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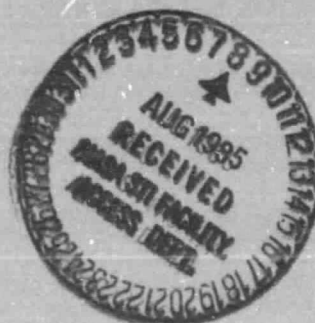
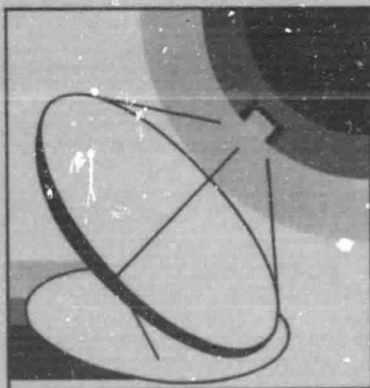
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View-Limiting Shrouds for Insolation Radiometers

E. W. Dennison
G. F. Trentelman



May 15, 1985

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ABSTRACT

Insolation radiometers (normal incidence pyrheliometers) are used to measure the solar radiation incident on solar concentrators for calibrating thermal power generation measurements. The measured insolation value is dependent on the atmospheric transparency, solar elevation angle, circumsolar radiation, and radiometer field of view. The radiant energy entering the thermal receiver is dependent on the same factors. The insolation value and the receiver input will be proportional if the concentrator and the radiometer have similar fields of view. This report describes one practical method for matching the field of view of a radiometer to that of a solar concentrator.

The concentrator field of view can be calculated by optical ray tracing methods, and the field of view of a radiometer with a simple shroud can be calculated by using geometric equations. The parameters for the shroud can be adjusted to provide an acceptable match between the respective fields of view. Concentrator fields of view have been calculated for a family of paraboloidal concentrators and receiver apertures. The corresponding shroud parameters have also been determined.

The effectiveness of this technique has been tested by comparing radiometer and concentrator measurements under a variety of sky conditions. Appropriate radiometer shrouds should be used to obtain accurate insolation measurements for determining solar concentrator and power conversion system efficiencies and for site surveys.

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SECTION I

INTRODUCTION

At the Parabolic Dish Test Site (a JPL facility for testing solar components), the need for accurate methods to measure insolation became especially important during the spring of 1982. At this time, large amounts of dust appeared in the upper terrestrial atmosphere as a result of a volcanic eruption in Mexico. Prior to this occurrence, definitive calorimeter and power measurements made at the Parabolic Dish Site Test (PDTS), located at Edwards Air Force Base, California, were limited to times when the insolation was greater than 950 W/m^2 , i.e., when the amount of circumsolar radiation was negligible. This limitation was used because of the inconsistent data that were found at low elevation angles and on days of high circumsolar radiation.

For more than a year after the appearance of the volcanic dust, the maximum insolation was less than 900 W/m^2 , and the amount of circumsolar radiation was significant. In addition, there was a substantial increase in the presence of high, thin cirrus clouds, which added significant errors to the calorimeter measurements. The presence of circumsolar radiation is clearly shown in Figure 1-1. In this photograph of Parabolic Dish Concentrator No. 1 (PDC-1) (described in Reference 1), the image of the sun is covered by the calorimeter. The bright halo around the calorimeter is the reflected circumsolar radiation.

Measurement of the efficiency of a thermal-to-electric power conversion system requires that the thermal power input to the thermal receiver be known accurately for different sky conditions and solar elevation angles. The standard procedure is to normalize the power input to the receiver to a standard value of insolation (1 kW/m^2 for JPL data). The normalizing factor is calibrated by simultaneously measuring the insolation with a radiometer and the focal plane power with a cold-water cavity calorimeter (which has an aperture of the same size as the receiver). During electric power measurements, the thermal power input to the receiver is determined from the calibrated insolation data.

The word "radiometer" is used herein to refer to both radiometers and normal incidence pyrheliometers (NIPs). If the calorimeter and the receiver have the same aperture, the radiometer measurement can be used to normalize all power measurements to a standard insolation value of 1 kW/m^2 . This report describes the calculations, implementation, and results of JPL's experience with this approach.

Three instruments were used to measure the insolation: an Eppley NIP and two versions of the cavity radiometer developed by J. M. Kendall, Sr., at JPL. One of the Kendall radiometers was of the Mark VI windowless design used for calibration of radiometers and the other was the Mark III quartz window design used for routine field measurements (Reference 2). The shrouds used to limit the field of view (FOV) of the radiometers were designed to simulate the FOV of PDC-1 with the cold-water cavity calorimeter (Figure 1-2). This report includes one method for calculating the shroud parameters to give a close match between a radiometer FOV and that of a paraboloidal solar concentrator with any thermal receiver.

