Enter B Matrix
	P↔S	31 42	
	GSB A	31 22 11	
	P↔S	31 42	
	RTN	35 22	
006	*LBL A	31 25 11	Enter A Matrix
	STO 4	33 04	
	↓	35 53	
	STO 3	33 03	
010	↓	35 53	
	STO 2	33 02	
	↓	35 53	
	STO 1	33 01	
	GSB 0	31 22 00	
	RCL 1	34 01	$A = \begin{pmatrix} a_1 & a_3 \\ a_2 & a_4 \end{pmatrix}$ (or B)
	RCL 2	34 02	
	RCL 3	34 03	
	RCL 4	34 04	
	RTN	35 22	
020	*LBL b	32 25 12	Recall |B| & B Matrix
	P↔S	31 42	
	GSB a	32 22 11	
	P↔S	31 42	
	RTN	35 22	
025	*LBL a	32 25 11	Recall |A| & A Matrix
	GSB 0	31 22 00	
	RCL 1	34 01	
	RCL 2	34 02	
	RCL 3	34 03	
030	RCL 4	34 04	
	STK	32 84	
	RTN	35 22	
033	*LBL 0	31 25 00	Compute |A| (|B|)
	RCL 4	34 04	
	RCL 1	34 01	
	x	71	
	RCL 2	34 02	
	RCL 3	34 03	
	x	71	
040	−	51	
	STO E	33 15	
	PSE	35 72	
	RTN	35 22	
044	*LBL E	31 25 15	Multiply E=AB
	P↔S	31 42	
	RCL 3	34 03	
	RCL 4	34 04	
	P↔S	31 42	
	RCL 4	34 04	
050	x	71	
	x↔y	35 52	
	RCL 2	34 02	
	x	71	
	+	61	
	STO D	33 14	
	P↔S	31 42	

STEP	KEY ENTRY	KEY CODE	COMMENTS
	RCL 3	34 03	
	RCL 4	34 04	
	P↔S	31 42	
060	RCL 3	34 03	
	x	71	
	x↔y	35 52	
	RCL 1	34 01	
	x	71	
	+	61	
	STO C	33 13	
	P↔S	31 42	
	RCL 1	34 01	
	RCL 2	34 02	
070	P↔S	31 42	
	RCL 4	34 04	
	x	71	
	x↔y	35 52	
	RCL 2	34 02	
	x	71	
	+	61	
	STO B	33 12	
	P↔S	31 42	
	RCL 1	34 01	
080	RCL 2	34 02	
	P↔S	31 42	
	RCL 3	34 03	
	x	71	
	x↔y	35 52	
	RCL 1	34 01	
	x	71	
	+	61	
	STO A	33 11	
	GSB 1	31 22 01	
090	RCL A	34 11	$E = \begin{pmatrix} e_1 & e_3 \\ e_2 & e_4 \end{pmatrix}$
	RCL B	34 12	
	RCL C	34 13	
	RCL D	34 14	
	RTN	35 22	
095	*LBL e	32 25 15	Recall |E| & E Matrix
	GSB 1	31 22 01	
	RCL A	34 11	
	RCL B	34 12	
	RCL C	34 13	
100	RCL D	34 14	
	STK	32 84	
	R/S	84	Outgoing Ray Matrix
	RCL B	34 12	$\begin{pmatrix} y' & \alpha' = \frac{u'}{N'_{K+1}} \\ \bar{y}' & \bar{\alpha}' = \frac{\bar{u}'}{N'_{K+1}} \end{pmatrix}$
	RCL C	34 13	
	RCL 0	34 00	
	÷	81	
	RCL D	34 14	N'_{K+1} stored in R_0 ?
	RCL 0	34 00	
	÷	81	
110	RCL A	34 11	
	↓	35 53	
	STK	32 84	

REGISTERS

0	1	2	3	4	5	6	7	8	9
N'_{K+1}	a_1	a_2	a_3	a_4	$C_1 = \frac{a_4}{\|A\|}$	$C_2 = -\frac{a_2}{\|A\|}$	$C_3 = -\frac{a_3}{\|A\|}$	$C_4 = \frac{a_1}{\|A\|}$	
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
	b_1	b_2	b_3	b_4	y	$\bar{y}$	u	$\bar{u}$	N_0

A	B	C	D	E	I
$e_1 = a_1 b_1 + a_3 b_2$	$e_2 = a_2 b_1 + a_4 b_2$	$e_3 = a_1 b_3 + a_3 b_4$	$e_4 = a_2 b_3 + a_4 b_4$	|A| (|B|	

67 Program Listing II

STEP	KEY ENTRY	KEY CODE	COMMENTS
	R/S	84	Compute angular magnification $m_A = \frac{\bar{u}'}{\bar{u}}$
	RCL D	34 14	
	RCL 0	34 00	
	÷	81	
	P⇆S	31 42	
	RCL 8	34 08	
	RCL 9	34 09	
120	P⇆S	31 42	
	÷	81	
	x≠0	31 61	
	÷	81	
	RTN	35 22	
125	*LBL 1	31 25 01	Compute |E|
	RCL D	34 14	
	RCL A	34 11	
	×	71	
	RCL B	34 12	
130	RCL C	34 13	
	×	71	
	−	51	
	STO E	33 15	
	PSE	35 72	
	RTN	35 22	
136	*LBL C	31 25 13	Enter N' N R
	↓	35 53	Compute $K = \frac{N'-N}{R}$
	−	51	
	↑	35 54	
140	x≠0	31 61	
	÷	81	
	R/S	84	→ K or Enter K here
	CHS	42	Refraction (Power) Matrix:
	ENTER	41	$\begin{pmatrix} 1 & -K \\ 0 & 1 \end{pmatrix}$
	1	01	
	x⇆y	35 52	
	0	00	
	x⇆y	35 52	
	1	01	
150	RTN	35 22	
151	*LBL D	31 25 14	Enter d' N'
	x≠0	31 61	Compute $D' = \frac{d'}{N'}$
	÷	81	
	R/S	84	→ D' or Enter D' here
	1	01	Thickness Matrix
	x⇆y	35 52	$\begin{pmatrix} 1 & 0 \\ D' & 1 \end{pmatrix}$
	0	00	
	ENTER	41	
	1	01	
160	RTN	35 22	
161	*LBL d	32 25 14	Enter y u N_0 N_{K+1}
	STO 0	33 00	Store N_{K+1} in R_0
	↓	35 53	
	P⇆S	31 42	
	STO 9	33 09	
	↓	35 53	
	STO 7	33 07	
	↓	35 53	

STEP	KEY ENTRY	KEY CODE	COMMENTS
	STO 5	33 05	
170	P⇆S	31 42	
	↑	35 54	$H = \begin{pmatrix} y & \alpha = uN \\ 0 & 0 \end{pmatrix}$
	↑	35 54	
	÷	81	
	0	00	
	x⇆y	35 52	
	0	00	
	R/S	84	Enter $\bar{y}$ $\bar{u}$ to expand H
	P⇆S	31 42	
	STO 8	33 08	
180	↓	35 53	
	STO 6	33 06	
	RCL 7	34 07	
	RCL 9	34 09	
	×	71	$H = \begin{pmatrix} y & \alpha = uN_0 \\ \bar{y} & \bar{\alpha} = \bar{u}N_0 \end{pmatrix}$
	RCL 8	34 08	
	RCL 9	34 09	
	×	71	
	RCL 5	34 05	
	P⇆S	31 42	
190	↓	35 53	
	RTN	35 22	
192	*LBL c	32 25 13	Enter Matrix x
	STO 5	33 05	$x = \begin{pmatrix} x_1 & x_3 \\ x_2 & x_4 \end{pmatrix}$
	↓	35 53	
	CHS	42	
	STO 7	33 07	
	↓	35 53	
	CHS	42	
	STO 6	33 06	
200	↓	35 53	Compute Determinant |X|
	STO 8	33 08	
	RCL 5	34 05	
	×	71	
	RCL 7	34 07	
	RCL 6	34 06	
	×	71	
	−	51	
	STO E	33 15	
209	*LBL 2	31 25 02	|X| = 0 ?
210	PSE	35 72	
	x=0	31 51	
	GTO 2	22 02	
	STO÷5	33 81 05	
	STO÷6	33 81 06	$C = \begin{pmatrix} C_1 & C_3 \\ C_2 & C_4 \end{pmatrix}$
	STO÷7	33 81 07	
	STO÷8	33 81 08	
	RCL 5	34 05	$= \begin{pmatrix} \frac{x_4}{\|x\|} & -\frac{x_3}{\|x\|} \\ -\frac{x_2}{\|x\|} & \frac{x_1}{\|x\|} \end{pmatrix}$
	RCL 6	34 06	
	RCL 7	34 07	
220	RCL 8	34 08	
221	RTN	35 22	
		84	
		84	
		84	

LABELS					FLAGS
A a_1↑a_2↑a_3↑a_4	B b_1↑b_2↑b_3↑b_4	C N'↑N↑R→K R/S	D d'↑N'→D' R/S	E → AB	0 —
a →|A| $a_1a_2a_3a_4$	b →|B| $b_1b_2b_3b_4$	c a_1↑a_2↑a_3↑a_4→C	d y↑u↑N_0↑N'_{K+1} R/S*	e →|E| $e_1e_2e_3e_4$	1 —
0 |A| (|B|)	1 |E|	2 C Matrix	3	4	2 —
5	6	7	8	9	3 —

