APART/PADE Version 7: a deterministic computer program used to calculate scattered and diffracted energy

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Abstract

The APART/PADE (Arizona's Paraxial Analysis of Radiation Transfer/Program for the Analysis of Diffracted Energy) code is a deterministic stray radiation analysis program capable of yielding quantitative descriptions of systems along with providing insight about the propagation paths. The program can be used to determine the image plane distribution due to external point sources, external extended sources such as the Earth, and for internally emitted radiation. The inclusion of the PADE program allows not only pure diffraction paths to be evaluated but also mixed modes of diffraction and scatter in any order. The program handles a large class of asymmetrical optical sensors and is designed to be most efficient with rotationally symmetric systems. Many additional related features of the program are discussed.

Introduction

There are three significant stages in the optimum design for the suppression of stray radiation in an optical system. The first, and often the most crucial, is the "preliminary" conceptual design. Decisions made at this time are, more often than not, irrevocable. The second stage is the quantitative analysis of the system's performance; and, finally, the third stage is the measurement of the system's performance.

This paper directs its full attention to the second event, the quantitative analysis of a system. Even more specifically than that, it describes how the APART/PADE (Arizona's Paraxial Analysis of Radiation Transfer/Paraxial Analysis of Diffracted Energy) stray light analysis program is used to analyze a system. APART/PADE is but one of many tools availabel to predict and understand the stray light transmittance characteristics of an optical system. Of all the tools, it is one of the most significant when one considers that it not only can predict a system's performance, but it can also answer the fundamental question, "Why does the sensor perform in the way that it does?" As will be described in the succeeding passages, the design of the program is such that when presented with the full breadth and depth of the output, one has a complete understanding of the stray light characteristics of the system that is being analyzed. Nevertheless, the system being analyzed may not faithfully represent the actual physical system. This situation may exist because the scattering characteristics of the mirror, blacks, etc. were significantly different than the BRDF model used in the program; or because the ideal size and placement of aperture stops, Lyot stops, and field stops were not implemented; or, more simply, because the system was not fabricated according to the design; or, finally, because some undetected special characteristic of the system was not input to the program. It is when the program is used in addition to the other tools that its real power can be realized.

The APART/PADE computer program represents the incorporation of concepts that are diametrically opposed to the concepts and approaches used by other computer codes to the traditional approaches, and to the novice's general feeling on how to analyze and improve the performance of an optical system. The two most outstanding conceptual differences are:

1) In all other approaches one starts with finding the stray light propagation paths from a source into the system. For reasons that will be made clear later, the approach in APART is to start at the image plane and work one's way back out toward the source.

2) The typical first improvement of a system is through the use of a lower scattering surface, i. e., a blacker black or a super-polished low scatter mirror. When using APART, coating changes are the last resort.

There are other conceptually unique features in APART/PADE that are described in detail elsewhere in the literature.[1] Also, the documenting here is intended to supplement a previous report on the characteristics of its conceptual predecessor the APART program.[2] The diffraction capability of the APART/PADE program is described in detail in another paper presented at this seminar.[3]

The approach developed in the following sections will be to take a representative optical system and determine what information about it would be desirable to know. It will start with the most basic information that is essentially required in a stray light analysis and expand to some system information which heretofore was not available. The approach is applicable to any general system, even without the use of the APART/PADE code. However, the overall attempt is to document the power the program has in calculating or graphically displaying the desired information.

The APART/PADE program represents approximately 18 man years of development and use. Work on the program continues to expand and improve its capabilities. A special effort is being made at improving the input requirements and making the code easier for a novice user.

The analysis begins at the image plane

What is the power, or irradiance distribution, on the image plane? That is the fundamental question. If it were known and if it were low enough, it would be the only question that need be asked and answered. One could either use a numerical calculation (including computer codes) or measure the actual system to determine this; in either case, assuming the result were low enough, he would be finished. Problems arise when the calculation is too difficult to calculate by "hand", too risky to wait until the system is built to test, or when, in any case, the system does not meet the design requirements. Then one must answer the second fundamental question: "Why not?" Let us see how APART/PADE can answer that question.

The APART/PADE program is a series of four individual programs that are run sequentially after the necessary information is gathered from each preceeding program. To help answer the question why or how the system performs as it does, the first program in the series is designed to look out from the detector and identify the "critical" elements in the system that can scatter to the detector. Vast improvements to a system can be made with only this information. It is almost always possible to remove many of the critical objects out of the view of the detector. The power transferred to the detector from such elements then goes to zero, something that can never be achieved with "better coatings". By determining what the remaining critical surfaces are we have isolated the potential trouble spots. Program One can then find what we refer to as "hot" elements in the system: the elements that receive power from a series of off-axis sources. Taking one such off-axis position, the analyst now has identified two important aspects of the system: he knows the set of all possible first-level paths, i. e., from the source to the "hot" elements; he also knows the set of all possible paths at the last level of scatter, i. e., from the "critical" elements to the detector. If the set of "hot" elements has any elements in common with the set of "critical" elements, he knows the significant path or paths. He no longer is concerned about where all the incoming radiation is going but only that fraction that belongs to a finite set of elements.

For example, the system shown in Figure 1 is input with the data shown in Figure 2. Object numbers and literal designations are assigned to each element in the system and are referenced throughout the series of programs. In Figure 2, the number associated with each object is the first integer after the description (CONE, DIFFRACT, DISK or OPTIC).

Program One has the capability of doing a preliminary quantitative stray light analysis when there are elements common to both sets of objects, (Figure 3). As in Program Three, it can also do this analysis for a series of off-axis positions of the point source and can summarize this information in a tabular form, as shown in Figure 4, and calculate it's own Point Source Transmittance Plot (PST) (Figure 5), that can later be compared with Program Three's more complete analysis. Program One is also able to produce graphical pictures of what can be seen from any position in any space, (Figure 6).

Typically, for large off-axis angles the set of hot elements and critical elements form two distinct sets, and the linking of the paths from the set of hot objects to the critical objects is determined by the user. The actual power transfer calculations are then performed in Program 3. Program One aids the user by graphically plotting the image of all objects as seen from any space of the system, (Figure 7), and/or the mechanical layouts of the system (Figure 1). This also helps the user see how hot elements can receive power via multiple reflections (or refractions), or how critical elements are seen in reflection from the image plane. By now the analysts have started to understand qualitatively, and to some extent quantitatively, how the system is funtioning.