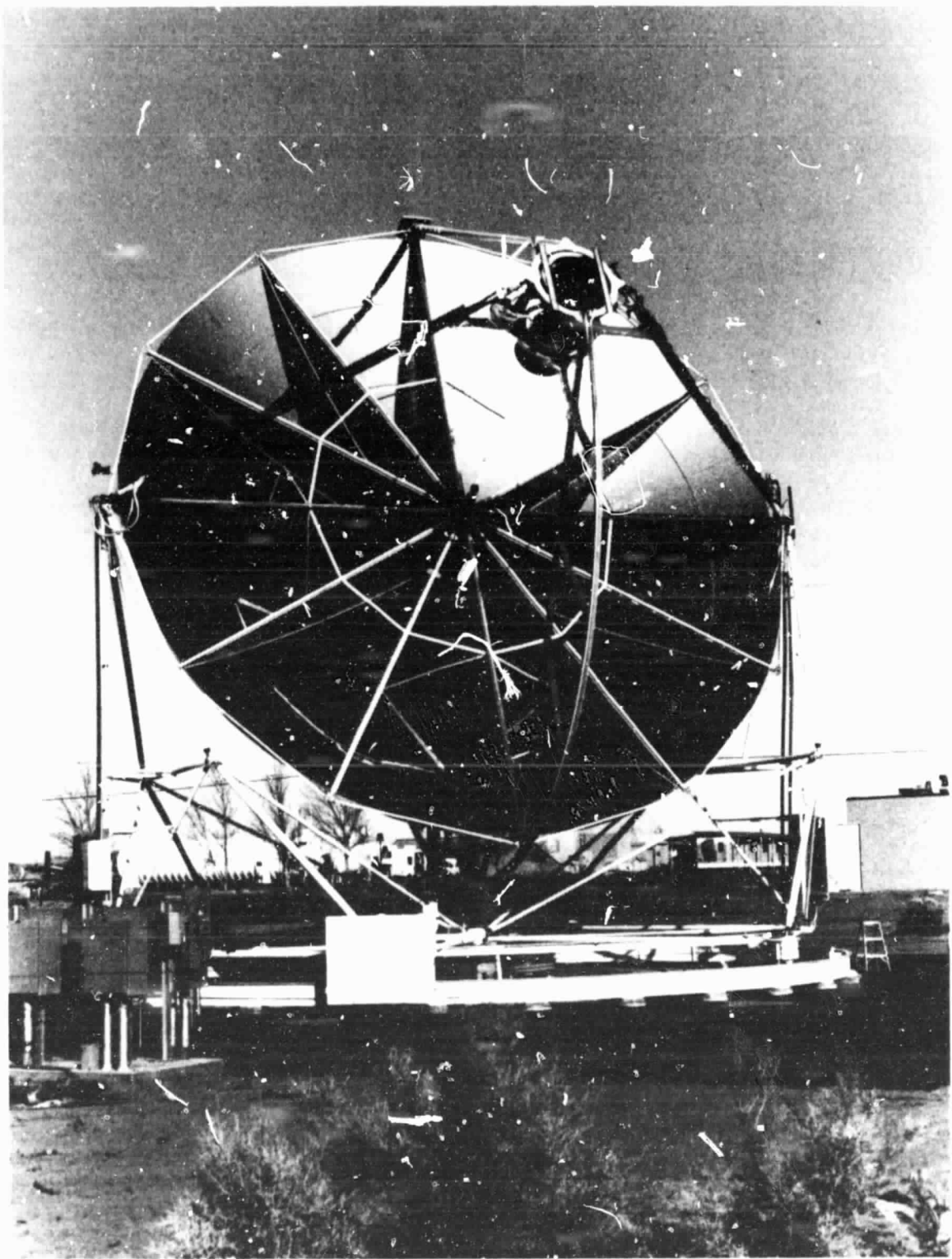


Figure 1-1. PDC-1 with Cold-Water Cavity Calorimeter
Mounted at the Focus

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Figure 1-2. Radiometer Shroud

SECTION II

FIELD-OF-VIEW CALCULATIONS

The quantitative description of the FOV of a concentrator or radiometer is referred to as the angular acceptance function (AAF) (Reference 3). The AAF is the amount of energy entering the receiver aperture divided by the amount of energy in a parallel beam of energy falling on the concentrator aperture (neglecting absorption losses). A point source at an infinite distance generates such a parallel beam of radiation. As a result, the AAF will be 1.0 for a source on the optical axis (total transmission) and will decrease to zero (no transmission) continuously from an inner limiting source angle to an outer limiting source angle. The form of a concentrator AAF is different from the AAF of a radiometer because of the respective optical geometries. As a result, the radiometer AAF cannot be matched exactly to the concentrator AAF, but the differences between these functions can be made acceptably small.

A. CONCENTRATOR AAF

The AAF of a paraboloidal concentrator may be determined by calculating the focal plane coordinates of light rays from point sources at infinite distances that have been reflected by the concentrator surface. The reflection points are distributed over the concentrator in such a way that each ray corresponds to an element of entrance aperture area. Every element has the same entrance aperture area. In practice, a thousand rays are sufficient to give an accurate AAF. The number of reflected rays that fall within the receiver aperture divided by the total number of incident rays is the concentrator acceptance fraction for each point source. To make these calculations, vector analysis is used to trace the paths of the light rays. A more complete derivation of this method of optical analysis is given in Reference 4, and the algorithms are summarized in Appendix A of this report.

These algorithms can be adapted to other types of concentrators, for example, concentrators made from reflecting facets. If the concentrator is made of many small facets mounted on a paraboloidal surface, the AAF of a paraboloid will generally give a sufficiently accurate representation of the concentrator.

It has been found that in practice it is convenient to represent the AAF as a function of the ratio of the tangent of the source angle (TA) divided by the tangent of the receiver radius angle (TR), the latter being receiver radius divided by the concentrator focal length. This parameter is referred to as the "radius number." In this form the AAF changes substantially with the concentrator f-number (focal length divided by diameter) and insignificantly with receiver aperture. When the AAF is expressed in terms of these dimensionless parameters, it can be easily applied to any paraboloidal concentrator with any receiver aperture (Figure 2-1). Slope errors of the reflecting surface are not included in these calculations because the radiometer AAF should be matched to the AAF of a perfect concentrator.

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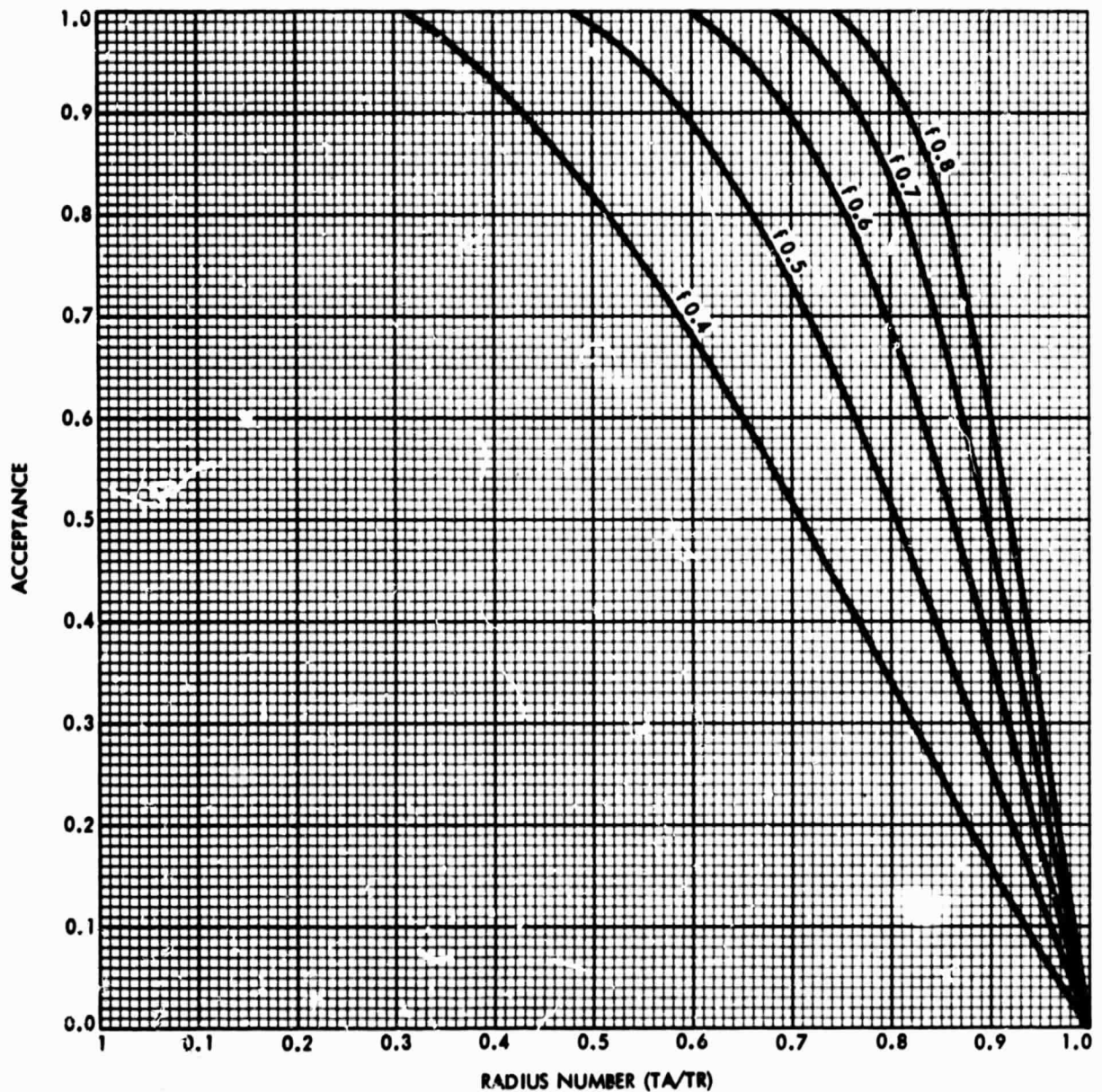