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n	3

* y↑u↑N_0↑N'_{K+1} → $\bar{y}$↑$\bar{u}$ R/S

Program Description I

Program Title Fraunhofer Diffraction of Light by Spherical Particles

Contributor's Name Bill P. Curry

Address Lakeview Drive, Route 1

City Decherd **State** Tennessee **Zip Code** 37324

Program Description, Equations, Variables This program uses Bessel functions computed by the standard series (for X<15) to generate intensity functions for Fraunhofer diffraction patterns of light scattered by spheres. For large size parameters (X≥15), Hankel's asymptotic forms are used. Nested addition and multiplication loops are used in calculating the Hankel forms. Angular intensity distributions of scattered light based on the Fraunhofer intensity functions are the asymptotic limits of the exact Mie scattering series solution for light scattering by spheres of arbitrary size. The angular scattering relations are stated below:

$$I_{1,2}(r,\theta,x,\eta)=\frac{I_0 i_{1,2}(x,\theta,\eta)}{(kr)^2}(\cos^2\phi, \sin^2\phi)$$

where $I_{1,2}$ is the light intensity (energy flux per unit area per unit time) scattered in either 1) the polarization state with electric vector perpendicular to the plane formed by incident and scattered vectors or 2) the parallel polarization state. The intensity functions of the Mie theory are $i_{1,2}(x,\theta,\eta)$, $x=\frac{\pi D}{\lambda}$ is the size parameter (based on particle diameter D and light wavelength λ), θ is the polar scattering angle and ϕ is the aximuthal scattering angle, $k=\frac{2\pi}{\lambda}$ is the incident light wave number, r is the distance from the scatterer to the obsever, and η is the particle refractive index. In the Fraunhofer limit, $i_F(x,\theta)=\lim_{x\to\infty} i_{1,2}(x,\theta,\eta)$, the effect of refractive index disappears. The Fraunhofer intensity functions are computed from $i_F(x,\theta)=\left[x^2\frac{J_1(x\sin\theta)}{x\sin\theta}\right]^2$, where $J_1(x\sin\theta)$ is the Bessel function of first order and argument $x\sin\theta$.

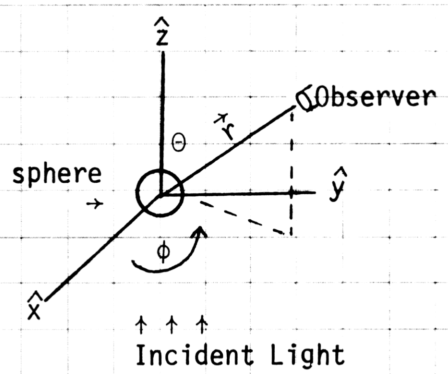
Bessel function accuracy is 7-8 places for $x'>15$, 4-5 places for $x'<15$ (more accuracy for small x') --$x'=x\sin\theta$. Least accuracy occurs for x' near 15, on account of unavaoidable roundoff error. Intensity functions cannot be computed at exactly 0° scattering. Instead, use very small numbers, such as $\theta=10^{-20}$° to obtain 0° scattering result. Program contains a limit restricting it to angles $0<\theta<180°$. Same precautions must be observed to approximate $\theta=180°$ as to approximate $\theta=0°$ (use $\theta=180-10^{-7}$°).

Program Description II

Sketch(es)

Geometry

Scattering sphere at origin →



Scattering particle has radius $\frac{D}{2}$

Incident light has wavelength λ

Incident light has electric vector along x-axis, magnetic vector along y-axis

Scattering plane is $\vec{r}$-$\hat{z}$ plane

Sample Problem(s) Consider scattering of light at 10.6 microns wavelength by sphere with 250 microns diameter at the angles stated:

Angle Θ	Fraunhofer Function $i_F(x,\Theta)$
1) $(10^{-3})°$	7.5348722×10^{6}
2) 2°	1.0157965×10^{6}
4°	1.3170225×10^{5}
6°	1.8250979×10^{4}
8°	3.3208465×10^{2}
10°	1.7535760×10^{3}

Size parameter is x=74.094166

NOTE: Program displays, in order, the following quantities:

1) Size parameter-$x=\frac{\pi D}{\lambda}$ (1second display)
2) Scattering angle - θ (5second display)
3) Bessel function-$J_1(x\sin\Theta)$ (1second display)
4) Fraunhofer intensity function - $i_F(x,\Theta)$ (5second display)

Solution(s)

Enter in the order stated the following keystrokes:

Problem #1: EEX, 3, chs, enter, 0, enter, 250, enter, 10.6, press"A" after result has been computed, stop program by pressing "R/S".

Problem #2: 2, enter, 2, enter, 250, enter, 10.6, press"A", allow program to step through the angels shown. After result has been computed, stop program by pressing "R/S".

Reference(s) Any standard text on optics of level equivalent to M. Born and E. Wolf, Optics, Pergramon Press, Oxford (1959).

Handbook of Mathematical Functions ed. by M. Abramowitz and I. Stegun, Nat'l Bureau of Standards, AMS 55, Washington (1964) pp. 355-435.

User Instructions

Fraunhofer Diffraction
(monodisperse)

Start

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1.	Load program (both sides) (If desired, replace f-x-in line #210 by R/S-optional)			
2.	Enter data in order shown: θ_o, $\Delta\theta$, D, λ	θ_o (degrees)	ENTER↑	θ_o (degrees)
	(θ_o is initial angle for sequence of calculations)			
		$\Delta\theta$ (degrees)	ENTER↑	$\Delta\theta$ (degrees)
		D (microns)	ENTER↑	D (microns)
		λ (microns)		λ (microns)
3.	Start calculation sequence - press "A"		A	
	Display pauses 1 second to output $x = \frac{\pi D}{\lambda}$			x(dimensionless)
	Display pauses 5 seconds to output θ after long program run (1 minute sometimes),			θ(degrees)
	Display pauses 1 second to show Bessel function			$J_1(x\sin\theta)$ (dimensionless)
	Display pauses 5 seconds to output Fraunhofer intensity function			$i_F(x,\theta)$ (dimensionless)
	After answer display, program automatically steps to next angle ($\theta_i = \theta_{i-1} + \Delta\theta$) and continues calculation sequence			
4.	Stop calculation sequence at any time numbers are displayed by pressing "R/S"		R/S	
	Program automatically stops at θ = 180°			

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	Main program
002	F3?	16 23 03	
003	GSB0	23 00	
004	GSB9	23 09	
005	RCL0	36 00	
006	PSE	16 51	Display $x=\frac{\pi D}{\lambda}$
007	RCL2	36 02	
008	PRTX	-14	Output θ
009	SIN	41	
010	x	-35	
011	STO3	35 03	
012	GSBb	23 16 12	
013	PSE	16 51	Display $J_1(x\sin\theta)$
014	GSBd	23 16 14	
015	GTOA	22 11	
016	*LBL0	21 00	
017	÷	-24	
018	Pi	16-24	
019	x	-35	
020	STO0	35 00	Data storage and size parameter calculation
021	R↓	-31	
022	STO1	35 01	
023	R↓	-31	
024	STO2	35 02	
025	RTN	24	
026	*LBLb	21 16 12	Bessel function calculation
027	RCL3	36 03	
028	1	01	If x'≥15, branch to asymptotic routines -LBLc. (x'=xsinθ)
029	5	05	
030	X≤Y?	16-35	
031	GTOc	22 16 13	
032	R↓	-31	
033	2	02	
034	÷	-24	
035	STO4	35 04	
036	X²	53	
037	CHS	-22	
038	STO5	35 05	
039	*LBL1	21 01	Series 1 loop
040	RCL5	36 05	
041	RCLI	36 46	
042	Yˣ	31	
043	RCLI	36 46	
044	N!	16 52	
045	RCLI	36 46	
046	1	01	
047	+	-55	
048	N!	16 52	
049	x	-35	
050	÷	-24	
051	ST+6	35-55 06	
052	RCL6	36 06	
053	RCL7	36 07	
054	GSB5	23 05	
055	X>Y?	16-34	Convergence check
056	GTO2	22 02	branch out of loop

STEP	KEY ENTRY	KEY CODE	COMMENTS
057	RCL6	36 06	
058	STO7	35 07	
059	ISZI	16 26 46	
060	GTO1	22 01	Branch end point for series 1 loop
061	*LBL2	21 02	
062	RCL7	36 07	
063	ST+6	35-55 06	
064	2	02	
065	ST÷6	35-24 06	
066	RCL4	36 04	
067	ST×6	35-35 06	
068	RCL6	36 06	
069	RTN	24	
070	*LBLc	21 16 13	Hankel asymptotic forms for Bessel functions
071	RCL3	36 03	
072	P⇄S	16-51	
073	STO3	35 03	
074	3	03	
075	ENT↑	-21	
076	4	04	
077	÷	-24	
078	Pi	16-24	
079	x	-35	
080	-	-45	$\alpha=x\sin\theta-3/4\pi$
081	R→D	16 46	
082	COS	42	
083	STO4	35 04	$\beta=8x$
084	LSTX	16-63	
085	SIN	41	
086	STO5	35 05	Branch to series 2 loop
087	GSB3	23 03	
088	ST×4	35-35 04	Branch to series 3 loop
089	GSB4	23 04	
090	ST×5	35-35 05	
091	RCL3	36 03	
092	Pi	16-24	
093	x	-35	
094	2	02	
095	÷	-24	
096	1/X	52	$J_1(x\sin\theta)=\sqrt{\frac{2}{\pi x\sin\theta}}$
097	√X	54	
098	RCL4	36 04	$\times[P_{(B)}\cos\alpha-Q_{(B)}\sin\alpha]$
099	RCL5	36 05	
100	-	-45	
101	x	-35	
102	P⇄S	16-51	
103	STO6	35 06	
104	RTN	24	
105	*LBL3	21 03	Series 2 loop branch to multiplication loop
106	RCL8	36 08	
107	GSBe	23 16 15	
108	RCL8	36 08	
109	GSB8	23 08	
110	RCL8	36 08	
111	CHS	-22	
112	Yˣ	31	

REGISTERS

0	1	2	3	4	5	6	7	8	9
$x=\frac{\pi D}{\lambda}$	$\Delta\theta$	θ	$x\sin\theta$	$\frac{x\sin\theta}{2}$	$\left(\frac{x\sin\theta}{2}\right)^2$	Part sum series 1	Prior Part sum ser 1		
S0	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**
Partial product	Part sum series 2	Part sum series 3	$x\sin\theta$	$P_{(B)}\cos\alpha$	$Q_{(B)}\sin\alpha$			Index Series 2	Index Series 3

A	B	C	D	E	I
Prior Partial sum series 2	Prior Partial sum series 3				Index series 1 Index-mult.

