DIRECTIONAL BAFFLES FOR LATERAL CONTROL OF RADIATOR EMISSION DIRECTION

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ABSTRACT

The design and performance of directional baffles for laterally limiting the emission direction of a thermal radiator are presented. Through the incorporation of circular and/or elliptical reflective surfaces, this design extends previous designs based on the Winston trough-type compound parabolic concentrators originally developed for concentrating solar energy. The optimal design of these baffles for use on the JWST observatory to control emission direction range in a cryogenic environment is described.

INTRODUCTION

The James Webb Space Telescope (JWST), successor to the Hubble Space Telescope, is currently under development for launch in 2013. JWST's large size and passive cryogenic thermal control architecture presents many unique thermal engineering challenges. One such challenge is the accommodation of an ambient temperature (~290K) electronics enclosure within the cryogenic region of JWST. As illustrated in Figure 1, JWST employs a large deployable sunshield as a thermal barrier. The sunshield divides the observatory into two thermal regions: a warm ambient temperature region on the sun side where the spacecraft bus is located and a <60K cold region on the anti-sun side encompassing the telescope and instruments. This thermal segregation is violated, however, due to limits on electrical harness length that require accommodating a number of ambient-temperature instrument electronics boxes on the cold side of the sunshield. The ~200 W thermal dissipation from these electronics is more than an order of magnitude higher than the total heat flow from all other sources to the cold side of the sunshield.

As discussed by Garrison[1], a range of heat transfer control techniques are being used to minimize the fraction of the 200W dissipation that makes its way into the adjacent cryogenic hardware. All ambient-temperature electronics located on the cold side of the sunshield are housed in an enclosure called the ISIM (Integrated Science Instrument Module) Electronics Enclosure, or IEC, shown in Figure 2. The electronics are mounted to four individual radiator panels. Observatory configuration constraints result in the IEC being somewhat recessed within the observatory structures and the sunshield. The IEC thermal accommodation approach is two pronged. First, a variety of conduction and radiation barriers are used to minimize heat transfer through the five sides of the IEC facing telescope and instrument surfaces. Second, radiator surfaces covered with directional baffles are employed on the sixth side (-V1 facing surface) to control the emission direction and direct as much energy as possible directly to space.