Figure 2-1. AAF As a Function of Radius Number for Paraboloidal Concentrators with Different f-Numbers

B. RADIOMETER AAF

Calculation of the AAF of a radiometer that is used for measuring insolation is based on a simple geometric model. This model assumes that the radiometer has a radiation collimeter (shroud) with circular front and detector apertures and no intervening optical elements (see Figure B-1). It is also assumed that the detector aperture is uniformly sensitive. The radiometer AAF algorithms are given in Appendix B.

C. MATCHING RADIOMETER AAF TO CONCENTRATOR AAF

The radiometer AAF can be matched to the concentrator AAF by using the front aperture radius and shroud length as adjustable parameters. With the radiometer detector radius as a known value, the shroud front aperture radius can be calculated from the aperture constant (see Equation B-19), and the detector aperture to front aperture separation can be calculated from the length constant and the thermal receiver radius (see Equation B-20). For the values given in the table below, the aperture and length parameters were selected by making the sum of the residuals a minimum and the extreme residuals equal.

f-number	0.4	0.5	0.6	0.7	0.8
Length constant (CL)	3.0	4.0	5.0	7.0	8.5
Aperture constant (CA)	2.147	3.196	4.263	6.207	7.746

When two solar concentrators are being tested at the same site, it may be possible in some cases to find compromise length and aperture constants that will give acceptable matches between the concentrator and radiometer AAF. It is, however, very important that the radiometer length be chosen to correspond to the thermal receiver aperture. For very long radiometer shrouds, it may be necessary to install internal baffles to prevent light from being scattered or reflected from the walls of the shroud.

Figure 2-2 shows the AAF for an $f/0.5$ paraboloidal concentrator¹ with three different receiver apertures and the AAF for the corresponding shrouded radiometers and a standard Eppler NIP. These curves were calculated for the parabolic dish (PDC-1) and the thermal receiver apertures used for the Stirling-cycle power conversion unit (Reference 5), the organic Rankine-cycle power conversion unit (Reference 6), and the cold-water cavity calorimeter. It should be noted that the difference between the Stirling-cycle thermal receiver and the Eppler NIP is substantial and that this receiver has an AAF that is close to the edge of the solar disk. Table 2-1 provides a detailed explanation of the curves in the figure.

¹Concentrator with an f-number equal to 0.5.