97 Program Listing II

STEP	KEY ENTRY	KEY CODE	COMMENTS
113	×	-35	Series 2 loop
114	ST+1	35-55 01	$P_{(B)}=\Sigma_{m=-\infty}^{\infty}\frac{B^{-2m}}{(2m)!}$
115	RCL1	36 01	
116	RCLA	36 11	
117	GSB5	23 05	$\Pi_{k=1}^{2m}(-1)^k[(2k-1)^2-4]$
118	X>Y?	16-34	
119	GTO6	22 06	Convergence check
120	RCL1	36 01	branch out of loop
121	STOA	35 11	
122	2	02	
123	ST+8	35-55 08	
124	GTO3	22 03	
125	*LBL4	21 04	Series 3 loop
126	RCL9	36 09	
127	GSBe	23 16 15	$Q_{(B)}=\Sigma_{m=0}^{\infty}\frac{B^{-2m'}}{(2m')!}$
128	RCL9	36 09	
129	GSB8	23 08	
130	RCL9	36 09	$\Pi_{k=1}^{2m'}(-1)^K[(2k-1)^2-4]$
131	CHS	-22	
132	Y^x	31	m'=m+1/2
133	×	-35	
134	ST+2	35-55 02	
135	RCL2	36 02	
136	RCLB	36 12	
137	GSB5	23 05	
138	X>Y?	16-34	Convergence check
139	GTO7	22 07	branch out of loop
140	RCL2	36 02	
141	STOB	35 12	
142	2	02	
143	ST+9	35-55 09	
144	GTO4	22 04	
145	*LBLe	21 16 15	Multiplication
146	STOI	35 46	loop
147	1	01	
148	STO0	35 00	
149	*LBLa	21 16 11	
150	RCLI	36 46	
151	2	02	
152	×	-35	
153	1	01	
154	-	-45	
155	X²	53	
156	4	04	
157	-	-45	
158	1	01	
159	CHS	-22	
160	RCLI	36 46	
161	Y^x	31	
162	×	-35	
163	ST×0	35-35 00	
164	DSZI	16 25 46	
165	GTOa	22 16 11	
166	RCL0	36 00	
167	RTN	24	
168	*LBL8	21 08	

STEP	KEY ENTRY	KEY CODE	COMMENTS
169	N!	16 52	Partial summands
170	÷	-24	for Hankel Asymptotic
171	RCL3	36 03	forms
172	8	08	
173	×	-35	
174	RTN	24	
175	*LBL5	21 05	Convergence test
176	-	-45	routine
177	ABS	16 31	
178	EEX	-23	
179	9	09	
180	CHS	-22	
181	RTN	24	
182	*LBL6	21 06	
183	RCL1	36 01	Branch endpoints
184	RTN	24	for series loops in
185	*LBL7	21 07	subroutine c
186	RCL2	36 02	
187	RTN	24	
188	*LBL9	21 09	
189	0	00	
190	STO6	35 06	
191	STO7	35 07	
192	STOI	35 46	
193	P⇄S	16-51	Initializing
194	STO2	35 02	subroutine
195	2	02	
196	STO8	35 08	
197	1	01	
198	STO9	35 09	
199	STO0	35 00	
200	STO1	35 01	
201	P⇄S	16-51	
202	RTN	24	
203	*LBLd	21 16 14	Calculation of
204	RCL3	36 03	$i_F(x,\theta)$ and final
205	÷	-24	output
206	RCL0	36 00	
207	X²	53	
208	×	-35	
209	X²	53	
210	PRTX	-14	
211	RCL1	36 01	Angle stepping loop
212	ST+2	35-55 02	
213	RCL2	36 02	
214	Pi	16-24	
215	R→D	16 46	
216	X>Y?	16-34	IF $\theta \geq 180°$, stop
217	RTN	24	
220			

LABELS

A Start	B	C	D	E
a Mult. loop	b Bessel Func	c Hankel Asympt forms	d Output Routine	e
0 Data sto	1 Ser 1 loop	2 Ser 1 end pt	3 Ser 2 loop	4
5 Conv. test	6 Ser 2 end pt	7 Ser 3 end pt	8	9

FLAGS

0	
1	
2	
3	Data entry sensor

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☐
1	☐	☒	GRAD	☐	SCI	☒
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n	7

Program Description I

Program Title KUBELKA - MUNK DIFFUSING LAYER REFLECTANCE AND TRANSMITTANCE

Contributor's Name LEE M. CHASE

Address 121 MASSOL AVE., APT 408

City LOS GATOS **State** CA **Zip Code** 95030

Program Description, Equations, Variables PROGRAM CALCULATES THE OPTICAL PROPERTIES OF A DIFFUSING LAYER, ACCORDING TO THE THEORY OF KUBELKA AND MUNK.

VARIABLES ARE: s = SCATTERING COEFFICIENT, k = ABSORPTION COEFFICIENT, d = THICKNESS OF LAYER, R = REFLECTANCE, T = TRANSMITTANCE, R_∞ = REFLECTANCE OF AN INFINITELY THICK LAYER.

EQUATIONS USED: FUNCTION A

$$T = 4\beta/((1+\beta)^2 e^{Kd} - (1-\beta)^2 e^{-Kd})$$

$$R = (1-\beta^2)(e^{Kd} - e^{-Kd})/((1+\beta)^2 e^{Kd} - (1-\beta)^2 e^{-Kd})$$

WHERE: $Kd = \sqrt{kd(kd+2sd)}$, $\beta = kd/Kd$

SPECIAL CASE, $kd \to 0$: $T = 1/(1+sd)$, $R = 1-T$

EQUATIONS USED: FUNCTION B

$$kd = \beta Kd$$

$$sd = 1/2(Kd/\beta - kd)$$

WHERE: $Kd = \sinh^{-1}(2R\beta/T(1-\beta^2)$, $\beta = \sqrt{(A-1)/(A+1)}$,

$$A = R(1+(1-T^2)/R^2)/2$$

SPECIAL CASE, $R \to 0$: $sd = 0$, $kd = -\ln T$

SPECIAL CASE, $R+T=1$: $sd = (1/T)-1$, $kd = 0$

EQUATIONS USED: FUNCTION C, D

$R_\infty = (1-\beta)/(1+\beta)$, $sd/kd = ((1/\beta^2)-1)/2$ WHERE $\beta = (1-R_\infty)/(1+R_\infty)$

Operating Limits and Warnings $T = 0$ CANNOT BE INPUT TO FUNCTION B. IN THIS CASE $R = R_\infty$ AND FUNCTION D CAN BE USED TO FIND sd/kd.

Program Description II

Sketch(es)

Sample Problem(s) TWO SAMPLES OF SHEET PLASTIC HAVE THE PROPERTIES IN THE TABLE BELOW. WHICH ON WILL TRANSMIT MORE LIGHT?

	sd	kd
SAMPLE 1	3	0
SAMPLE 2	1	.6

THE REFLECTANCE AND TRANSMITTANCE OF A SAMPLE HAVE BEEN MEASURED AND FOUND TO BE .5552 AND .1131 RESPECTIVELY. WHAT ARE THE SCATTERING AND ABSORPTION COEFFICIENTS?

Solution(s)

	KEYSTROKES		
SAMPLE 1	3 [↑] 0 [A]	→ .7500***	(R)
		→ .2500	(T)
SAMPLE 2	1 [↑] .6 [A]	→ .3254***	(R)
		.2540	(T)

.5552 [↑] .1131 [B] → 2.9996*** (sd)
.4999 (kd)

Reference(s)

1. WENDLANDT, W. W., "REFLECTANCE SPECTROSCOPY", pp 55-62, INTERSCIENCE PUBLISHERS, 1966.
2. KUBELKA, P., "NEW CONTRIBUTIONS TO THE OPTICS OF INTENSELY LIGHT-SCATTERING MATERIALS. PART I", J. OPT. SOC. AM., 38, pp 448-457, MAY 1945.

User Instructions

KUBELKA - MUNK

1 ◀ ▶ 2

$sd \uparrow kd \rightarrow R, T$	$R \uparrow T \rightarrow sd, kd$	$\rightarrow R_\infty$	$R_\infty \rightarrow sd/kd$	$sd/kd \rightarrow R_\infty$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	LOAD SIDE 1 AND SIDE 2				
2	FIND APPLICABLE CASE IN LIST BELOW				
	AND INPUT APPLICABLE VALUES:				
	a) sd AND kd KNOWN,	sd	ENTER ↑		sd
	COMPUTE R AND T	kd	A		R, T
	OPTIONAL: COMPUTE R_∞		C		R_∞
	b) R AND T KNOWN, *	R	ENTER ↑		R
	COMPUTE sd AND kd	T	B		sd, kd
	OPTIONAL: COMPUTE R_∞		C		R_∞
	c) R_∞ KNOWN, COMPUTE sd/kd	R_∞	D		sd/kd
	d) sd/kd KNOWN, COMPUTE R_∞	sd/kd	E		R_∞
	* NOTE: IF T = 0 THEN $R = R_\infty$ AND				
	OPTION c) MUST BE CHOSEN				
	THEN ONLY THE RATIO sd/kd CAN				
	BE DETERMINED.				