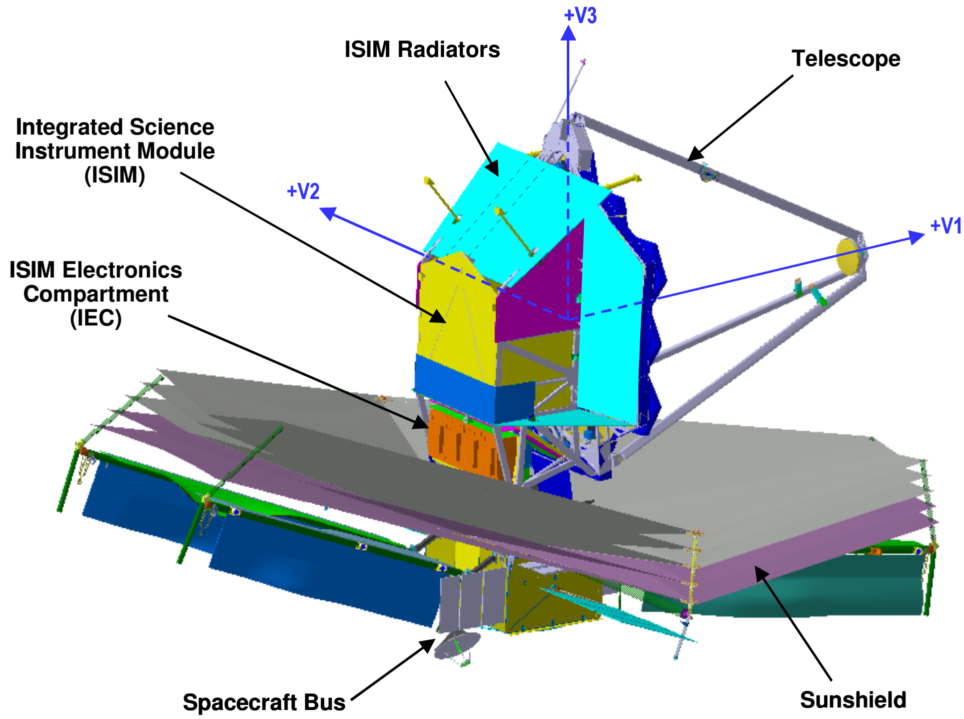


Figure 1: Drawing of deployed James Webb Space Telescope

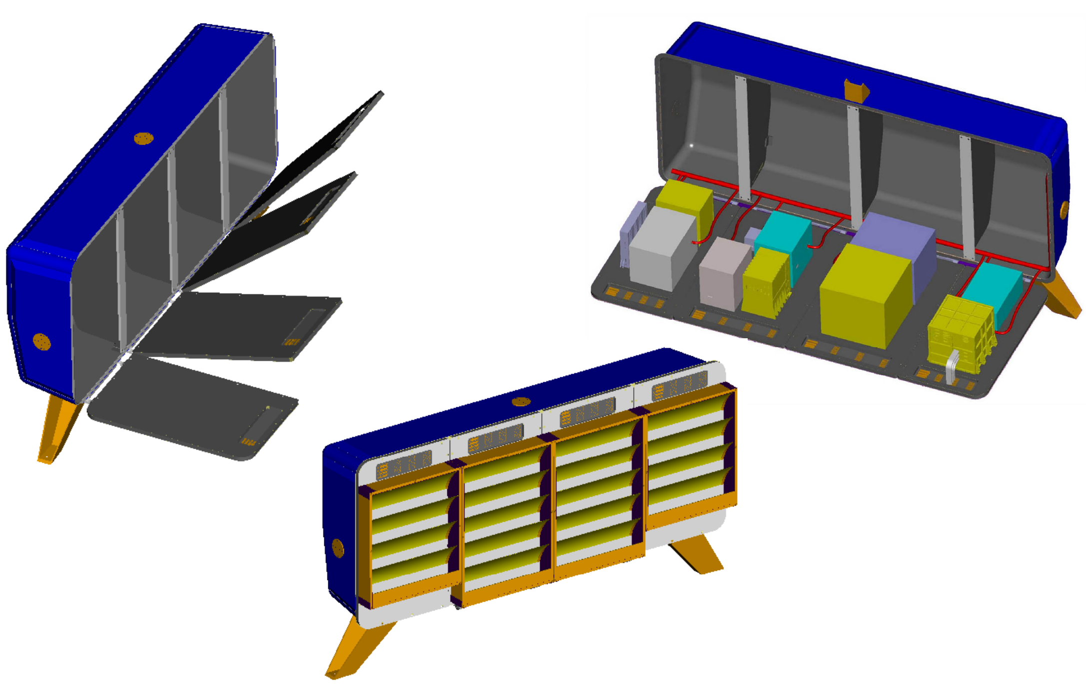


Figure 2: Drawings of IEC showing electronics accommodation on four radiator panels

The emission angle control problem arising from the IEC's location on the observatory is illustrated in Figure 3. The directional baffles are required to minimize the fraction of IEC emitted energy that strikes the bottom of the ISIM and, as best as possible, limit the fraction of emitted energy that strikes the sunshield. It is desirable to minimize the energy that strikes the sunshield at steeper angles because there is a higher likelihood of that energy reflecting or scattering back to the cryo-temperature telescope and instruments. Radiator emission pattern control is only required in the V1-V3 plane. The directional baffles do not change the V1-V2 plane emission pattern. The resulting desired emission pattern resembles an orange slice.

Other requirements relevant to directional baffle performance and design are related to dimensional constraints: the radiator surface area available and the allowable baffle depth. Figure 4 shows the IEC dimensional constraints. The impact of these dimensions will be explained later. For now, it is only important to note that IEC radiator area is limited and that the volume available for the directional baffles is relatively flat.