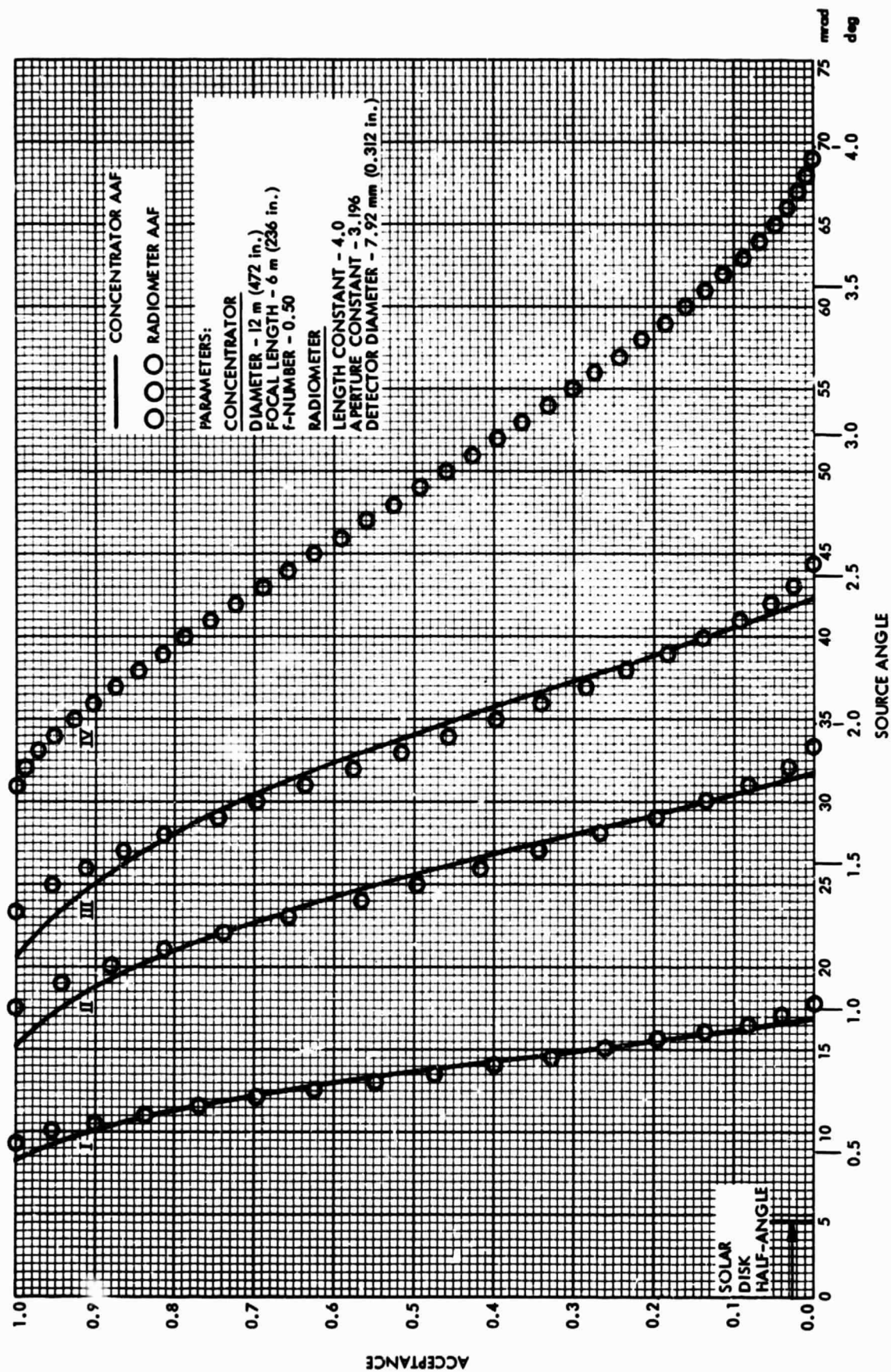


Figure 2-2. Radiometer and Parabolic Concentrator AAF

Table 2-1. Explanation of Curves in Figure 2-2, Radiometer and Parabolic Concentrator AAF^a

Curve	Application	Concentrator Receiver Diameter, cm (in.)	Radiometer	
			Front Aperture Diameter, mm (in.)	Aperture Detector Separation, cm (in.)
I	Stirling Receiver	20.32 (8.0)	25.33 (0.997)	93.51 (36.816)
II	Rankine Receiver	38.10 (15.0)	25.33 (0.997)	49.87 (19.635)
III	Calorimeter	50.80 (20.0)	25.33 (0.997)	37.40 (14.726)
IV	Eppley NIP	-	20.62 (0.812)	20.64 (8.125)

^aThe radiometer detector diameter is 7.92 mm (0.312 in.).

SECTION III

EXPERIMENTAL RESULTS

A series of calorimeter measurements were made using PDC-1 and the shrouded radiometers to verify the expected advantages of using an FOV-limiting shroud on an insolation radiometer. One of the radiometers was an Eppley NIP mounted on the concentrator. The other radiometers were of the Kendall type and were attached to an equatorial mount with a clock drive. The boresight alignment images were checked frequently during the measurement period to ensure that no erroneous data resulted from tracking errors.

The thermal power measured by the calorimeter and the insolation measured by the radiometers were plotted for each measurement period. To test the validity of this technique, the calorimeter values were divided by each of the radiometer values and the results were also plotted. These ratios gave the net power output of the concentrator normalized to 1 kW/m^2 under sky conditions that varied from light haze to thin cirrus clouds. No completely clear days occurred during the time these tests were made. During the passage of the cirrus clouds, the normalized power values showed a substantial variation over short periods of time as a result of the long time-constant of the calorimeter relative to the time-constants of the radiometers.

Figures 3-1a and 3-1b show the radiometer data plots for two different days. Figures 3-2a and 3-2b show the corresponding plots of the direct and normalized power measurements. Figure 3-2a demonstrates that the normalized power is relatively constant under a wide range of sky conditions. The value of the normalized power in this figure was too high because of a faulty flow meter. This problem was corrected, and the normalized power values shown in Figure 3-2b more accurately represent the performance of PDC-1.

The insolation values measured with these modified radiometers were lower than the values that would have been obtained with standard radiometers. However, the purpose of these measurements was to determine the relationship between the radiometers and the net power throughput of a concentrator having a specific aperture. This calibration would have been used to determine the operating efficiency of the power conversion units that were to have been used with PDC-1.

During this limited test program, it was not possible to make a direct comparison between these shrouded radiometers and standard radiometers. However, these measurements did demonstrate that the normalized power output of PDC-1 was constant under a wide range of sky conditions.