INPUT CARD LISTING

```
* TEST DECK FOR PADE/APART VERSION 7
* F/10 CASSEGRAIN TELESCOPE

PLOT 0 3

COATING BAFFLES .01
COATING OPTICS .001 -2.
 ELIPTEDGE 11 -1 1 2 2 -10 =EDGE OF SUNSHIELD
  TILT-DEC ANGLE 10. ZCIR -5.
 CONE 10 -1 8 -10 2 -5 .105 =SUN SHIELD
  SLICE FRONT 10.
  TILT-DEC 1
 DIFRACT 12 -1 1 -5 1.0247 =EDGE OF MAIN BAFFLE
 CONE 1 -1 8 -5.0000 1.0247 -.49995E-01 1.0000  =MAIN BAFFLE
 CONE 2 -1 2 -3.4231 .33623 -3.9098 .24044  =INNER SECONDARY BAFFLE
 CONE 3 -1 5 -2.0214 .18019 0 .18019  =INNER CONICAL BAFFLE
 DISK 4 -1 1 -5.0000 .32835 0.  =INNER ENTRANCE PORT
 CONE 5 1 1 -5.0000 .32835 -3.4231 .33623  =OUTER SECONDARY BAFFLE
 CONE 6 1 5 -.50926E-02 .31914 -2.0214 .18019  =OUTER CONICAL BAFFLE
 DIFRACT 13 -1 1 -.05 1 =EDGE OF PRIMARY
OPTIC 7 -1 6 0. 1.0000 .31914 =PRIMARY MIRROR
  RD -10.000
  CC -1.0353
 REPEAT  1  2  3  4  5  6  13
OPTIC 8 1 5 -3.9000  .24044 0. =SECONDARY MIRROR
  RD -2.9333
  CC -3.1576
 REPEAT  1  2  3  4  5  6
DISK 9 -1 1 .50000 .99911E-01 0. =FINAL IMAGE PLANE

IGNORE 11  2 13
COBSCUR  .33627
POINT SOURCE ANGLES 2 10
SCAN
 1 3 -1.0246 -5.0001 -1.01
 3 1 -.05 .4999 3.03 PICTURE -.5
XEQ
```

Figure 1. Representative input deck that will perform a preliminary quantitative stray light analysis in Program One.

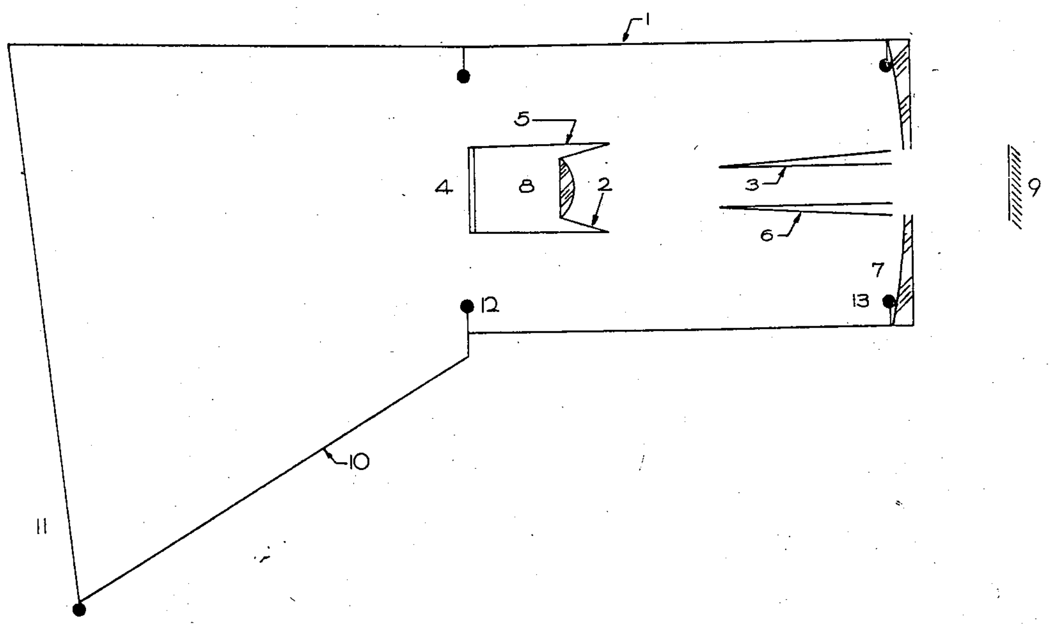


Figure 2. A profile of a representative system.

PATH	POWER ON	OBJECT	X GCF OF	OBJECT	X REFLECT =	DET POWER	(PERCENT)
1	.98751E-01	-6.02	.83323E-05	-6.02	.10000E-01	.82283E-08	.03
2	.91329E-01	-6.01	.55143E-05	-6.02	.10000E-01	.50362E-08	.02
3	.85891E-02	2.02	.15359E-03	2.01	.10000E-01	.13192E-07	.05
4	-.24287E-01	2.02	.15359E-03	2.01	.10000E-01	.37302E-07	.15
5	.99389E-02	1.01	.18756E-03	1.02	.10000E-01	.18641E-07	.08
6	-.37409E-01	1.01	.18756E-03	1.02	.10000E-01	.70162E-07	.29
7	.10863	2.02	.19637E-03	2.02	.10000E-01	.21331E-06	.89
8	-.29578	2.02	.19637E-03	2.02	.10000E-01	.58080E-06	2.41
9	.10461	2.02	.69861E-02	2.03	.10000E-01	.73080E-05	30.33
10	-.32671	2.02	.46289E-02	2.03	.10000E-01	.15123E-04	62.77
11	.83261E-01	-8.02	.16411E-01	-8.03	.11238E-04	.15356E-07	.06
12	-.13680	-8.02	.22087E-01	-8.03	.11265E-04	.34037E-07	.14
13	.61996E-01	8.02	.16414E-01	8.03	.11052E-04	.11246E-07	.05
14	-.81430	8.02	.16297E-01	8.03	.11000E-04	.14597E-06	.61
15	.44958	-7.01	.80715E-03	-7.02	.23149E-03	.84000E-07	.35
16	-1.0611	-7.01	.80749E-03	-7.02	.23185E-03	.19865E-06	.8
17	.35466	7.01	.81119E-03	7.02	.23062E-03	.66337E-07	.28
18	-.85510	7.01	.80956E-03	7.02	.22874E-03	.15835E-06	.66

```
         POWER PER UNIT AREA ON DETECTOR FROM OFF-AXIS SOURCE
TOTAL ---------------------------------------------------------- = .24092E-04
          POWER PER UNIT AREA AT SENSOR FROM OFF-AXIS SOURCE
```

	OBJECT		PERCENT
1	MAIN BAFFLE	CONE	.37
2	INNER SECONDARY BAFF	CONE	96.61
6	OUTER CONICAL BAFFLE	CONE	.06
7	PRIMARY MIRROR	REFL	2.11
8	SECONDARY MIRROR	REFL	.86

Figure 3. Power transfer calculation performed in Program One.

SUMMARY FOR DETECTOR POSITION Y = 0. Z = 18.500

SOURCE	ANGLE	PST	MAJOR CONTRIBUTOR PERCENT	OBJN	DESCRIPTION	TYPE
1	2.0	.14986E-01	57.57	20. SEC.	APT	DISK
2	3.0	.20464E-01	52.88	20. SEC.	APT	DISK
3	4.0	.20609E-01	50.83	20. SEC.	APT	DISK
4	5.0	.19239E-01	49.46	20. SEC.	APT	DISK
5	6.0	.12704E-01	40.92	20. SEC.	APT	DISK
6	7.0	.59688E-02	34.14	18. SEC.	DISK 5	DISK

Figure 4. Percent of contribution for a series of off axis angles as calculated by Program One.

The quantitative calculations

The major quantitative calculations that an analyst uses in the final analysis are found in Program Three. Therefore, we will temporarily bypass the discussion of Program Two, and proceed to Program Three output.