67 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBL A	31 25 11	sd↑kd→R,T
002	STO B	33 12	
003	X=0?	31 51	is kd=0 ?
004	GTO 1	22 01	YES
005	X⇌Y	35 52	NO
006	STO A	33 11	
007	2	02	
008	X	71	
009	+	61	
010	RCL B	34 12	
011	X	71	
012	√x	31 54	
013	STO 0	33 00	
014	1/X	35 62	
015	RCL B	34 12	
016	X	71	
017	STO 1	33 01	
018	1	01	
019	+	61	
020	X²	32 54	
021	RCL 0	34 00	
022	eˣ	32 52	
023	X	71	
024	1	01	
025	RCL 1	34 01	
026	−	51	
027	X²	32 54	
028	RCL 0	34 00	
029	CHS	42	
030	eˣ	32 52	
031	X	71	
032	−	51	
033	STO 2	33 02	
034	RCL 0	34 00	
035	eˣ	32 52	
036	↑	41	
037	1/X	35 62	
038	−	51	
039	1	01	
040	RCL 1	34 01	
041	X²	32 54	
042	−	51	
043	X	71	
044	X⇌Y	35 52	
045	÷	81	
046	STO D	33 14	
047	−X−	31 84	
048	RCL 1	34 01	
049	4	04	
050	X	71	
051	RCL 2	34 02	
052	÷	81	
053	STO E	33 15	
054	GTO 2	22 02	
055	*LBL 1	31 25 01	kd=0
056	X⇌Y	35 52	
057	STO A	33 11	
058	1	01	
059	+	61	
060	1/X	35 62	
061	STO E	33 15	
062	1	01	
063	−	51	
064	CHS	42	
065	STO D	33 14	
066	−X−	31 84	
067	0	00	
068	STO 1	33 01	
069	R↓	35 53	
070	RCL E	34 15	
071	*LBL 2	31 25 02	
072	RTN	35 22	
073	*LBL B	31 25 12	R↑T→sd, kd
074	STO E	33 15	
075	X²	32 54	
076	1	01	
077	−	51	
078	CHS	42	
079	X⇌Y	35 52	
080	STO D	33 14	
081	X=0?	31 51	IS R=0?
082	GTO 3	22 03	YES
083	RCL E	34 15	NO
084	+	61	
085	1	01	
086	−	51	
087	X=0 ?	31 51	IS R+T=1 ?
088	GTO 4	22 04	YES
089	R↓	35 53	NO
090	RCL D	34 14	
091	X²	32 54	
092	÷	81	
093	1	01	
094	+	61	
095	2	02	
096	÷	81	
097	RCL D	34 14	
098	X	71	
099	STO 2	33 02	
100	1	01	
101	−	51	
102	RCL 2	34 02	
103	1	01	
104	+	61	
105	÷	81	
106	√x	31 54	
107	STO 1	33 01	
108	2	02	
109	X	71	
110	RCL 1	34 01	
111	X²	32 54	
112	CHS	42	

REGISTERS

0	1	2	3	4	5	6	7	8	9
Kd	β	USED							

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I
sd	kd	R_∞	R	T	

67 Program Listing II

STEP	KEY ENTRY	KEY CODE	COMMENTS
113	1	01	
114	+	61	
115	÷	81	
116	RCL E	34 15	
117	÷	81	
118	RCL D	34 14	
119	X	71	
120	↑	41	
121	X^2	32 54	
122	1	01	
123	+	61	
124	$\sqrt{X}$	31 54	
125	+	61	
126	LN	31 52	
127	STO 0	33 00	
128	RCL 1	34 01	
129	X	71	
130	STO B	33 12	
131	RCL 0	34 00	
132	RCL 1	34 01	
133	÷	81	
134	−	51	
135	CHS	42	
136	2	02	
137	÷	81	
138	STO A	33 11	
139	-X-	31 84	
140	RCL B	34 12	
141	GTO 5	22 05	
142	*LBL 3	31 25 03	R=0
143	RCL E	34 15	
144	LN	31 52	
145	CHS	42	
146	STO B	33 12	
147	0	00	
148	STO A	33 11	
149	-X-	31 84	
150	X⇄Y	35 52	
151	GTO 5	22 05	
152	*LBL 4	31 25 04	R+T = 1
153	RCL E	34 15	
154	1/X	35 62	
155	1	01	
156	−	51	
157	STO A	33 11	
158	-X-	31 84	
159	0	00	
160	STO B	33 12	
161	STO 1	33 01	
162	*LBL 5	31 25 05	
163	RTN	35 22	
164	*LBL C	31 25 13	→ R_∞
165	1	01	
166	RCL 1	34 01	
167	−	51	
168	1	01	
169	RCL 1	34 01	
170	+	61	
171	÷	81	
172	STO C	33 13	
173	RTN	35 22	
174	*LBL D	31 25 14	
175	STO C	33 13	
176	1	01	
177	−	51	
178	CHS	42	
179	RCL C	34 13	R_∞ → sd/kd
180	1	01	
181	+	61	
182	÷	81	
183	STO 1	33 01	
184	X^2	32 54	
185	1/X	35 62	
186	1	01	
187	−	51	
188	2	02	
189	÷	81	
190	RTN	35 22	
191	*LBL E	31 25 15	sd/kd → R_∞
192	2	02	
193	X	71	
194	1	01	
195	+	61	
196	$\sqrt{X}$	31 54	
197	1/X	35 62	
198	STO 1	33 01	
199	1	01	
200	−	51	
201	CHS	42	
202	1	01	
203	RCL 1	34 01	
204	+	61	
205	÷	81	
206	STO C	33 13	
207	RTN	35 22	
210			
220			

LABELS

A	B	C	D	E
sd↑kd→R,T	R↑T→sd,kd	→ R_∞	R_∞ → sd/kd	sd/kd → R_∞
a	b	c	d	e
0	1 kd=0 ?	2 USED	3 R=0 ?	4 R+T = 1 ?
5 USED	6	7	8	9

FLAGS

0	
1	
2	
3	

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☐	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n 4	

Program Description I

Program Title RAY TRACE PARABOLA

Contributor's Name DARREL D. TORGERSON

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Program Description, Equations, Variables PROGRAM DETERMINES DIRECTION COSINES OF INPUT RAY AND LOCAL NORMAL TO PARABOLIC SURFACE. THE DIRECTION COSINES OF THE REFLECTED ARE THEN DETERMINED BY THE FOLLOWING FORMULA:

$$k_r = k_i - 2aK_s$$
$$l_r = l_i - 2aL_s$$
$$m_r = m_i - 2aM_s$$

WHERE:

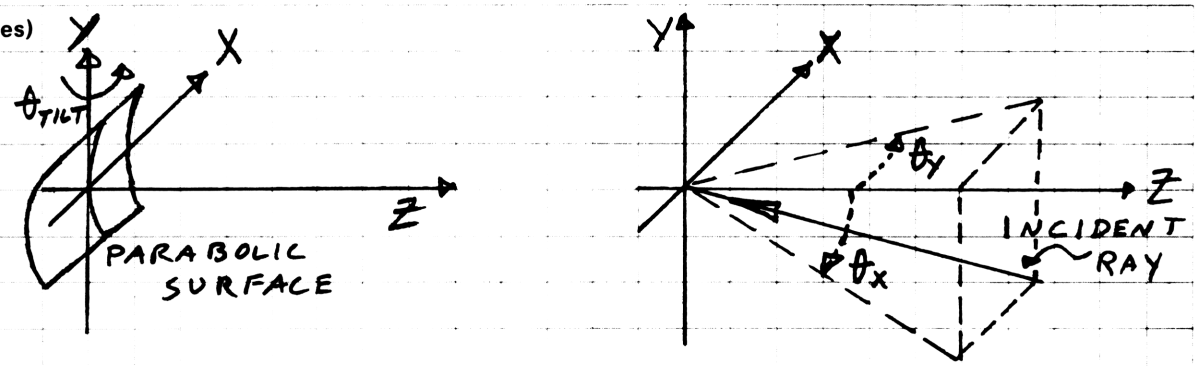
k_i, l_i, m_i ARE DIR. COSINES OF INCIDENT RAY
K_s, L_s, M_s ARE DIR. COSINES OF SURFACE NORMAL
k_r, l_r, m_r ARE DIR. COSINES OF REFLECTED RAY

$$a = k_i K_s + l_i L_s + m_i M_s$$

Operating Limits and Warnings NOTE THAT WHEN Z_{OBJECT} IS STORED BY KEYS f e A FLAG IS SET WHICH CAUSES THE INPUT RAY DIRECTION COSINES TO BE CALCULATED FROM A FINITE SOURCE. THIS FLAG IS CLEARED WHEN THE INCIDENT ANGLES θ_x AND θ_y FROM A SOURCE AT INFINITY ARE ENTERED BY KEY B.