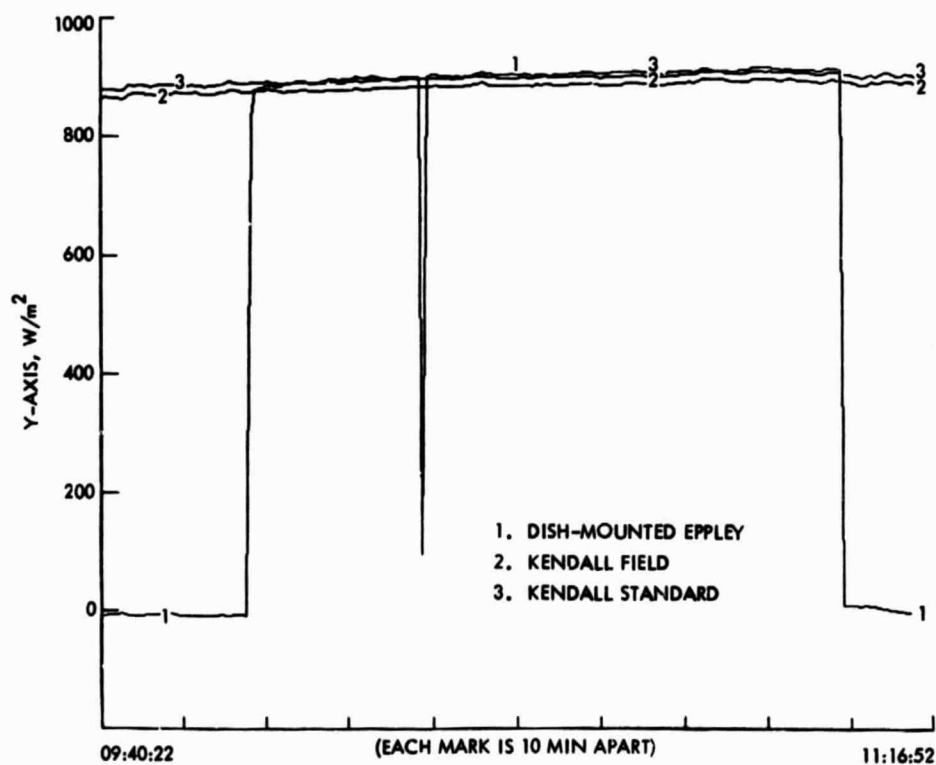
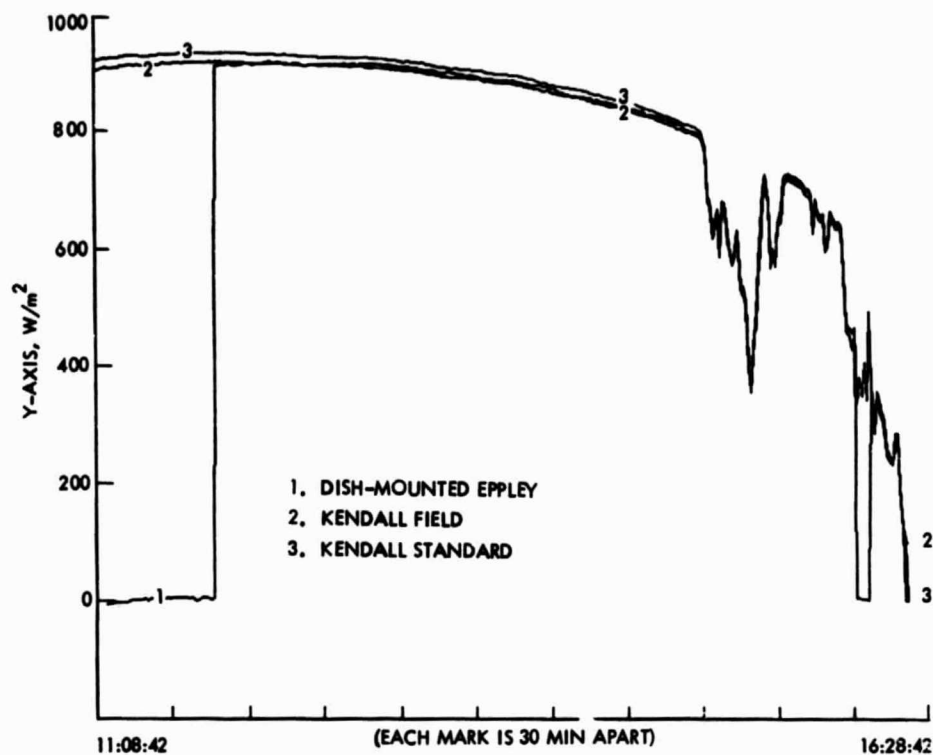
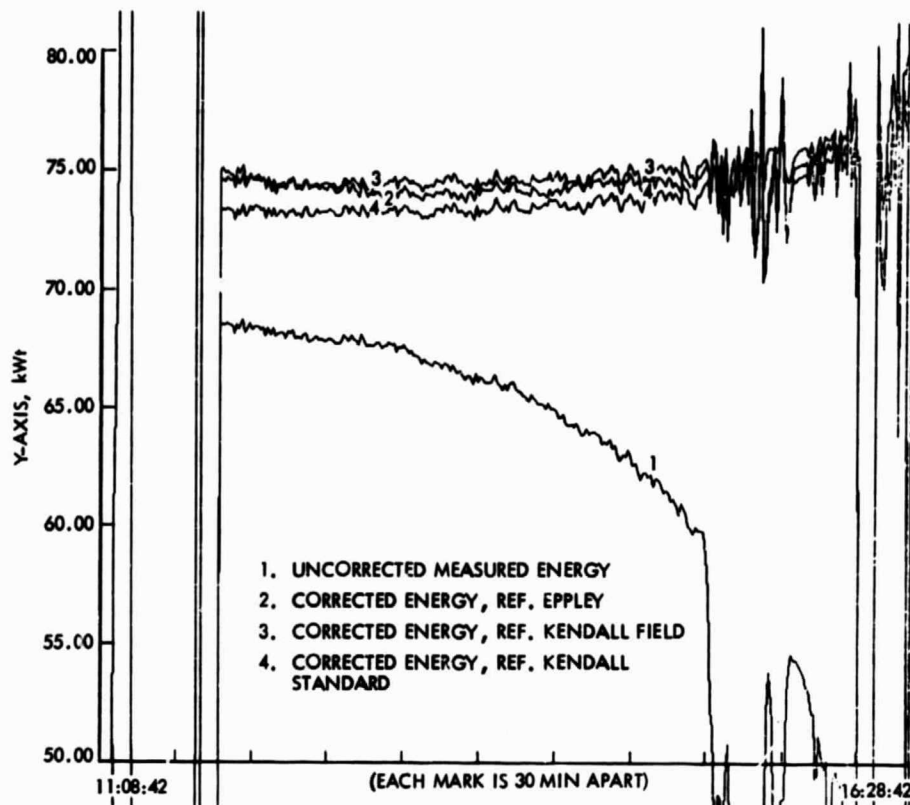
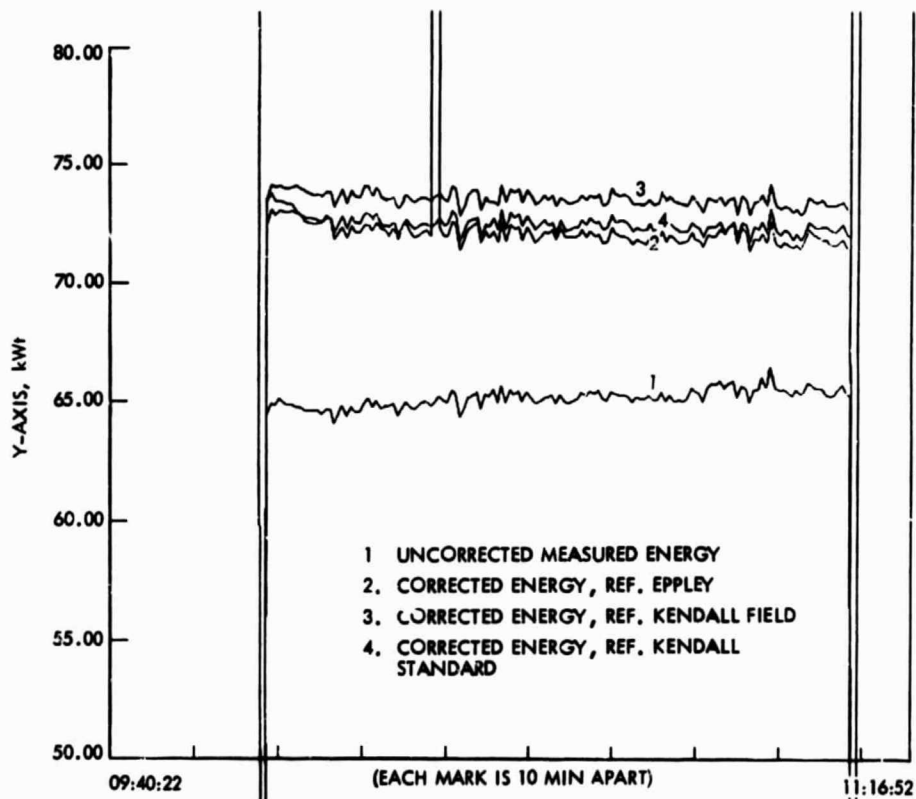