One would like to know the power or irradiance on the image and in some cases, it's distribution. Typical APART/PADE output of such information is shown in Figure 8. It would also be valuable to know how much of the power on the detector comes from each critical object, as a function of the off-axis position of the point source as shown in Figure 9. The program can also give a percent table that is a function of each scattering level to determine the significance of higher levels of scatter. In some cases there may be more than one path of radiation to the critical object that contributes a major portion of the power to the image plane. APART/PADE can trace the power propagated along every path and thereby pick out the major path, as shown in Figure 10. In APART/PADE the objects are divided up into sections. The trace routine and the percent tables identify the relative contribution from the entire object, but not which sections of that object are the contributors. Certainly it would be unusual for every area of the critical object to contribute the same amount of power to every area of the detector. Figure 11 shows the power contributed by each section of a critical object to one single section on the detector. This is normally done for all detector sections and all critical objects.

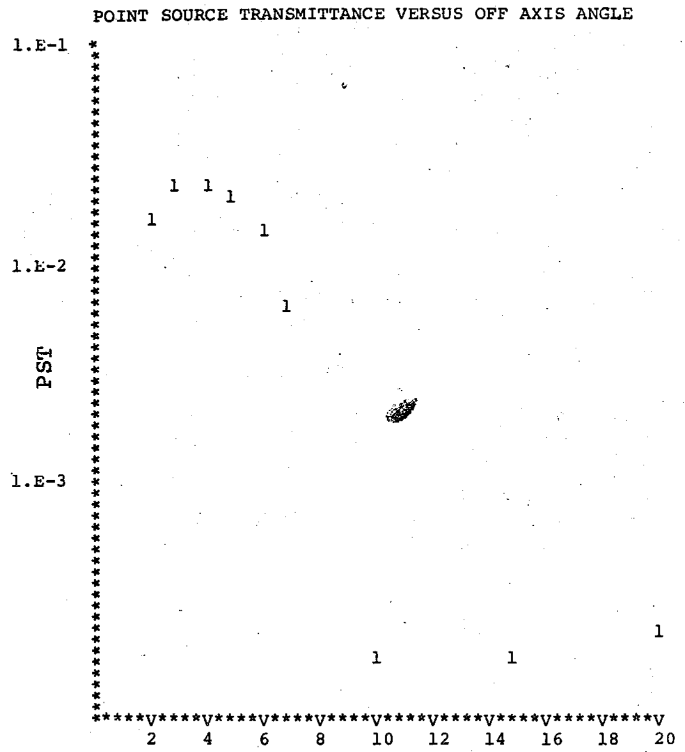


Figure 5. Point Source Transmittance plot from Program One.

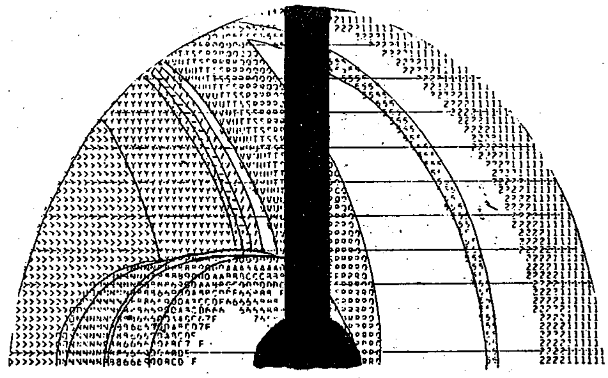


Figure 6. Objects as seen from a position in object space 5° off axis. Each character represents a different object that can be seen from the selected observation point. Dark shadow enhanced by hand.

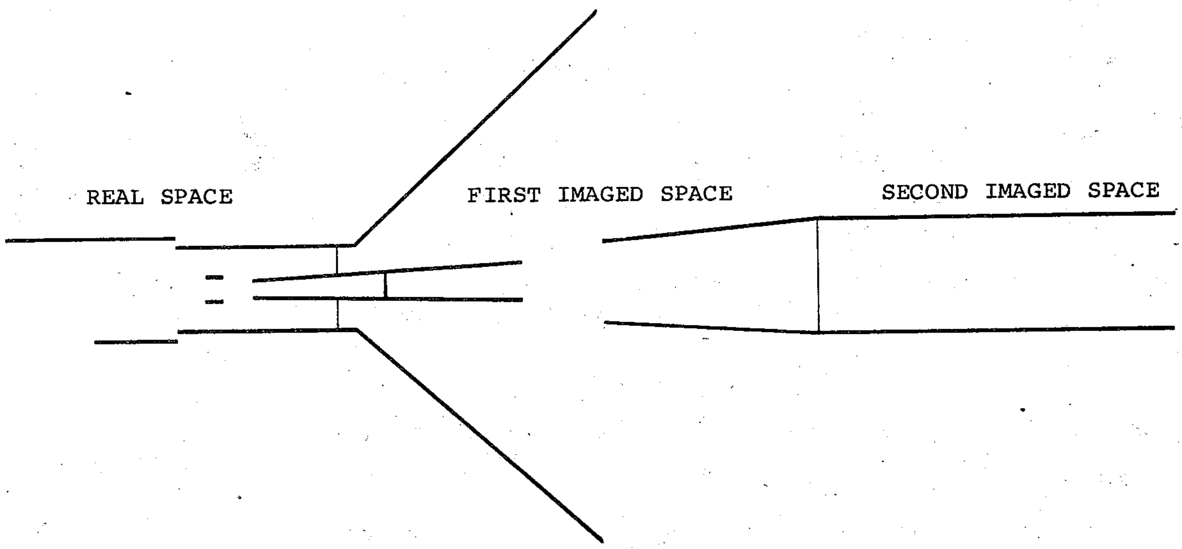


Figure 7. Profile of a telescope system and it's imaged surfaces as "seen" from object space.

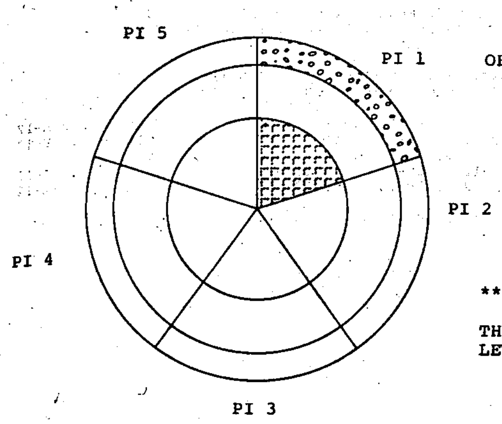
Geometrical Configuration Factors (GCF)

As described elsewhere,[2] the basic power transfer equation used in APART/PADE is

$$\phi_C = \phi_S \text{ BRDF GCF}$$

where ϕ_C is the power on the collector section, ϕ_S is the power on the source section, BRDF represents the scattering characteristics of the source, and GCF is the Geometrical Configuration Factor (or the projected solid angle of the collector as seen from the source) of the source-collector combination. Briefly

$$\text{GCF} = A_C \cos\theta_C \cos\theta_S / R^2$$



OBJECT 30 THE DETECTOR PLANE

THE POWER DISTRIBUTION ON OBJECT 30 FROM LEVEL 4 SCATTER IS:
(PI OR Y SECTIONS DOWN, Z OR X SECTIONS ACROSS)