Program Description II

Sketch(es)



Sample Problem(s) a) FOR A PARABOLIC MIRROR WITH A FOCAL LENGTH OF 50 CM FIND THE COORDINATES OF A REFLECTED RAY IN AN IMAGE PLANE 50 CM FROM THE MIRROR WITH THE MIRROR TILTED $-1°$ AND WITH THE INCIDENT AT AN ANGLE OF $\theta_X = 0.5°$, $\theta_Y = 2°$ HITTING THE MIRROR AT $X_m = 5$, $Y_m = 6$.

b) WITH THE SAME TILT AND ANGLE OF INCIDENCE SCAN THE MIRROR FROM $X_m = 5$ TO $X_m = -5$, AND $Y_m = -2$ TO $Y_m = 13$ IN 5 CM. INCREMENTS.

NOTE THAT P = 2 F.L.

Solution(s) a) 100 STO A, 50 KEY f d, 1 CHS KEY f b, 0.5 ENTER 2 KEY B, 5 ENTER 6 KEY D

OUTPUT $X_i = -3.53977$

$Y_i = 0.42261$

b) f P>S, 4 STO 0, 5 STO 7, 2 CHS STO 8, 7.5 CHS STO 9, 5 STO 3, f P>S, KEY A

OUTPUT $X_m = 5.000000000$

$X_i = -3.53848$

$Y_i = 0.44899$ ETC

Reference(s)

User Instructions

RAY TRACE PARABOLA

PRINT CONST	θ_y TILT		Z_i	Z_o
SCAN MIR.	θ_x & θ_y	X_m–SCAN Y	X_m & Y_m–STP	X_o & Y_o

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	LOAD BOTH SIDES OF CARD				
2	INITIALLIZE				
	STORE PARABOLIC CONSTANT	P	STO	A	
	STORE NUMBER OF Y SCAN				
	POINTS N = INCREMENTS + 1	N	f	P>S	
			STO	0	
	STORE MIRROR END POINTS	X_{START}	STO	7	
		Y_{START}	STO	8	
	$X_{STOP} = X_{END} - \Delta X/2$	X_{STOP}	STO	9	
	STORE INCREMENT SIZE	ΔX & ΔY	STO	3	
3	SELECT TILT OF MIRROR		f	P>S	
	ABOUT Y AXIS	θ_y TILT	f	b	θ_y TILT
4	SELECT IMAGE PLANE	Z_{IMAGE}	f	d	Z_{IMAGE}
5	FINITE OBJECT DISTANCE?				
	SELECT OBJECT DISTANCE	Z_{OBJECT}	f	e	Z_{OBJECT}
	SELECT POINT ON OBJECT	X_o	ENTER		
		Y_o		E	X_o
6	INFINITE OBJECT DISTANCE?				
	SELECT INCIDENT ANGLES	θ_x	ENTER		
		θ_y		B	$-\cos\theta_x \cos\theta_y$
7	SELECT RUN MODE				
	ONE RAY	X_{MIRROR}	ENTER		
		Y_{MIRROR}		D	X_{IMAGE}
					Y_{IMAGE}
	ONE Y_m SCAN	X_{MIRROR}		C	X_{MIRROR}
					X_i
					Y_i
					IMAGE
					PAIRS TO END
	SCAN ENTIRE MIRROR			A	X_{m1}
					X_i
					Y_i
					ETC
					X_{m2}
					X_i
					Y_i
					ETC
8	PRINT CONSTANTS (R0,		f	a	CONST.
	RSEC 0 TO 9, RA TO I)				

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLa	21 16 11	PRINTS CONSTANTS
002	RCL0	36 00	
003	PRTX	-14	
004	P⇄S	16-51	
005	PREG	16-13	
006	P⇄S	16-51	
007	R/S	51	
008	*LBLA	21 11	
009	CF0	16 22 00	INITIALIZES SCAN
010	P⇄S	16-51	
011	RCL0	36 00	
012	STOI	35 46	
013	RCL7	36 07	
014	F2?	16 23 02	SCAN Y ONLY?
015	GSB3	23 03	
016	DSP9	-63 09	INITIAL X_m
017	PRTX	-14	
018	DSP5	-63 05	
019	STO1	35 01	
020	RCL8	36 08	
021	STO2	35 02	
022	*LBL4	21 04	
023	RCL1	36 01	CALCULATES Z_m
024	X²	53	
025	RCL2	36 02	
026	X²	53	
027	+	-55	
028	RCLA	36 11	
029	÷	-24	
030	2	02	
031	÷	-24	
032	RCL1	36 01	
033	RCL2	36 02	
034	P⇄S	16-51	
035	STO8	35 08	
036	STO2	35 02	
037	R↓	-31	
038	STO7	35 07	
039	X⇄Y	-41	
040	→P	34	TRANSFORMS X_m AND Z_m TO TILTED COORDINATES X_θ AND Z_θ
041	X⇄Y	-41	
042	RCLE	36 15	
043	+	-55	
044	X⇄Y	-41	
045	→R	44	
046	STO3	35 03	
047	X⇄Y	-41	
048	STO1	35 01	
049	F1?	16 23 01	FINITE OBJECT?
050	GSB1	23 01	
051	RCLB	36 12	
052	STO4	35 04	
053	RCLC	36 13	
054	STO5	35 05	
055	RCLD	36 14	
056	STO6	35 06	

STEP	KEY ENTRY	KEY CODE	COMMENTS
057	*LBL6	21 06	
058	RCLA	36 11	
059	STO9	35 09	
060	RCL7	36 07	
061	→P	34	
062	RCL8	36 08	
063	→P	34	
064	ST÷9	35-24 09	
065	CHS	-22	
066	ST÷7	35-24 07	
067	ST÷8	35-24 08	
068	RCL7	36 07	
069	RCL9	36 09	
070	→P	34	
071	X⇄Y	-41	TRANSFORMS NORMAL TO MIRROR TO TILTED COORDINATES
072	RCLE	36 15	
073	+	-55	
074	X⇄Y	-41	
075	→R	44	
076	STO9	35 09	
077	X⇄Y	-41	
078	STO7	35 07	
079	RCL4	36 04	
080	×	-35	
081	RCL5	36 05	
082	RCL8	36 08	
083	×	-35	
084	+	-55	
085	RCL6	36 06	
086	RCL9	36 09	
087	×	-35	
088	+	-55	
089	2	02	
090	×	-35	
091	ST×7	35-35 07	
092	ST×8	35-35 08	
093	ST×9	35-35 09	
094	RCL7	36 07	
095	ST-4	35-45 04	
096	RCL8	36 08	
097	ST-5	35-45 05	
098	RCL9	36 09	
099	ST-6	35-45 06	
100	RCL0	36 00	
101	RCL3	36 03	
102	-	-45	
103	RCL6	36 06	
104	÷	-24	
105	ST×4	35-35 04	
106	ST×5	35-35 05	
107	RCL4	36 04	
108	RCL1	36 01	
109	+	-55	
110	PRTX	-14	PRINTS X_{IMAGE}
111	RCL5	36 05	
112	RCL2	36 02	

REGISTERS

0	1	2	3	4	5	6	7	8	9
Z_{IMAGE}	X_m (TILT)	Y_m	Z_m (TILT)	USED	USED	USED	USED	USED	USED

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
# POINTS	X_m	Y_m	ΔX = ΔY	X_{OBJECT}	Y_{OBJECT}	Z_{OBJECT}	X_m START	Y_m START	X_m END $- \frac{\Delta X}{2}$

A	B	C	D	E	I
PARABOLIC CONST. P	USED	USED	USED	TILT ANGLE θ_Y TILT	USED

'97 Program Listing II

STEP	KEY ENTRY	KEY CODE	COMMENTS
113	+	-55	
114	PRTX	-14	PRINTS Y_{IMAGE} ONE POINT ON MIRROR?
115	F0?	16 23 00	
116	R/S	51	
117	P⇄S	16-51	
118	RCL3	36 03	
119	ST+2	35-55 02	
120	DSZI	16 25 46	END OF Y SCAN?
121	GTO4	22 04	
122	F2?	16 23 02	SCAN Y ONLY?
123	GTO2	22 02	
124	RCL0	36 00	
125	STOI	35 46	
126	RCL8	36 08	
127	STO2	35 02	
128	RCL3	36 03	
129	ST-1	35-45 01	
130	RCL9	36 09	
131	RCL1	36 01	
132	SPC	16-11	
133	DSP9	-63 09	
134	PRTX	-14	PRINTS NEW X_m
135	DSP5	-63 05	
136	X>Y?	16-34	LAST X_m ?
137	GTO4	22 04	
138	P⇄S	16-51	
139	R/S	51	
140	*LBL1	21 01	
141	P⇄S	16-51	
142	RCL4	36 04	CALCULATES DIRECTION COSINES OF RAY FROM OBJECT TO MIRROR FOR OBJECT AT FINITE DISTANCE
143	RCL5	36 05	
144	RCL6	36 06	
145	P⇄S	16-51	
146	CHS	-22	
147	RCL3	36 03	
148	+	-55	
149	STO6	35 06	
150	R↓	-31	
151	CHS	-22	
152	RCL2	36 02	
153	+	-55	
154	STO5	35 05	
155	R↓	-31	
156	CHS	-22	
157	RCL1	36 01	
158	+	-55	
159	STO4	35 04	
160	RCL5	36 05	
161	→P	34	
162	RCL6	36 06	
163	→P	34	
164	ST÷4	35-24 04	
165	ST÷5	35-24 05	
166	ST÷6	35-24 06	
167	GTO6	22 06	
168	*LBLb	21 16 12	