Figure 3-1. Radiometer Data Plots for February 22 and July 14, 1983



(a)
February 22



(b)
July 14

Figure 3-2. Direct and Normalized Power Measurements for February 22 and July 14, 1983

SECTION IV

RECOMMENDATIONS

Because this program for evaluating the effectiveness of an approach to insolation measurements was limited, it is recommended that these experiments be repeated with other concentrators and radiometers. These tests should be made with a wide range of sky conditions and solar elevation angles using both standard and shrouded radiometers. These data would be useful for determining the accuracy of existing radiometer records. It appears that shrouded radiometers should be used to standardize efficiency measurements of solar concentrators, receivers, and power conversion assemblies.²

Finally, it is recommended that future site surveys be made with both standard and shrouded radiometers to ensure that proposed solar power systems are suitable for proposed sites. This is most important when the proposed site has a substantial number of days with strong haze or thin clouds.

²A power conversion assembly is defined as the thermal receiver plus engine plus alternator.

SECTION V

CONCLUSION

It is possible to match the field of view of a radiometer (NIP) to the field of view of a specific solar concentrator and thermal receiver. The field of view can be quantitatively represented by the angular acceptance function. With the use of simple algorithms, it is possible to calculate the AAF for concentrators and radiometers. The radiometer shroud parameters can be adjusted to make an acceptable match between these functions. Based on the available data, it appears that insolation measurements made with a correctly shrouded radiometer will correlate with the solar thermal power entering the receiver aperture at the focus of a concentrator. This correlation is maintained under a variety of sky conditions and solar elevation angles. With the use of this type of radiometer, the efficiency of a concentrator can be accurately measured, and proposed solar power sites can be realistically evaluated.

SECTION VI

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APPENDIX A

PARABOLOID ANGULAR ACCEPTANCE FUNCTION ALGORITHMS

Figure A-1 shows the geometric relationship of the vectors and the paraboloidal reflecting surface. The equation of the reflecting surface is:

$$Z_m = \frac{X_m^2 + Y_m^2}{4f} \quad (A-1)$$

where X_m , Y_m , and Z_m are the surface coordinates and f is the focal length. The incident ray unit vector is given by:

$$\hat{I} = \sin \alpha \cos \beta \hat{x} + \sin \alpha \sin \beta \hat{y} + \cos \alpha \hat{z} \quad (A-2)$$

where α and β are the radial and azimuthal angles of the source. Because there is no preferred azimuth direction, β can be set equal to zero. The surface normal vector is given by:

$$\hat{N} = -\frac{X_m}{2f} \hat{x} - \frac{Y_m}{2f} \hat{y} + \hat{z} \quad (A-3)$$

The surface normal unit vector is given by:

$$\hat{N} = \frac{\hat{N}}{|\hat{N}|} \quad (A-4)$$

The reflected ray unit vector is given by:

$$\hat{R} = (\hat{I} \cdot \hat{N}) \hat{N} - \hat{N} \times (\hat{I} \times \hat{N}) \quad (A-5)$$

This vector can be calculated by using the following matrix multiplication:

$$\begin{bmatrix} \hat{R}_x \\ \hat{R}_y \\ \hat{R}_z \end{bmatrix} = \begin{bmatrix} (\hat{N}_x^2 - \hat{N}_y^2 - \hat{N}_z^2) & 2\hat{N}_x\hat{N}_y & 2\hat{N}_x\hat{N}_z \\ 2\hat{N}_x\hat{N}_y & (\hat{N}_y^2 - \hat{N}_x^2 - \hat{N}_z^2) & 2\hat{N}_y\hat{N}_z \\ 2\hat{N}_x\hat{N}_z & 2\hat{N}_y\hat{N}_z & (\hat{N}_z^2 - \hat{N}_x^2 - \hat{N}_y^2) \end{bmatrix} \begin{bmatrix} \hat{I}_x \\ \hat{I}_y \\ \hat{I}_z \end{bmatrix} \quad (A-6)$$

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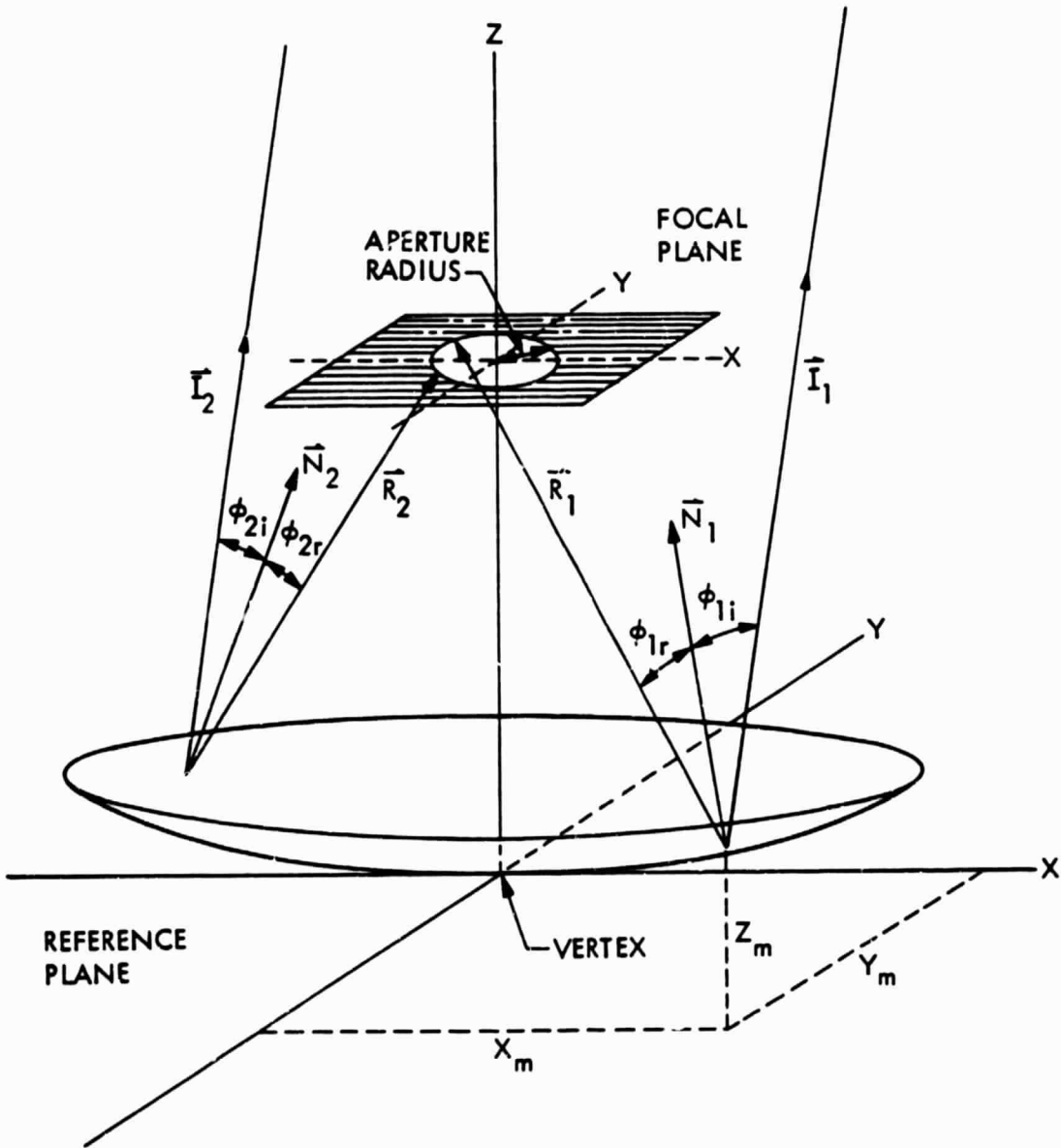