1	1.34E-13	1.37E-13	1.39E-13
2	1.32E-13	1.33E-13	1.33E-13
3	1.31E-13	1.30E-13	1.29E-13
4	1.32E-13	1.33E-13	1.33E-13
5	1.34E-13	1.37E-13	1.39E-13

*****TOTAL POWER ADDED TO THIS OBJECT = 2.008430E-12

THE TOTAL ENERGY RECEIVED BY OBJECT 30 THRU 4
LEVELS OF SCATTERED RADIATION IS:

1	1.35E-11	1.34E-11	1.33E-11
2	1.37E-11	1.39E-11	1.40E-11
3	1.38E-11	1.42E-11	1.44E-11
4	1.37E-11	1.39E-11	1.40E-11
5	1.35E-11	1.34E-11	1.33E-11

*****THE TOTAL POWER ON THIS OBJECT IS 2.057886E-10

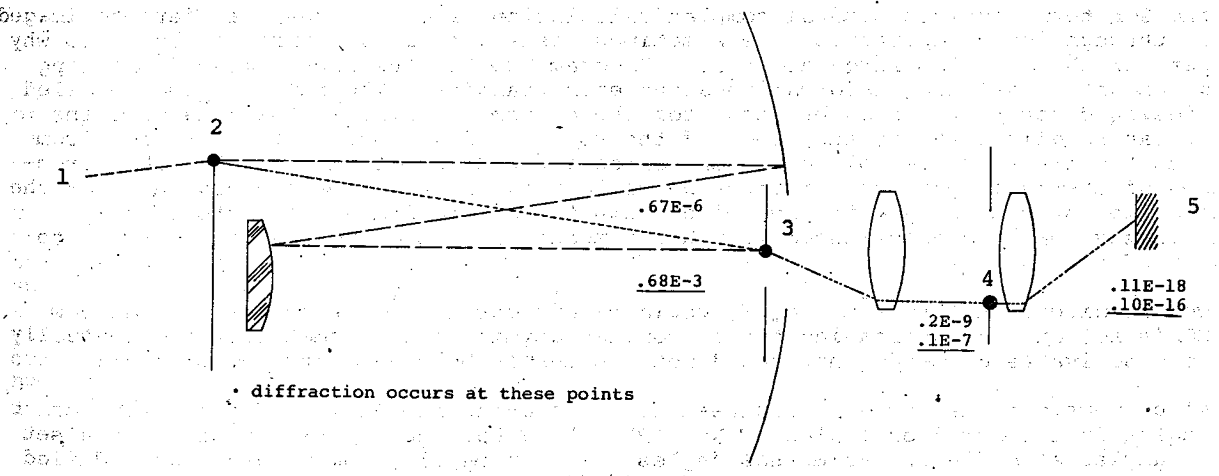
Figure 8. The power distribution across an image plane after four levels of scatter. Note that the top array contains the increments of power added at this level, and that the amount is insignificant where compared to the sum of previous levels.

	OBJECTS	OFF AXIS POSITION 1	2	3	4	5	6	7	8	9
6	INNER CONICAL BAFFLE	14.7	17.6	20.5	50.0	54.5	60.4	71.3	86.5	87.1
8	OUTER SECONDARY VANE	45.6	42.3	39.0	26.2	24.1	21.2	17.1	8.2	7.8
9	SECONDARY MIRROR	3.1	3.6	4.1	0.0	0.0	0.0	0.0	0.0	0.0
10	PRIMARY MIRROR	3.4	3.0	2.7	0.0	0.0	0.0	0.0	0.0	0.0
12	APERTURE STOP	27.1	27.0	27.1	19.1	17.2	14.8	11.6	5.3	5.1
19	INNER SECONDARY DISK	6.1	6.4	6.6	4.7	4.2	3.6	0.0	0.0	0.0
	TOTAL POWER	.206E-09	.147E-09	.839E-10	.182E-11	.162E-11	.140E-11	.113E-11	.879E-12	.688E-12
	SOURCE ANG	30.0	35.0	40.0	45.0	50.0	55.0	60.0	70.0	80.0

Figure 9. Percent of power contributed by each object as a function of off axis source position.

TRACE OF THE PROPAGATED RADIATION

SOURCE NUM	POWER	COLLECT NUM	SOURCE NUM	POWER	COLLECT NUM	SOURCE NUM	POWER	COLLECT NUM	SOURCE NUM	POWER	COLLECT NUM	POWER
1.01	.31E+21	2.01	2.01	.10E+01	3.03	3.03	.68E-03	4.05	4.05	.10E-07	5.07	.10E-16
1.01	.31E+21	2.01	2.03	.10E+01	3.03	3.03	.67E-06	4.05	4.05	.20E-09	5.07	.11E-18



OBJECTS
1 POINT SOURCE
2 SECONDARY DISK
3 FIELD STOP
4 LYOT STOP
5 DETECTOR

PATH A
1) POINT SOURCE TO 2
2) 2 TO 3 VIA REFLECTION OFF THE PRIMARY AND SECONDARY
3) 3 TO 4
4) 4 TO 5

PATH B
1) POINT SOURCE TO SECONDARY DISK
2) SECONDARY DISK TO FIELD STOP DIRECTLY
3) FIELD STOP TO LYOT STOP
4) LYOT STOP TO DETECTOR

Figure 10. Power trace along each path.