STEP	KEY ENTRY	KEY CODE	COMMENTS
169	STOE	35 15	STORES TILT ANGLE θ_Y TILT
170	R/S	51	
171	*LBLE	21 15	
172	P⇄S	16-51	STORES OBJECT COORDINATES X_0 AND Y_0
173	STO5	35 05	
174	X⇄Y	-41	
175	STO4	35 04	
176	P⇄S	16-51	
177	R/S	51	
178	*LBLD	21 14	
179	SF0	16 21 00	
180	P⇄S	16-51	TRACES ONE RAY AT SPECIFIED MIRROR COORDINATES X_m AND Y_m
181	STO2	35 02	
182	X⇄Y	-41	
183	STO1	35 01	
184	GTO4	22 04	
185	*LBL2	21 02	
186	P⇄S	16-51	
187	R/S	51	
188	*LBLC	21 13	STOP Y SCAN
189	P⇄S	16-51	
190	STO1	35 01	TRACES RAYS IN Y_m DIR. AT SPECIFIED X_m
191	P⇄S	16-51	
192	SF2	16 21 02	
193	GTOA	22 11	
194	*LBL3	21 03	RECALLS X_m FOR Y SCAN
195	RCL1	36 01	
196	SF2	16 21 02	
197	RTN	24	
198	*LBLB	21 12	
199	CF1	16 22 01	CALCULATES DIRECTION COSINES OF INCIDENT RAYS AT θ_X AND θ_Y FROM OPTICAL AXIS FOR OBJECT AT INFINITY
200	SIN	41	
201	CHS	-22	
202	STOB	35 12	
203	R↓	-31	
204	LSTX	16-63	
205	COS	42	
206	X⇄Y	-41	
207	SIN	41	
208	STOC	35 13	
209	R↓	-31	
210	LSTX	16-63	
211	COS	42	
212	×	-35	
213	CHS	-22	
214	STOD	35 14	
215	R/S	51	
216	*LBLe	21 16 15	
217	SF1	16 21 01	STORES OBJECT COORDINATE Z_{OBJECT}
218	P⇄S	16-51	
219	STO6	35 06	
220	P⇄S	16-51	
221	R/S	51	
222	*LBLd	21 16 14	STORES IMAGE COORD. Z_i
223	STO0	35 00	
224	R/S	51	

LABELS

A SCAN MIRROR	B θ_x & θ_y	C X_m & SCAN Y	D X_m & Y_m - STOP	E X_0 & Y_0	0 ONE RAY
a PRINT CONSTANTS	b θ_Y TILT	c	d Z_{IMAGE}	e Z_{OBJECT}	1 FINITE OBJECT
0	1 DIR. COS.	2 Y STOP	3 X_m — Y SCAN	4 PROG. ENTR.	2 Y SCAN
5	6 ENTER FINITE COS.	7	8	9	3

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n	5

Program Description I

Program Title Paraxial Ray Tracing Part 1-Tracing

Contributor's Name Morton S. Lipkins

Address 3 Nemeth Street

City Malverne **State** New York **Zip Code** 11582

Program Description, Equations, Variables This program will trace a paraxial ray thru a centered lens system of up to 7 surfaces. All the data may be stored at one time by the subordinate storing program, Part 2. Image and object distances and Back Focal Length (BFL) are calculated. Effective Focal Length (EFL), image height, and lateral and longitudinal magnification are optional. Aperture approximations and slope angles at each surface are optional.

The following conventions apply with respect to each surface. See sketch, Page 4.

1. The ray goes from left to right
2. Distances to the left are positive, to the right are negative.
3. Slope angles are positive if the ray is above the axis before axial intersection, negative if below.
4. With respect to distances purpendicular to the axis, those above are positive, those below are negative.
5. Angles are equal to their sines and tangents.
6. Symbols, see sketch Page 4.

   y_1 =height above or below the axis of the intersection of the ray with surface R_1.

   u_1 = slope of the ray before intersection with surface R_1.

   u_1' = slope of the ray after refraction thru surface R_1.

Continued on Page 2.

Operating Limits and Warnings

Program Description I

Program Title Paraxial Ray Tracing, Part 1-Tracing

Contributor's Name Morton S. Lipkins

Address 3 Nemeth Street

City Malverne, **State** New York **Zip Code** 11565

Program Description, Equations, Variables

6. Symbols (continued)

ℓ_1 = distance from R_1 to the axial intercept from which the ray comes.

ℓ_1' = distance from R_1 to the axial intercept to which the ray goes after refraction.

c_1 = curvature = $1/R_1$.

N_1 = index of refraction preceeding the surface R_1.

$N_1' = N_2$ = index of refraction succeeding the surface R_1.

t_1 = axial distance between 2 surfaces R_1 & R_2

h_1 = height of the object above or below the axis.

h_1' = height of the image above or below the axis.

m = lateral magnification.

$\overline{m}$ = longitudinal magnification.

7. Formulae(see sketch Page 4.

$C_1 = 1/R_1$	$y_2 = y_1 - t_1 u_1'$	$\ell_1' = \ell_2$	$m = h'/h$
$y_1 = \ell_1 u_1$	$\ell_1' = y_1/u_1'$	$N_1' = N_2$	$\overline{m} = m^2$
$u_1' = \dfrac{c_1 y_1 (N_1' - N_1) + N_1 u_1}{N_1'}$	$h' = y_n - \ell_n' u_n'$	$u_1' = u_2$	$EFL = y_1/u_n'$

Operating Limits and Warnings 1. When storing R for a flat surface, the input is 0.00.

2. When storing an **infinite** ℓ the input is 0.00.

3. y should be set to ½ the aperture of surface R_1 in order that the approximate apertures of the succeeding surfaces be calculated.

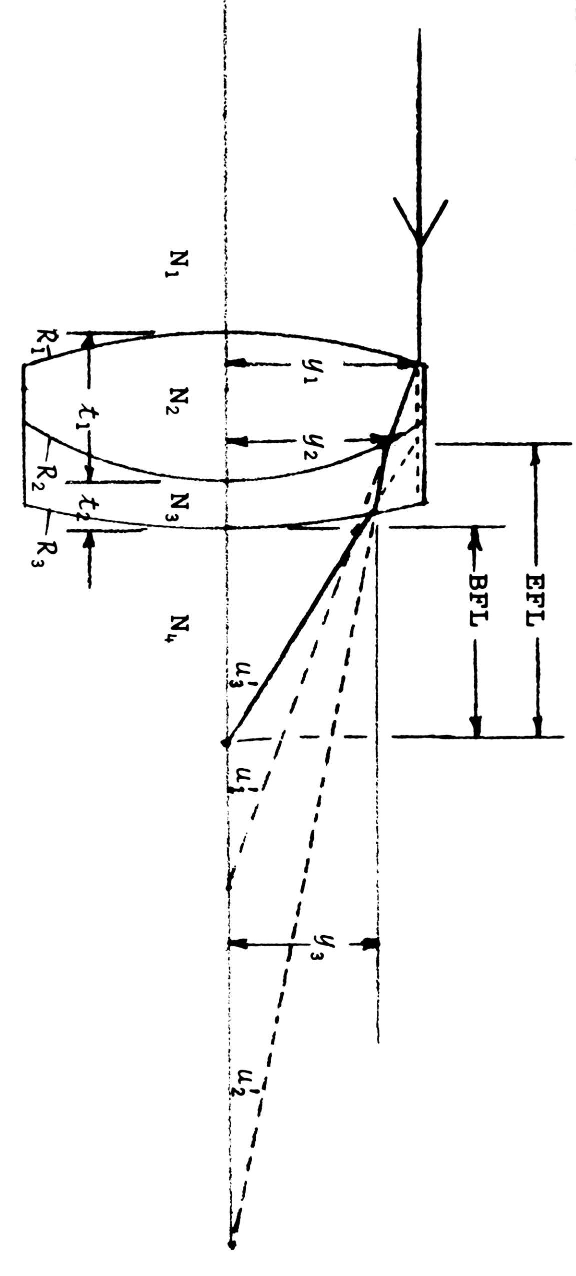


fig. 1

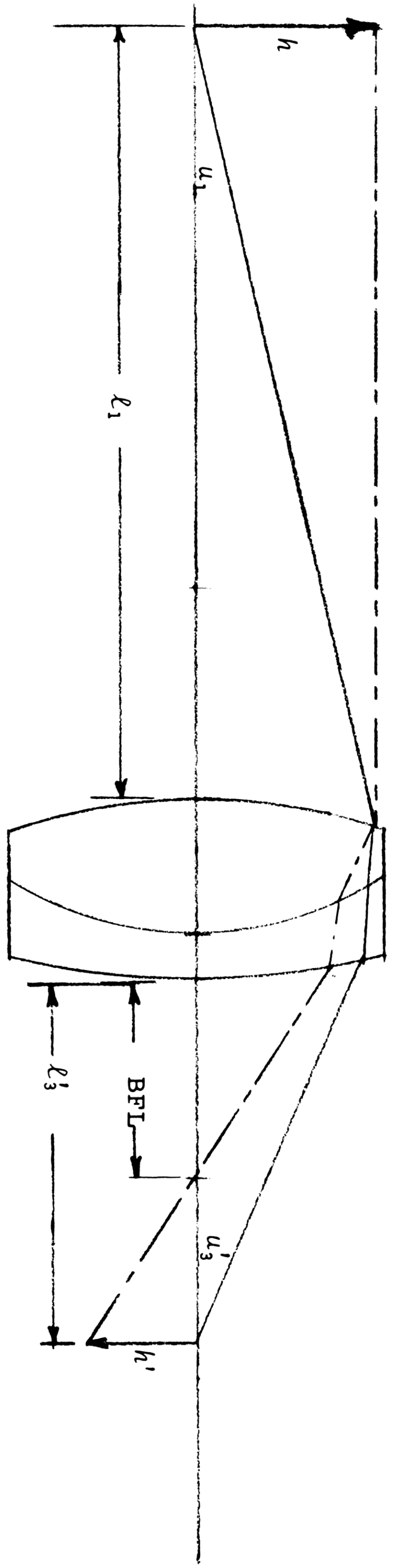


fig. 2

PROBLEMS

Given: A lens system of 3 surfaces (drawings, Page 4)

$R_1 = 1.674$	$R_2 = -1.032$	$R_3 = -2.350$
$N_1 = 1.0$	$N_2 = 1.517$	$N_3 = 1.649$
$N_1' = N_2 = 1.517$	$N_2' = N_3 = 1.649$	$N_3' = N_4 = 1.0$
$t_1 = 0.349$	$t_2 = 0.100$	
$u_1 = 0.0$		
$\ell_1 = 0.0$		
$y_1 = 0.55$		

Problem 1

Trace a Ray parallel to the axis, entering surface R_1 at y_1 (fig 1).
a. Determine the Back Focal Length (BFL).
b. Determine the Effective Focal Length (EFL).
c. Determine the aperture y at each surface.
d. Determine the Ray Slope u at each surface.