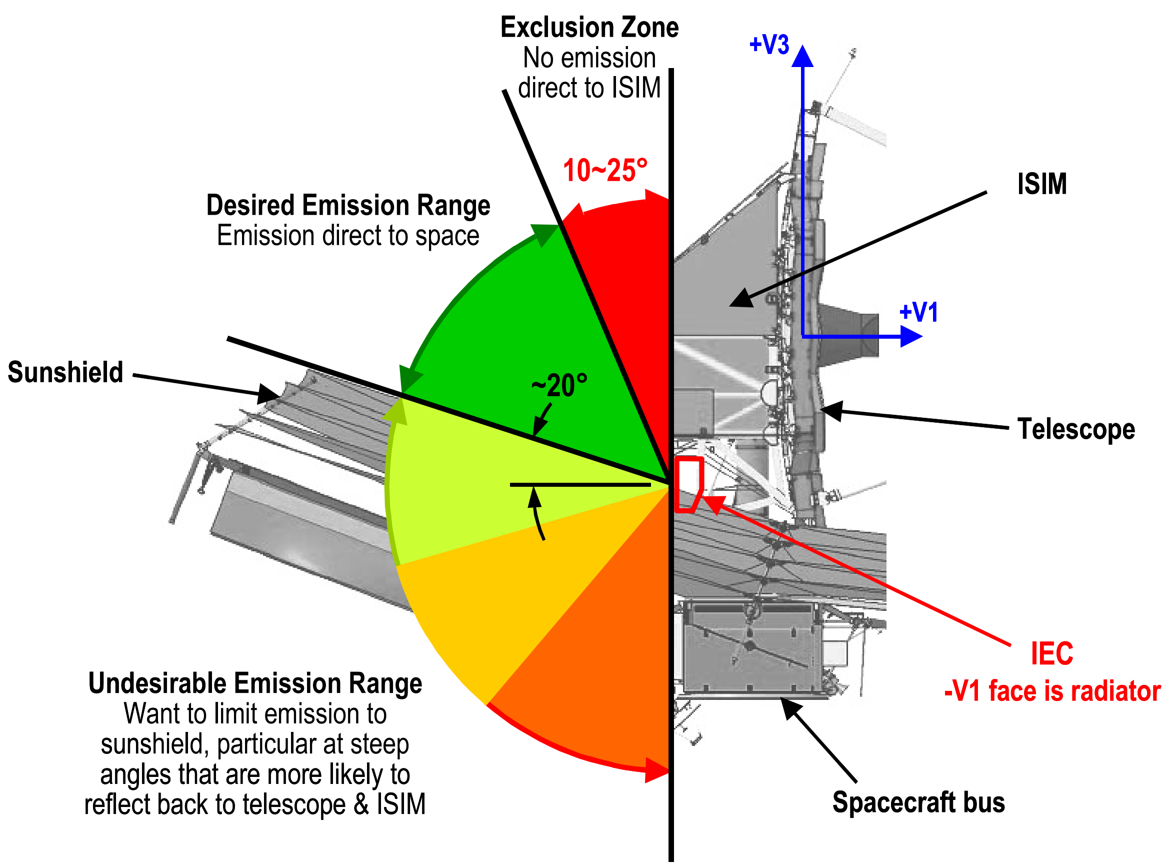


Figure 3: IEC emission range control requirements

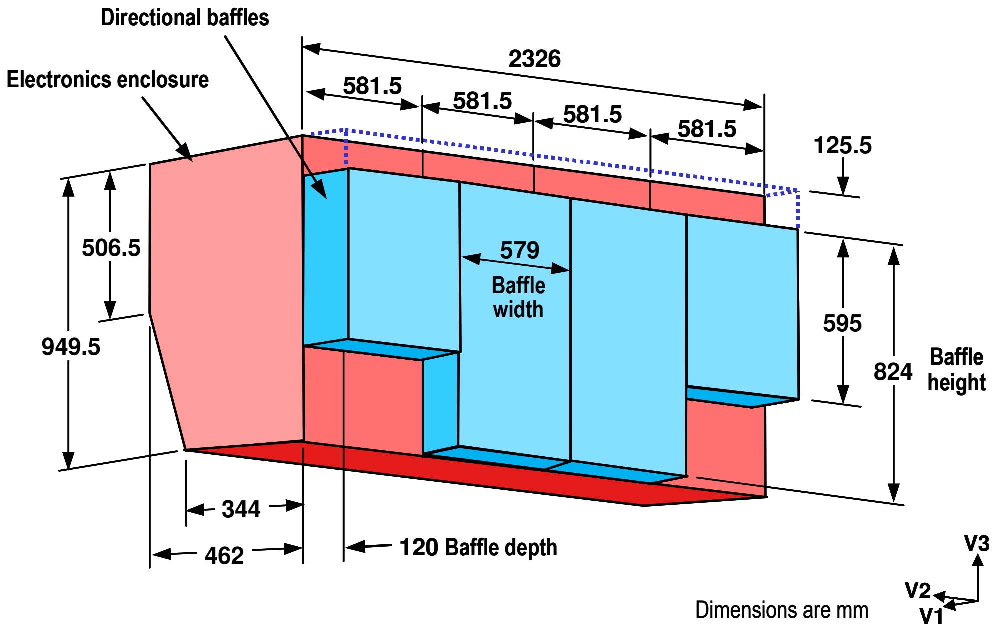


Figure 4: IEC dimensional constraints

CPC DESIGN EVOLUTION TO PROVIDE LATERAL CONTROL

In response to the need to laterally control the emission direction of the IEC radiators, a directional baffle design utilizing multiple curved mirror-like reflector surfaces has been developed. The optical design of this directional baffle is an extension of the Winston trough-like solar concentrator developed in the 1970's to provides moderate (~10X) concentration levels without the need to continuously track the sun[2]. The Winston trough-type concentrator is, in turn, based on the Winston axisymmetric, or cone-type, concentrators initially developed for amplifying light collection by PMT's used in the detection of Cherenkov radiation[3]. Winston cones and its derivatives have been widely used for numerous purposes in the past 40+ years[4]. Nature discovered this optical device far earlier, as numerous organisms, including humans, have incorporated into their retinal cone receptors light-concentrating refractive structures utilizing the same optical design[5].