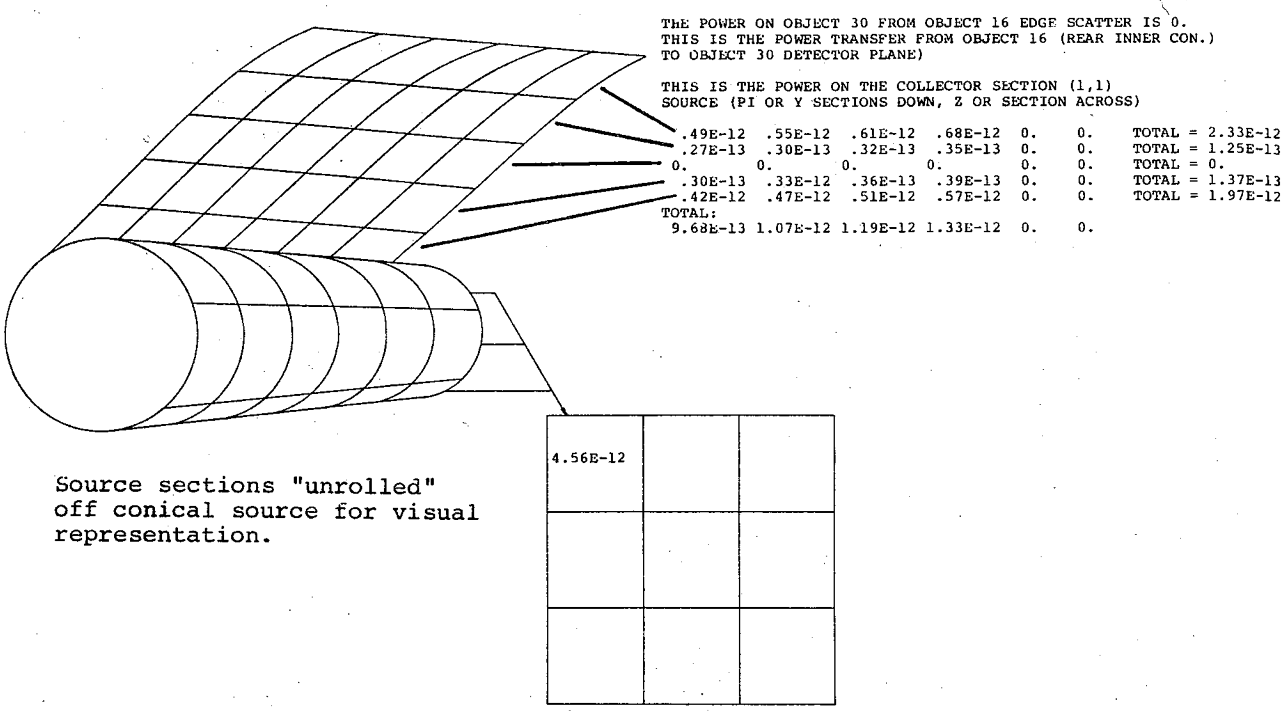


Figure 11. Increments of power contributed to just one of the detector sections by one particular critical object.

In most of the data presented so far, our attention has been focussed on the power terms ϕ_S and ϕ_C. Let us now focus our attention on the third term, the GCF. It involves the geometry of the system and hence requires complex and costly computations. That is why in the APART/PADE code these values are calculated in a separate program (Program Two) and stored on disk files for later random retrival and use. Of the three terms, this is the only term that can make power transfers go to zero; ϕ_S can be zero also but only because some previous GCF was zero. Program Two outputs a table of the GCF's, as shown in Figure 12. This number can be made as accurate as one desires, thereby leaving any uncertainty in the analysis to the BRDF term, which will be discussed shortly.

Since the GCF term involves several complex calculations and involves transfers to imaged objects and through imaged apertures, one sometimes needs additional confirmation as to why a GCF is zero or why it is as large as it is. Program Two has the capability of printing out a large amount of detailed information about each transfer. The depth of the detailed output is designed for the user rather than for the customer. Some of the data that the expert user can readily find are the areas of the source and collector, the distance from the source to the image of the collector, the direction cosines of that vector, the direction cosines of the real space vector into the collector, the real space coordinates of the source and collector points, and the imaged coordinates of the imaged collector, etc. Suffice it to say that the experienced user has a means of answering any challenge as to the validity of his data.

Since we are discussing Program Two, it would be appropriate to state that it can compute the GCF's for an ever-increasing set of complex asymmetrical geometries. Conceptually there is no conceivable geometry that could not eventually be coded into the program.

In previous versions one normally was restricted to doing an analysis for a series of off-axis angles in the meridional plane. Now APART/PADE has the capability of doing a set of off-axis angles at different azimuthal angles. More recently, the program was modified to handle systems that have the source at a fixed off-axis angle but which rotates about the optical axis.

As an aid to the user, Program Two generates a table of "hot" elements as a function of the off-axis position, as shown in Figure 13. This table has proved to be very useful in limiting the number of propagation paths that need to be calculated in Program Three at each off-axis position.

```
  TRANSFER NUMBER      5
THE SOURCE IS OBJECT  0THE POINT SOURCE IN SPACE  1.  THE COLLECTOR IS OBJECT  1 THE MAIN BAFFLE
THE SOURCE IS A POINT WHOSE DISTANCE IS -.100E+11 AND ANGLES OF     2.0  10.0  30.0
********************* PROJECTED SOLID ANGLE *******************
           SOURCE Z-SECTIONS LEFT TO RIGHT      ****      COLLECTOR Z-SECTIONS DOWN WITHIN GROUPS
                  1         2         3
COLLECTOR
PI SECT   1
              .817E-22  .364E-21  .103E-20
              .814E-22  .363E-21  .103E-20
              .812E-22  .362E-21 0.
              .809E-22  .361E-21 0.
              .807E-22  .360E-21 0.
              .804E-22  .359E-21 0.
              .802E-22  .358E-21 0.
              .799E-22 0.        0.
PI SECT   2
              .461E-22  .187E-21  .448E-21
              .460E-22  .187E-21  .376E-21
              .458E-22  .186E-21 0.
              .457E-22  .186E-21 0.
              .455E-22  .185E-21 0.
              .454E-22  .159E-21 0.
              .453E-22  .132E-21 0.
              .451E-22  .132E-21 0.
PI SECT   3
             0.        0.        0.
             0.        0.        0.
             0.        0.        0.
             0         0.        0.
             0.        0.        0.
             0.        0.        0.
             0.        0.        0.
             0.        0.        0.
PI SECT   4
             0.        0.        0.
             0.        0.        0.
             0.        0.        0.
             0.        0.        0.
             0.        0.        0.
             0.        0.        0.
             0.        0.        0.
             0.        0.        0.
```

Figure 12. Geometric Configuration Factors (GCFs) of a representative transfer as calculated in Program Two.

BRDF's

Finally, we get to the coating characteristics. As stated in the introduction, they are almost the last option to be exercised and sometimes the last hope. The BRDF values of a single coating from one surface to sections of another surface could vary by several orders of magnitude. Typically, scatter from a diffuse black can vary from below 10^{-2} at near normal angles of incidence and observation, to above 100 or even 1000 at large angles of incidence and near specular observation angles.

Because in the APART/PADE program the transfers are done from a point on some source section to a point on some collector section, the variation of the BRDF from other points of the same source or collector section could be considerable. Therefore, APART/PADE has been programmed to determine the mean calculated BRDF when doing the transfer from one object to another. Because each object normally has been divided into sections, the value represents the mean value of all the section-to-section transfers. APART/PADE will also calculate the range of values used, the standard deviation, and a figure of merit called the coefficient of variation (Figure 14). With this information, the user can see how sensitive the calculations were to the variations in the calculated BRDF values. The smaller the range of variations in these values, and assuming the model faithfully represents the surface scattering characteristics, the more assurance can be given that the analysis will be accurate. We plan to incorporate into the program variations that can be expected over a single collector section. This could be used to perhaps choose yet a more accurate BRDF. Also, variations in existing measured BRDF data for a specific coating. When this is done, we will then be able to assign meaningful error bars on the PST curve.

In summary, APART/PADE can show the user how much power is transmitted, which critical object is most important, which path is the most important, and how much power from each section gets to each section of the image plane. The user should now understand the sensor in great depth and with experience, recommend major improvements.

Further Data processing

The program has the capability of plotting the Point Source Transmittance (PST) as defined in any of four ways:

1) Detector Power/Power in
2) Detector Irradiance/Irradiance on the Entrance Port
3) Detector Power/Power in an Axis
4) Detector Irradiance/Irradiance in normal to the line of sight.