Solution

a. Store the data with the Storing Program Part 2 and record the data.
b. Feed the Tracing Program, Part 1, side 1 and side 2.
c. Print option, keystroke f E ------------------------output 1.00
d. Keystrokes 3 A-------------------------------------- u_2 0.112 ***
y_2 0.511 ***
u_3 0.063 ***
y_3 0.505 ***
u_4 0.244 ***

BFL 2.069 ***
e. Keystroke B-------------------------------------- EFL 2.255 ***

Problem 2

Trace a Ray from the axial point of an object 18" to the left of the above lens, and 0.55" high, (fig 2).
a. Determine the axial point of the image ℓ_3'.
b. Determine the image height h'.
c. Determine the lateral magnification m.
d. Determine the longitudinal magnification $\overline{m}$.

Solution

a. Assuming that the data from problem 1 is still in the calculator, feed the Storing Program, Part 1, side 1 and side 2.
   1. Keystroke 6 C -------------------------------------- 6.
   2. Input 0 R/S-- 6.
   3. Input -18 R/S-- 7.
b. Feed the Tracing Program, Part 1, side 1 and side 2.
c. Print option off fE----------------------------------- 0.00
d. Input 3 A --- 2.390 ℓ_n'
e. Input 0.55 E--- 0.000
f. Input halt 3 R/S ------------------------------------ 2.069 BFL
g. Input halt 2.390 R/S--------------------------------- -0.078 h'
-0.142 m
+0.020 $\overline{m}$

User Instructions

PARAXIAL RAY TRACING PART 1 - Tracing

n Start	EFL			h E	P? n R/S	ℓ'_n R/S

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1.	Store lens data with Storing Program, Part 2.				
2.	Load data card from Part 1 if data is not al-				
3.	ready in the calculator.				
3.	Load the Tracing Program, Part 1, side 1 and				
	side 2 .				
4.	Input n (number of surfaces) then A to start.	n	A		BFL or ℓ'_n
	This step takes 35 seconds for 3 surfaces.				
	If u_1 and ℓ_1 are zero, BFL will be calculated.				
	If only 1 of the 3 items u_1 ℓ_1 or y_1 is zero,				
	then ℓ'_n (image distance) will be calculated.				
5.	Optional: EFL (Effective Focal Length) but		B		EFL
	only if the output from step 3 is BFL (Back				
	Focal Length.)				
6.	Optional: Select print output mode for Ray		f	E	0.00/1.00
	Slopes u and Surface Apertures y at each				
	surface. u_2 0.112 ***				
	y_2 0.511 ***				
	u_3 0.063 ***				
	y_3 0.505 ***				
	u_4 0.244 ***				
	BFL 2.069 ***				
7.	Optional: Image height h', Linear magnifi-				
	cation m, Longitudinal magnification $\overline{m}$.				
	1. Step 3 to calculate ℓ'_n	n	A		ℓ'_n
	2. Input h	h	E		0.00
	3. Input halt. Key n (number of surfaces)	n	R/S		BFL
	4. Input halt. Key ℓ'_n from step 7-1	ℓ'_n	R/S		h' m $\overline{m}$

97 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	Stipulate the number of surfaces.
002	2	02	
003	×	-35	
004	6	06	
005	+	-55	
006	DSP3	-63 03	
007	STO2	35 02	Address the data registers. Start with number 4
008	SF2	16 21 02	
009	4	04	
010	STOI	35 46	The 3 items of data, u_1 ℓ_1 y_1 are manipulated here. See Page 6 step 4. Any 2 items may be given and the 3rd will be calculated. It will be printed if the option is set.
011	GSB5	23 05	
012	RCLE	36 15	
013	X=0?	16-43	
014	GTOd	22 16 14	
015	RCL0	36 00	
016	X=0?	16-43	
017	GTO6	22 06	
018	×	-35	
019	F1?	16 23 01	
020	PRTX	-14	
021	STO1	35 01	
022	GTOb	22 16 12	
023	*LBLd	21 16 14	
024	RCL1	36 01	
025	RCL0	36 00	
026	X=0?	16-43	
027	GTOb	22 16 12	
028	÷	-24	
029	F1?	16 23 01	
030	PRTX	-14	
031	STOE	35 15	
032	GTOb	22 16 12	
033	*LBL6	21 06	
034	RCL1	36 01	
035	RCLE	36 15	
036	X=0?	16-43	
037	GTOb	22 16 12	
038	÷	-24	
039	F1?	16 23 01	
040	PRTX	-14	
041	STO0	35 00	
042	GTOb	22 16 12	
043	*LBLb	21 16 12	Calculate u' and store for the calculation of y for the next surface.
044	RCLA	36 11	
045	RCL1	36 01	
046	×	-35	
047	RCLC	36 13	
048	RCLB	36 12	
049	-	-45	
050	×	-35	
051	RCLB	36 12	
052	RCLE	36 15	
053	×	-35	
054	+	-55	
055	RCLC	36 13	
056	÷	-24	

STEP	KEY ENTRY	KEY CODE	COMMENTS
057	F1?	16 23 01	Print u' if the option is set.
058	PRTX	-14	
059	STOE	35 15	Calculate y and store for the next surface.
060	RCL1	36 01	
061	RCLD	36 14	
062	RCLE	36 15	
063	×	-35	
064	-	-45	
065	RCL2	36 02	Final y? If yes, calculate BFL. If no, proceed to the next surface.
066	RCLI	36 46	
067	X=Y?	16-33	
068	GTO1	22 01	
069	R↓	-31	
070	R↓	-31	
071	F1?	16 23 01	
072	PRTX	-14	
073	STO1	35 01	
074	GTO5	22 05	
075	*LBL1	21 01	Calculate BFL and stop.
076	RCL1	36 01	
077	RCLE	36 15	
078	÷	-24	
079	SPC	16-11	
080	PRTX	-14	
081	F0?	16 23 00	
082	GTOa	22 16 11	
083	RTN	24	
084	STOD	35 14	
085	SPC	16-11	
086	RTN	24	
087	*LBLB	21 12	Calculate EFL.
088	RCL7	36 07	
089	GSBC	23 13	
090	RCLE	36 15	
091	÷	-24	
092	PRTX	-14	
093	RTN	24	
094	*LBL5	21 05	Recall data from the data registers 4 to 24 as needed for storage into the program registers A thru E, 0 and 1.
095	GSB2	23 02	
096	X≠0?	16-42	
097	GSB7	23 07	
098	STOA	35 11	
099	GSB3	23 03	
100	STOB	35 12	
101	GSB2	23 02	
102	STOC	35 13	
103	GSB3	23 03	
104	STOD	35 14	
105	F2?	16 23 02	1st Surface? Recall 7 items of data.
106	GTO4	22 04	
107	GTOb	22 16 12	
108	*LBL7	21 07	C=1/R
109	1/X	52	
110	RTN	24	
111	*LBL4	21 04	
112	GSB2	23 02	

REGISTERS

0	1	2	3	4	5	6	7	8	9
used	used	used	used						

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I
used	used	used	used	used	used

97 Program Listing II

STEP	KEY ENTRY	KEY CODE	COMMENTS
113	STOE	35 15	Balance of data for 1st Surface.
114	GSB3	23 03	
115	STO0	35 00	
116	GSB2	23 02	
117	STO1	35 01	
118	ISZI	16 26 46	Summon next data register.
119	RTN	24	
120	*LBL2	21 02	Recall 1st item from the data register.
121	RCLi	36 45	
122	GSBC	23 13	
123	RTN	24	
124	*LBL3	21 03	Recall 2nd item from the data register.
125	RCLi	36 45	
126	GSBD	23 14	
127	ISZI	16 26 46	
128	RTN	24	
129	*LBLC	21 13	Restore decimal to the 1st item recalled from the data register.
130	INT	16 34	
131	EEX	-23	
132	3	03	
133	CHS	-22	
134	x	-35	
135	RTN	24	
136	*LBLD	21 14	Restore decimal and polarity to the 2nd item recalled from the data register.
137	FRC	16 44	
138	ABS	16 31	
139	EEX	-23	
140	1	01	
141	x	-35	
142	ENT↑	-21	
143	INT	16 34	
144	5	05	
145	X⇄Y	-41	
146	X>Y?	16-34	
147	GTOc	22 16 13	
148	STO3	35 03	
149	LSTX	16-63	
150	FRC	16 44	
151	GTO9	22 09	
152	*LBLc	21 16 13	
153	4	04	
154	-	-45	
155	STO3	35 03	
156	R↓	-31	
157	R↓	-31	
158	CHS	-22	
159	FRC	16 44	
160	*LBL9	21 09	
161	1	01	
162	0	00	
163	RCL3	36 03	
164	2	02	
165	-	-45	
166	Y^x	31	
167	X	-35	
168	RTN	24	