The common feature of these Winston non-imaging optical concentrators is the use of opposing parabolic reflector surfaces. Consequently, they are often called by the more generic name *compound parabolic concentrator* (CPC). Each parabola has its focus at the opposite edge of the exit aperture and axis inclined at the limit angle of acceptance of the entrance pupil. A ray trace through a CPC is shown in Figure 5. Figure 6 illustrates a range of CPC devices.

Used as a concentrator, a CPC reflects all of energy incident on the entrance aperture over the angular range of acceptance to the exit aperture of the CPC. Energy entering the entrance aperture outside the angular range of acceptance is reflected back out the entrance aperture. Because of this characteristic, Winston cones have been used as thermal shields on spacecraft instrument cryo-radiators to reduce heat loads from external sources. A radiator located at the

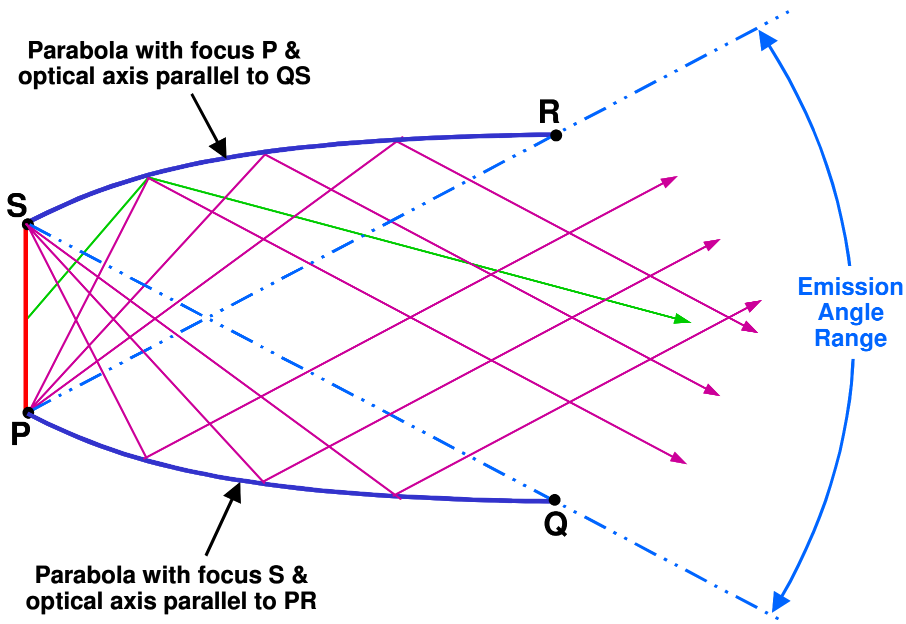


Figure 5: Ray trace through classic CPC-type shield. Purple rays from edges of radiator (shown in red) are reflected by parabolic reflectors to limits of emission angle range. Rays from other points on radiator are reflected within emission angle limits.

base of the Winston cone is shielded from incident energy—from the Sun, for example—coming from outside the acceptance range of the cone. For the IEC directional baffles, the goal is the reverse—to shield cryo-temperature JWST observatory elements from IEC radiator thermal emissions.