OBJECTS LOADED BY THE POINT SOURCE

POINT SOURCE AZIMUTH 0.00

	POINT SOURCE ANGLES	2.00	10.00	30.00
OBJECT 11.01	EDGE OF SUNSHIELD	X	X	X
OBJECT 12.01	EDGE OF MAIN BAFFLE	X	X	X
OBJECT 13.01	EDGE OF PRIMARY	X	X	
OBJECT 10.01	SUN SHIELD	X	X	X
OBJECT 1.01	MAIN BAFFLE	X	X	X
OBJECT 3.01	INNER CONICAL BAFFLE		X	
OBJECT 6.01	OUTER CONICAL BAFFLE	X	X	
OBJECT 7.01	PRIMARY MIRROR	X	X	
OBJECT 6.02	OUTER CONICAL BAFFLE	X		
OBJECT 2.02	INNER SECONDARY BAFF	X		
OBJECT 8.02	SECONDARY MIRROR	X		

Figure 13. Objects loaded by the Point Source.

PREV SOU 40.01 PREV COL 1.01 SOU 1.01 COLL 7.02
COEFFICIENT OF VARIATION= .139E+03

13 VALUES MEAN = .663E-01 + OR - .256E-01
STAN DEV = .922E-01
RANGE = .911E-02 .246E+00

Figure 14. APART/PADE calculated mean BRDF value and range.

A plot of the fourth type is shown in Figure 15. Normally such data is for the total image plane, but the program can plot data for any individual detector section or select groups of sections.

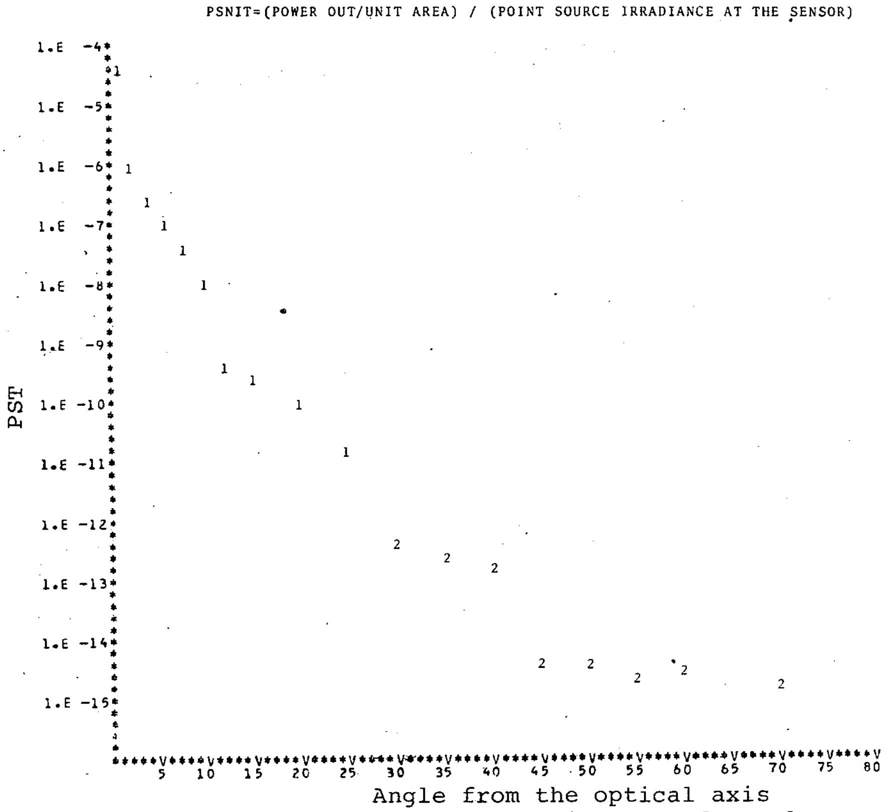
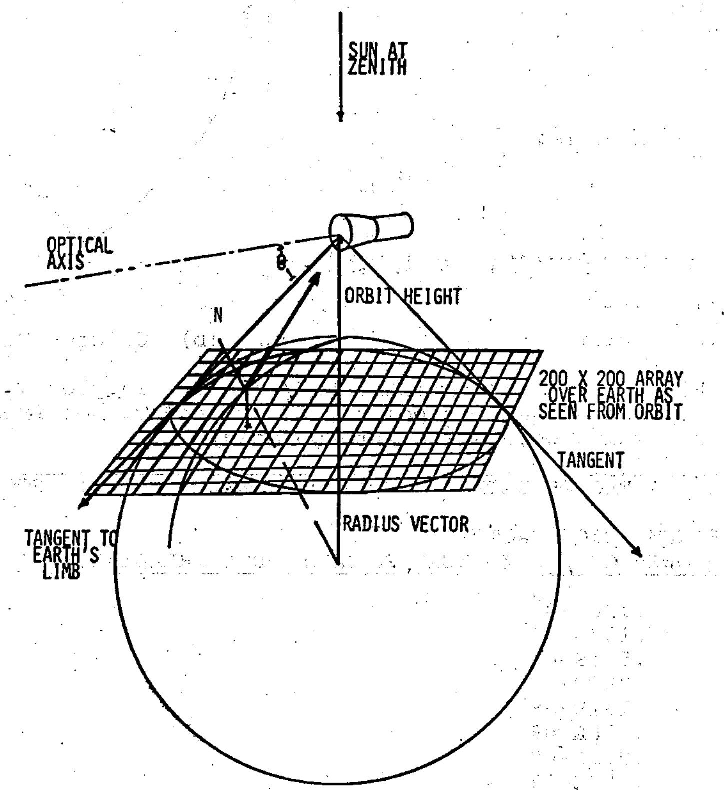


Figure 15. Point Source Transmittance of a telescope.

This capability is even more significant when used with the broad source or Earth integration routines of Programs Three and Four, especially when the Earth is partially within the field of view. Then the program will use the PST data (in the form of #4 above) to determine the contribution from one of two grid patterns of 40,000 sectors of the cap of the Earth that can be seen from the sensor at its orbital altitude, as shown in Figure 16 (for a square grid pattern). Sectors outside the circular base of the cap will obviously have a zero contribution, while for those inside a corresponding point on the Earth's surface is found. It is then from such points that the program will calculate the scattered or thermally emitted energy as a function of the angle from the sensor's optical axis to the Earth's limb (horizon). As shown in Figure 17, the program can do this for up to five different wavebands.



200 X 200 SAMPLE ARRAY ON THE EARTH

Figure 16. The grid pattern on the Earth used to calculate the Earth's contribution due to scattered sunlight.