STEP	KEY ENTRY	KEY CODE	COMMENTS
169	*LBLe	21 16 15	Print toggle.
170	F1?	16 23 01	
171	GTO8	22 08	
172	SF1	16 21 01	
173	1	01	
174	RTN	24	
175	*LBL8	21 08	
176	CF1	16 22 01	
177	0	00	
178	RTN	24	
179	*LBLE	21 15	Set $y_1 = h$.
180	EEX	-23	
181	3	03	
182	x	-35	
183	STO7	35 07	
184	0	00	Set u_1 and $\ell_1 = 0$ and store in the data register 6.
185	STO6	35 06	
186	SF0	16 21 00	
187	R/S	51	Input halt for n. Calculate ℓ_n'.
188	GSBA	23 11	
189	*LBLa	21 16 11	Input halt for ℓ_n'.
190	R/S	51	
191	STOD	35 14	
192	RCL1	36 01	Calculate h' and print.
193	RCLD	36 14	
194	RCLE	36 15	
195	x	-35	
196	-	-45	
197	PRTX	-14	
198	CF0	16 22 00	Calculate m and print.
199	RCL7	36 07	
200	GSBC	23 13	
201	÷	-24	
202	PRTX	-14	
203	X^2	53	Calculate $\overline{m}$ and print.
204	PRTX	-14	
205	RTN	24	
206	R/S	51	

LABELS

A start	B E F L	C decode	D decode	E ℓ_n'
a h' m $\overline{m}$	b u_1'	c decode	d u_1	e print
0	1 B F L	2 recall	3 recall	4 recall
5 recall	6 ℓ_1	7 reciprocal	8 print	9

FLAGS

0	ℓ_n'
1	print
2	1st surf.
3	

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☐	DEG	☐	FIX	☐
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n ____	

Program Description I

Program Title PARAXIAL RAY TRACING, Part 2 - Storing

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Program Description, Equations, Variables This program, Part 2, stores data for the Paraxial Ray Tracing Program, Part 1. Data for 7 surfaces can be stored. After storing, the Tracing Program is loaded into the calculator. The Tracing Program has subroutines for recalling, decoding and using the data.

Registers A to E, and 0 to 3 are used by the Ray Tracing Program. Therefore, upon initializing, this program presents, sequentially, registers 4 to 19 for storing. Two items of data will be loaded into each register, coded for the preservation of decimals and polarity. Each entry is assumed to contain a three place decimal. The range of each entry is .001 to 999.999.

The data to be stored must be grouped by surface as follows:
(see sketches, Tracing Program page 4.

Surface 1	Surface 2	etc.
R_1	R_2	
N_1	N_2	
N_2	N_3	
t_1	t_1	
u_1		
ℓ_1		
y_1		

Only the 1st surface requires 7 input items. The rest require only 4 input items each.

Operating Limits and Warnings

When storing R for a flat or plano surface, the input is 0.00 .

When storing an infinite ℓ the input is 0.00 .

Problem - Store the lens data of the problem on page 4 of the Tracing Program, Pt. 1

Keystrokes	Display Output	Print Output
A	4.	4.
1.674 R/S	4.	1.674
1.0 R/S	5.	1.000
		5.
1.517 R/S	5.	1.517
.349 R/S	6.	0.349
		6.
0 R/S	6.	0.000
0 R/S	7.	0.000
		7.
.55 R/S	8.	.550
		8.
-1.032 R/S	8.	-1.032
1.517 R/S	9.	1.517
		9.
1.649 R/S	9.	1.649
.10 R/S	10.	0.100
		10.
-2.35 R/S	10.	-2.350
1.649 R/S	11.	1.649
		11.
1.0 R/S	11.	1.000

User Instructions

PARAXIAL RAY TRACING Part 2 Store

Initialize | N | DEL

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Load side 1 and side 2				0.
2	Initialize		A		4.
3	Input item 1	R_1	R/S		4.
4	" " 2	N_1	R/S		5.
5	" " 3	N_2	R/S		5.
6	" " 4	t_1	R/S		6.
7	" " 5	u_1	R/S		6.
8	" " 6	ℓ_1	R/S		7.
9	" " 7	y_1	R/S		8.
	Only the first surface will require 7 input				
	items. All of the subsequent surfaces will				
	require only 4 input items. Steps 10 to 13				
	are typical of the subsequent surfaces.				
10	Input item 8	R_2	R/S		8.
11	" " 9	N_2	R/S		9.
12	" " 10	N_3	R/S		9.
13	" " 11	t_2	R/S		10.
14	If an input error is made in the nth register,				
	key n, then re-store both items., following	n	C		n
	the input steps above.				
15	To store in a register out of turn, use the				
	error proceedure, step 14.				

97 Program Listing I

STEP	KEY ENTRY	KEY CODE	COMMENTS
001	*LBLA	21 11	Clear Registers.
002	CLRG	16-53	
003	P⇄S	16-51	
004	CLRG	16-53	
005	SF2	16 21 02	Set discriminant for order of entry. Start with register 4. Print register number.
006	DSP0	-63 00	
007	4	04	
008	STOI	35 46	
009	PRTX	-14	
010	*LBLB	21 12	Display current register number.
011	DSP0	-63 00	
012	RCLI	36 46	
013	R/S	51	
014	DSP3	-63 03	Print entry.
015	PRTX	-14	
016	F2?	16 23 02	1st or 2nd entry?
017	GTO1	22 01	
018	X<0?	16-45	2nd entry negative?
019	GSBb	23 16 12	Criteria for entrys less than 1.
020	.	-62	
021	9	09	
022	9	09	
023	9	09	
024	X⇄Y	-41	
025	X>Y?	16-34	
026	GTO6	22 06	
027	EEX	-23	Move decimal for storing 2nd entry.
028	1	01	
029	CHS	-22	
030	GSBd	23 16 14	
031	.	-62	Code for entrys less than 1.
032	2	02	
033	GTOe	22 16 15	
034	*LBL1	21 01	Move decimal and store 1st entry.
035	X<0?	16-45	
036	SF0	16 21 00	
037	EEX	-23	
038	3	03	
039	x	-35	
040	ST+i	35-55 45	
041	7	07	Skip 2nd entry in register 7.
042	RCLI	36 46	
043	X=Y?	16-33	
044	GTOc	22 16 13	
045	GTOB	22 12	
046	*LBL6	21 06	Criteria for entrys less than 10.
047	9	09	
048	.	-62	
049	9	09	
050	9	09	
051	9	09	
052	X⇄Y	-41	
053	X>Y?	16-34	
054	GTO7	22 07	
055	EEX	-23	Move decimal for
056	2	02	
057	CHS	-22	storing 2nd entry.
058	GSBd	23 16 14	
059	.	-62	Code for entrys less than 10.
060	3	03	
061	GTOe	22 16 15	
062	*LBL7	21 07	Criteria for entrys less than 100.
063	9	09	
064	9	09	
065	.	-62	
066	9	09	
067	9	09	
068	9	09	
069	X⇄Y	-41	
070	X>Y?	16-34	
071	GTO8	22 08	
072	EEX	-23	Move decimal for storing 2nd entry.
073	3	03	
074	CHS	-22	
075	GSBd	23 16 14	
076	.	-62	Code for entrys less than 100.
077	4	04	
078	GTOe	22 16 15	
079	*LBL8	21 08	Code for negative 2nd entry.
080	EEX	-23	
081	4	04	
082	CHS	-22	
083	GSBd	23 16 14	
084	.	-62	Code for entrys more than 100
085	5	05	
086	GTOe	22 16 15	
087	*LBLb	21 16 12	Code for negative 2nd entry.
088	CHS	-22	
089	.	-62	
090	4	04	
091	GSB2	23 02	
092	R↓	-31	
093	RTN	24	
094	*LBLd	21 16 14	
095	x	-35	
096	GTO2	22 02	
097	*LBLe	21 16 15	
098	GSB2	23 02	
099	CF0	16 22 00	
100	ISZI	16 26 46	Summon next register and print register number.
101	RCLI	36 46	
102	DSP0	-63 00	
103	PRTX	-14	
104	SF2	16 21 02	
105	GTOB	22 12	
106	RTN	24	
107	*LBLc	21 16 13	
108	8	08	
109	STOI	35 46	
110	DSP0	-63 00	
111	PRTX	-14	
112	SF2	16 21 02	

REGISTERS

0	1	2	3	4	5	6	7	8	9
Used	Used	Used	Used						
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I
Used	Used	Used	Used	Used	Used

97 Program Listing II

STEP	KEY ENTRY	KEY CODE	COMMENTS
113	GTOB	22 12	
114	RTN	24	
115	*LBLC	21 13	Error correction.
116	STOI	35 46	
117	DSP0	-63 00	
118	PRTX	-14	
119	0	00	
120	STOi	35 45	
121	SF2	16 21 02	
122	GTOB	22 12	
123	*LBL2	21 02	Set proper polarity for storing 2nd entry.
124	F0?	16 23 00	
125	CHS	-22	
126	ST+i	35-55 45	
127	RTN	24	
128	R/S	51	

LABELS					FLAGS
A Start	B Sorting	C Error	D	E	0
a	b Code	c Skip	d Decimal	e Summon	1
0	1 Store	2 Polarity	3	4	2 Entry ?
5	6 Criteria	7 Criteria	8 Decimal	9	3

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☐	DEG	☒	FIX	☒
1	☐	☐	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☐			n	

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