Figure A-1. Vector Analysis for Computing the AAF of a Paraboloidal Concentrator

The reflected rays intercept the focal plane at the following coordinates:

$$X_p = (f - Z_m) * \frac{\hat{R}_x}{\hat{R}_z} + X_m \quad (A-7)$$

and

$$Y_p = (f - Z_m) * \frac{\hat{R}_y}{\hat{R}_z} + Y_m . \quad (A-8)$$

The radial distance of an intercepted ray from the optical axis is:

$$RD = \sqrt{X_p^2 + Y_p^2} . \quad (A-9)$$

If RD is smaller than RR (the thermal receiver radius), the ray is accepted. For each source point the number of accepted rays divided by the total number of rays is the angular acceptance factor.

The radius number is:

$$RN = \frac{TA}{TR} \quad (A-10)$$

where

$$TA = \tan (\alpha) \quad (A-11)$$

and

$$TR = \frac{RR}{f} . \quad (A-12)$$

RN can be used as the independent variable. This facilitates a direct comparison between the AAFs of a concentrator and a radiometer.

APPENDIX B

RADIOMETER ANGULAR ACCEPTANCE FUNCTION EQUATIONS

The geometric relationship of the variables are shown in Figures B-1 and B-2. The separation of the projection of the center of the entrance aperture on the detector aperture plane from the center of the detector aperture is:

$$S = H * TA \quad (B-1)$$

where TA is the tangent of the source angle (α) and H is the separation of the front and detector apertures. Using the law of cosines for plane triangles:

$$RD^2 = RA^2 + S^2 - 2 * S * RA * \cos(\gamma) \quad (B-2)$$

(RA is the front aperture radius and RD is the detector radius) where

$$\cos(\gamma) = \frac{B}{RA} \quad (B-3)$$

which gives

$$RD^2 = RA^2 + S^2 - 2 * S * B \quad (B-4)$$

Solving for B gives:

$$B = \frac{RA^2 + S^2 - RD^2}{2 * S} \quad (B-5)$$

and

$$A = B - S \quad (B-6)$$

Using the formula for the area of a segment of a circle:

$$SA = RD^2 * \arccos\left(\frac{A}{RD}\right) - A * \sqrt{RD^2 - A^2} \quad (B-7)$$