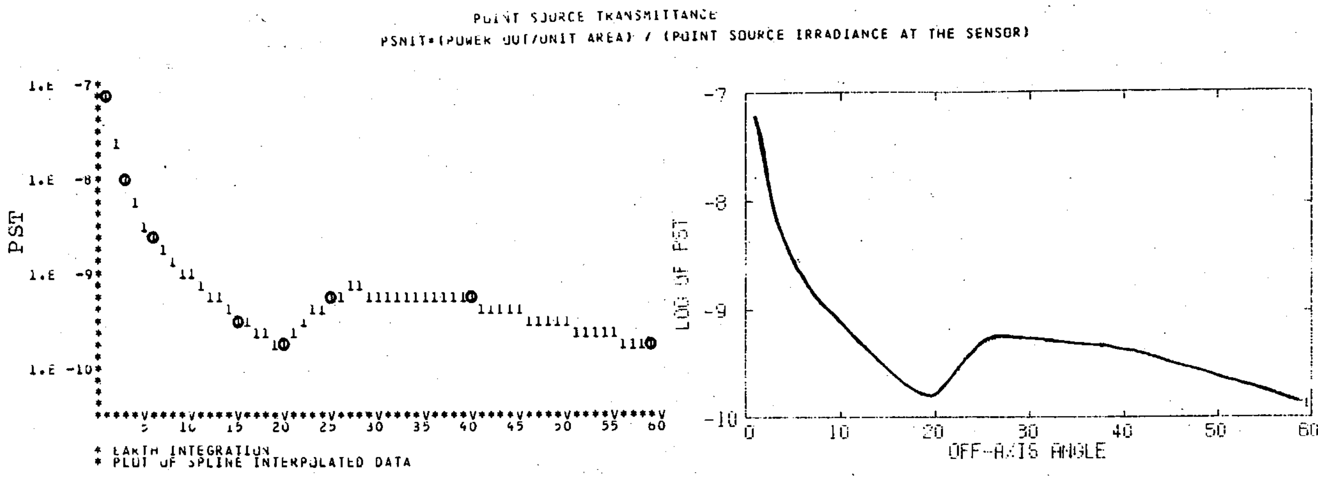
EARTH MODEL RESULTS

EARTH FLUX DENSITY = .24014 DUE TO THERMALLY EMITTED RADIATION. BLACKBODY TEMP. = 288.0°K
EMISSIVITY = 1.00000 ORBIT HEIGHT = .3000E+07 INCHES IN BLOCK 4

EARTH LIMB ANG	DETECTOR POWER	DETECTOR IRRADIANCE	BAND 1	BAND 2	BAND 3
10.0	.311E-11	.977E-9	.248E-9	.206E-9	.141E-9
15.0	.309E-11	.971E-9	.247E-9	.205E-9	.140E-9
20.0	.295E-11	.927E-9	.235E-9	.196E-9	.133E-9
25.0	.239E-11	.751E-9	.198E-9	.158E-9	.108E-9
30.0	.530E-12	.167E-9	.424E-10	.352E-10	.240E-10
FRACTION OF TOTAL BLACKBODY POWER PER BAND			.254E-00	.211E-00	.144E-00

Figure 17. Detector irradiance due to thermally emitter earth radiation for three different wavebands.

Part of the optional output of the Earth integration routine is a table and a plot of the spline-interpolated PST data, (Figure 18 and Table 1). In the actual calculations, the program calculates and uses the actual off-axis angular value, whereas the table is done for a fixed increment (1°) in angle. The table does, however, give a good feel of the shape of the PST curve used by the program.



(a) Line Printer Plot (b) Calcomp Plot

Figure 18. Plot of the interpolated PST values. In plot (a) the circles represent analysis points, i. e., the values from which the remaining points are interpolated.

INTERPOLATED TRANSMISSION FACTOR DATA (SECTION OR AZIMUTH 1) STORED IN BLOCK 1

ANGLE (DEGREES)	TRANSMISSION FACTOR (POWER OUT/UNIT AREA)/POINT SOURCE IRRADIANCE AT SENSOR
1.0	.396E-07
2.0	.137E-07
3.0	.531E-08
4.0	.287E-08
5.0	.181E-08
6.0	.126E-08
7.0	.952E-09
8.0	.752E-09
9.0	.606E-09
10.0	.493E-09
11.0	.403E-09
12.0	.330E-09
13.0	.271E-09
14.0	.223E-09
15.0	.185E-09
16.0	.155E-09
17.0	.131E-09
18.0	.113E-09
19.0	.103E-09
20.0	.103E-09

Table 1. Spline interpolated PST data.

Program Four is being developed to handle routines that take the outputs from the previous programs, especially Program Three, and utilize them in special downstream type calculations. In it are no less than three Earth integration routines: One handles the average characteristics of the total image plane area for rotationally symmetric systems, which applies to the one described above. The second will yield the image plane distribution for rotationally symmetric systems, and the third will calculate the image plane distribution for systems that have only a bilaterial symmetry. In the latter case, the program requires a set of azimuthal PST data to calculate the power or irradiance contributions properly.

In order to better understand from what location on the Earth the power is coming from, the program can supply a binary map of the contributing sections, as shown in Figure 19. Furthermore, the usual PST has a relatively steep falloff with increasing off-axis angles, while the solid angle subtended by the Earth in some annulus about that position is

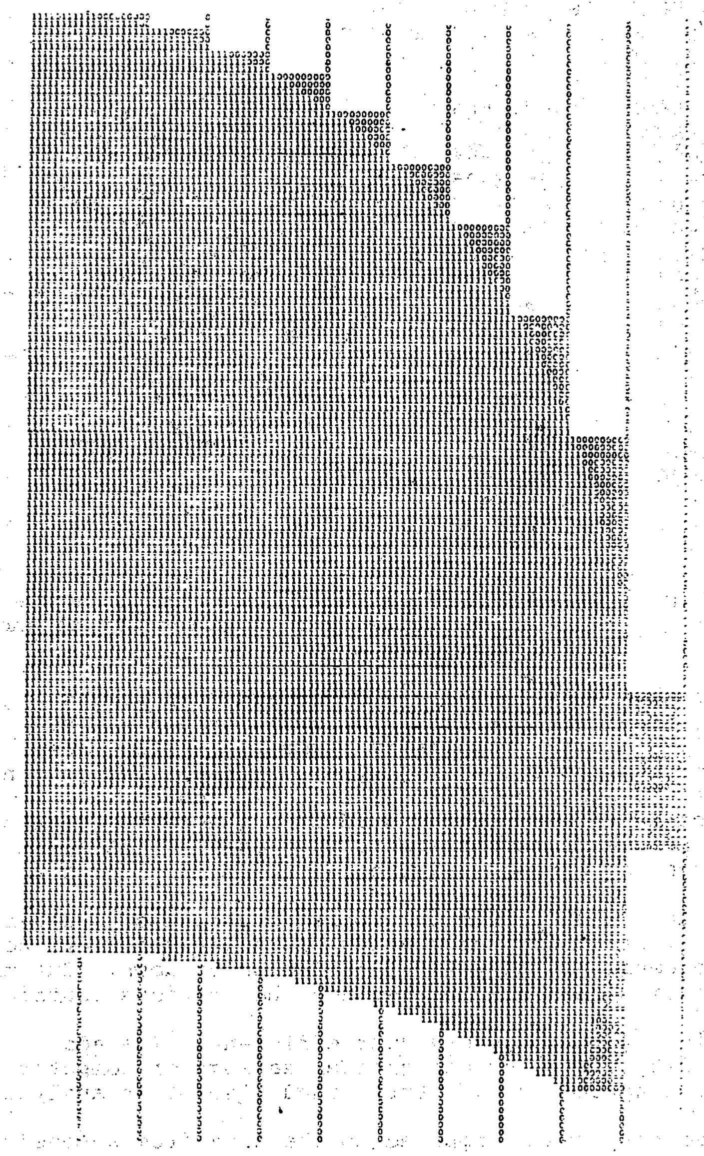


Figure 19. Binary map of sectors on the Earth that contribute power to the image plane.

increasing. Therefore, one often wonders where the peak vane of contribution is coming from. Figure 20 shows the amount of power contributed for each one degree increment from the optical axis.