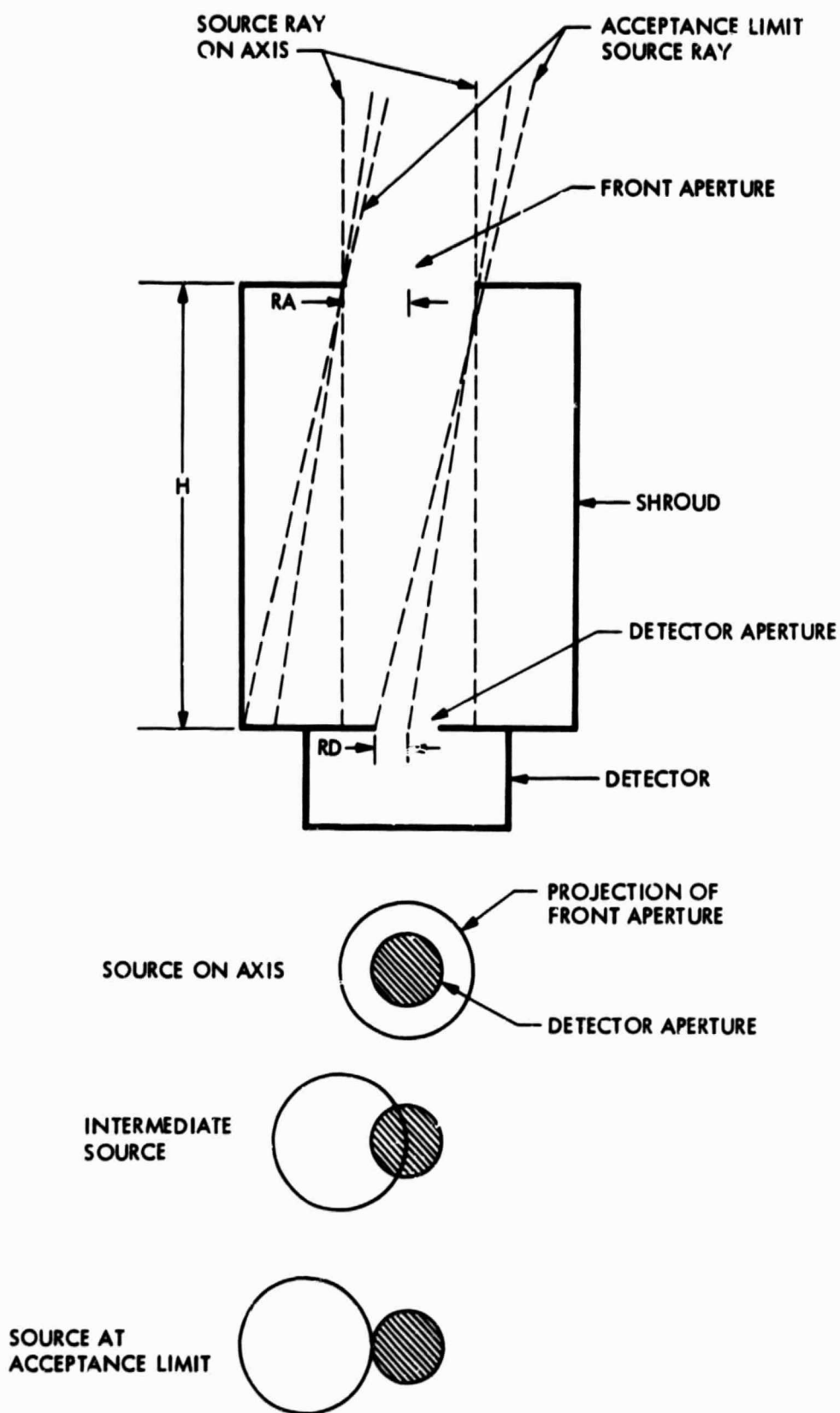


Figure B-1. Radiometer and Shroud Geometry

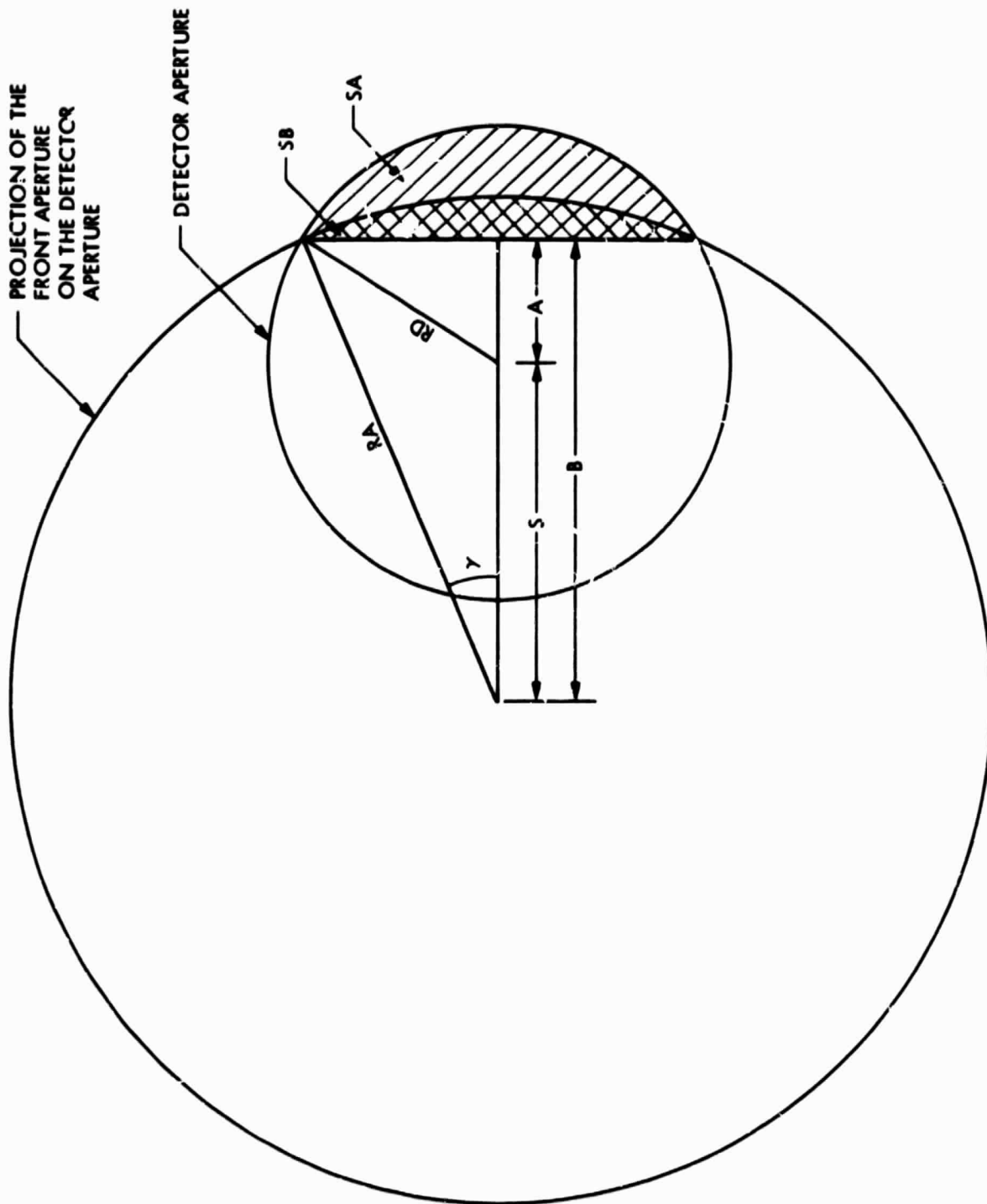


Figure B-2. Expanded View of Radiometer and Shroud Geometry

and

$$SB = RA^2 * \arccos \left(\frac{B}{RA} \right) - B * \sqrt{RA^2 - B^2} . \quad (B-8)$$

The fraction of the detector area that is uncovered is the acceptance fraction and is given by:

$$AR = \frac{\pi * RD^2 + SB - SA}{\pi * RD^2} \quad (B-9)$$

$$= 1 + \frac{(SB - SA)}{\pi * RD^2} . \quad (B-10)$$

To avoid ambiguity in calculation, it is convenient to substitute:

$$\frac{\pi}{2} - \arcsin \left(\frac{A}{RD} \right) \quad (B-11)$$

for

$$\arccos \left(\frac{A}{RD} \right) \quad (B-12)$$

in (B-7) and similarly in (B-8).

One convenient way to match the radiometer AAF to the concentrator AAF is to select a shroud length parameter (CL) and adjust a front aperture parameter (CA) to achieve the best agreement between the two AAFs. The aperture parameter is defined as:

$$CA = \frac{RA}{RD} \quad (B-13)$$

and the length parameter as:

$$CL = \frac{H * RR}{RD * f} \quad (B-14)$$

$$= \frac{H}{RD} * TR . \quad (B-15)$$

Where the tangent of the thermal receiver radius is:

$$TR = \frac{RR}{f} , \quad (B-16)$$

RR is the thermal receiver radius and f is the focal length or the "f" number if the diameter is set equal to one. Defining the radius number as:

$$RN = \frac{TA}{TR} , \quad (B-17)$$

Equation (B-1) can be written as:

$$S = CL * RN * RD . \quad (B-18)$$

The AAF of a radiometer is represented by AR as a function of RN and can be directly compared with the concentrator AAF. The front aperture radius and the front aperture to detector aperture separation can be calculated from the following equations:

$$RA = CA * RD \quad (B-19)$$

and

$$H = \frac{CL * RD}{TR} . \quad (B-20)$$