Percent table permutations

Program Four can take one or two percent tables, such as the one shown in Figure 9, and do some very inexpensive parameterizations on a system.

For instance, one might want to calculate what the image plane power, PST, and earth integration value would be if a recommended design change were made. Suppose one of the critical objects was removed from the field of view. By attaching the stored percent table along with the power at each position, the amount of power contributed by the critical object can be calculated and subtracted from the total. A new percent table and PST can then be calculated, and from this a new Earth integration accomplished. This might take only a few seconds on the computer compared to 80 or more seconds to rerun the entire analysis to yield exactly the same results.

The permutations on the above concept are almost endless. For example, let us say that the critical object is not removed, but it's BRDF is scaled up or down. The percent table can easily be altered to handle this situation.

EARTH CONTRIBUTION AS A FUNCTION OF THE ANGLE
BETWEEN THE OPTICAL AXIS AND THE EARTH'S HORIZON
EARTH HORIZON ANGLE = 10.000
ORBITAL HEIGHT = .300E+07 METERS

	ENT. PORT IRRADIANCE	IMAGE PLANE IRRADIANCE	IMAGE PLANE POWER
10	.360E+00	.102E-02	.102E-04
11	.402E+00	.952E-03	.952E-05
12	.477E+00	.879E-03	.879E-05
13	.498E+00	.681E-03	.681E-05
14	.539E+00	.533E-03	.533E-05
15	.574E+00	.404E-03	.404E-05
16	.598E+00	.296E-03	.296E-05
17	.713E+00	.241E-03	.241E-05
18	.687E+00	.157E-03	.157E-05
19	.805E+00	.123E-03	.123E-05
20	.701E+00	.722E-04	.722E-06
21	.846E+00	.588E-04	.588E-06
22	.862E+00	.390E-04	.390E-06
23	.882E+00	.262E-04	.262E-06
24	.836E+00	.162E-04	.162E-06
25	.108E+01	.131E-04	.131E-06
26	.897E+00	.647E-05	.647E-07

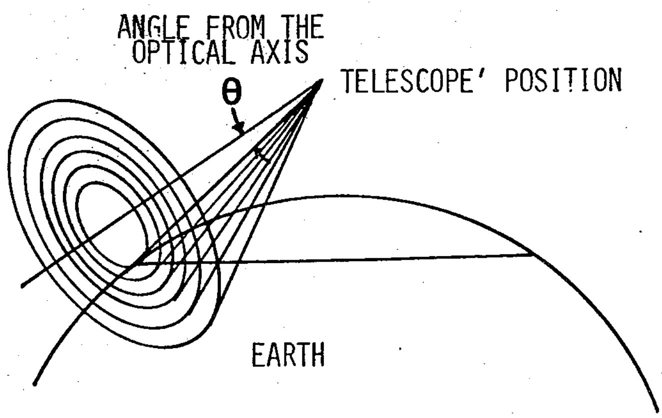


Figure 20. Image plane irradiance and power due to the Earth as a function of the angle from the optical axis.

Data from two different percent tables can be combined in various ways to produce additional analyses at substantial savings. The following method was used when analyzing the IRAS system: essentially it is a rotationally symmetric system except for three asymmetrical objects, one of which was the secondary support struts. One percent table was generated for all the rotationally symmetric objects. This table represented the performance at all azimuths for these objects. Percent tables were then generated at these other azimuths for the struts. Then, in order, each percent table was added to the first to represent validly the total system's performance at each azimuth, at about one fourth the cost.

The program can replace the data from one table with that of another. This would be useful for parametric analyses where the coating characteristics are not linear, i.e., the percent table could not be validly scaled up or down. But the particular transfer can be rerun and its data used to replace the previous contributions.

The APART/PADE code is, by design, very cost efficient. The additional features are optimizing the use of existing data by get greater savings of computational time, money, and effort, and by shortening the overall turnaround time of an analysis.

The concepts presented here can be applied to the data from anyone's analysis. They represent a portion of the capability that has already been incorporated into the APART/PADE code.

The present conceptual limitations of APART/PADE

It is sometimes asked, "What are the conceptual limitations of the APART/PADE code?" Its original concepts data to the first version of the APART program, which had no diffraction capability and could only be used for rotationally symmetric objects. Long ago this was changed to include an ever-increasing set of asymmetrical transfers. PADE, the diffraction program, was developed and the programs combined so that scatter and diffraction paths could be combined in any order, and recently the thermal emittance capability of the program was developed. The only known remaining conceptual limitation to the program is the efficient and accurate representation of <u>multiple</u> specular reflections off conical surfaces. There are currently three ways that the program can handle single specular reflections off conical surfaces in an efficient and accurate manner. The problem with <u>multiple</u> specular reflections is first keeping track of the convergence and divergence of the beam. Points are not imaged into points but rather into lines or surfaces. The second problem is not trivial either: one would be required to keep track of how much of the specular beam is incident on each succeeding surface. Both are presently computational nightmares. However, Dave Rock[4] has made some progress along these lines and the original GUERAP II (Perkin-Elmer's version)[5] such a capability.[5] We are looking for yet a different concept that will avoid unreasonable computational costs. It might be noted that we are not aware of any well-baffled specular baffle system that cannot be analyzed with the current version of the program, although it would be easy enough to dream up such a system.

General comments

Before one is erroneously left with the feeling that a stray light analysis is quick and easy, one last comment might be directed toward the user and the use of the stray light analysis programs themselves, be they APART, APART/PADE, or GUERAP. The experienced user of any of the programs must be well-qualified in four major areas of optics:

1) He or she must understand optical designs and imaging characteristics as well as most qualified optical designers.
2) They must understand stray light suppression systems, i. e., basic baffle designs, placement of stops, etc.
3) They must have a knowledge of the scattering characteristics (BRDF's) of many coatings at many wavelengths and have a feel for the range of variations that can be encountered in those coatings.
4) And, finally, they must be aware of the current capabilities of the program code that they use to analyze systems.

For the above reasons, the development of a stray light analysis is not a one or two day affair. Putting in the structure from blue prints, optical prescriptions, and measured BRDF data can consume a considerable amount of time. Then the user will usually meticulously study the data to understand some of the subtle fine points of the system and all optical-mechanical options that he can exercise to improve the performance of the system.

Conclusion

The APART/PADE code offers such complete and in-depth analysis that not only is the performance of this system clearly defined, but one can also answer with greater confidence why the system performs as it does. The concepts used in the program then direct where and how improvements to the system can be made and how much improvement can be expected.

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4. Rock, D. F., "Radiation transfer via reflection from non-imaging specular surfaces," Proc. SPIE, Vol. 257, Sept. 1980, Radiation Scattering in Optical Systems.
5. Perkin-Elmer, GUERAP II User's Guide, Technical Report, SAMSO TR73-309, Feb. 1974.