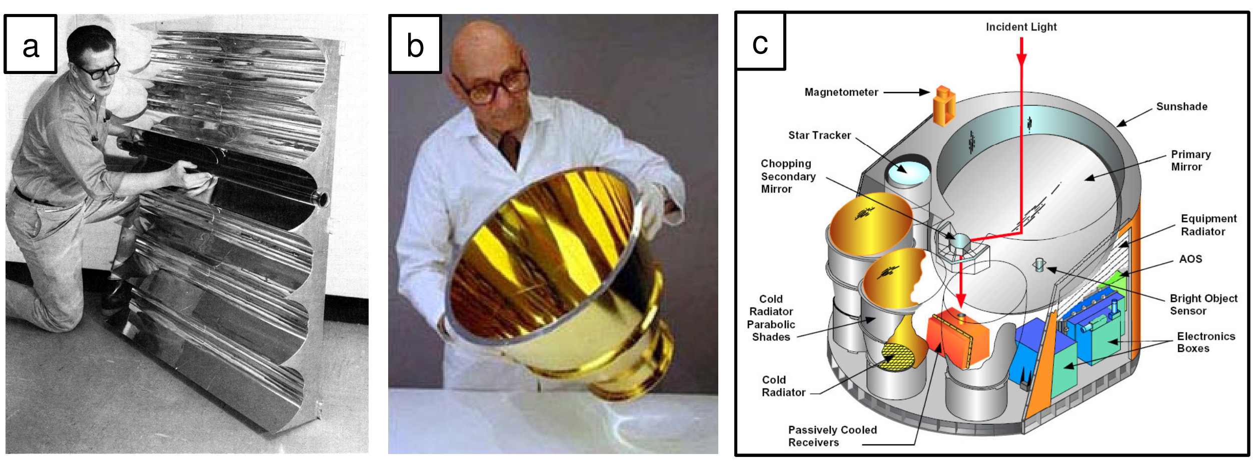


Figure 6: (a) Winston trough-type solar concentrator; (b) Winston cone thermal radiation shield from Atmospheric Chemistry Experiment (ACE); (c) Submillimeter Wave Astronomy Satellite (SWAS) instrument showing incorporation three cryo-radiators shielded by Winston cones.

Where the IEC directional baffle differs from previous designs is that it provides a laterally skewed emission angle range and allows close packing of multiple baffles (or CPC's) on a single flat radiator. Multiple baffles are required to fully cover the radiator without exceeding the allowable baffle depth. It has been noted previously that different parabolic shapes can be combined in one CPC to provide a non-symmetric acceptance angle[6]. However, adjusting the parabolic curves alone does not allow for close packing of multiple baffles on a flat radiator panel unless angled radiator fins are added, as illustrated in Figure 7. The addition of radiator fins is undesirable due to their additional mass and conductive thermal resistance. The ideal directional baffle has parallel exit and entrance planes.

Two approaches were developed to provide parallel entrance and exit planes. The first, shown in Figure 8, adds an elliptical reflector surface. This elliptical surface is located between one parabola and the radiator surface and forms a continuous surface (no slope change) with the parabola at their juncture. In the case where the emission angle limit is 90º from the radiator normal, the elliptical reflector completely replaces the parabola.

The second approach adds a second optical stage consisting of a circular reflector surface between the radiator and parabolic reflectors. This circular reflector relays the real radiator surface to a virtual location that is tilted. The virtual radiator surface creates, in effect, a virtual radiator fin of very low mass (the mass of a reflector strip being much less than a conductor fin) and very low thermal resistance (as long as the reflector surface has high reflectivity and high specularity).

This second design was selected for further development for the IEC. It is considered superior to the first approach for the following two reasons.

- The area of the reflector strips for a given radiator area is less with the circular reflector approach. This results in a lower mass baffle assembly.

- The fraction of energy emitted by the radiator and subsequently reflected by the baffles is less using the circular reflector. Each reflection results in some fraction of the energy being absorbed or scattered instead of specularly reflected. Absorbed energy is eventually re-emitted, typically in a direction outside the design emission angle range. Similarly, energy that is scattered instead of being specularly reflected can exit the baffle in a direction outside the desired emission angle range. Note that energy scattered or emitted by the circular reflector is of less concern as all energy passing through the virtual radiator surface is properly controlled by the parabolic reflectors.

Both the elliptical and circular reflectors can be used together in a directional baffle. While the performance of such designs has not yet been fully explored, Figure 10 shows qualitatively the performance of a proof-of-concept functional model of one such directional baffle model. This baffle consists of three reflector cells—a cell being one set of reflector surfaces—with each cell comprised of one circular, one elliptical, and one parabolic reflector strip. The design emission angle range is 0 to 90º for this model.

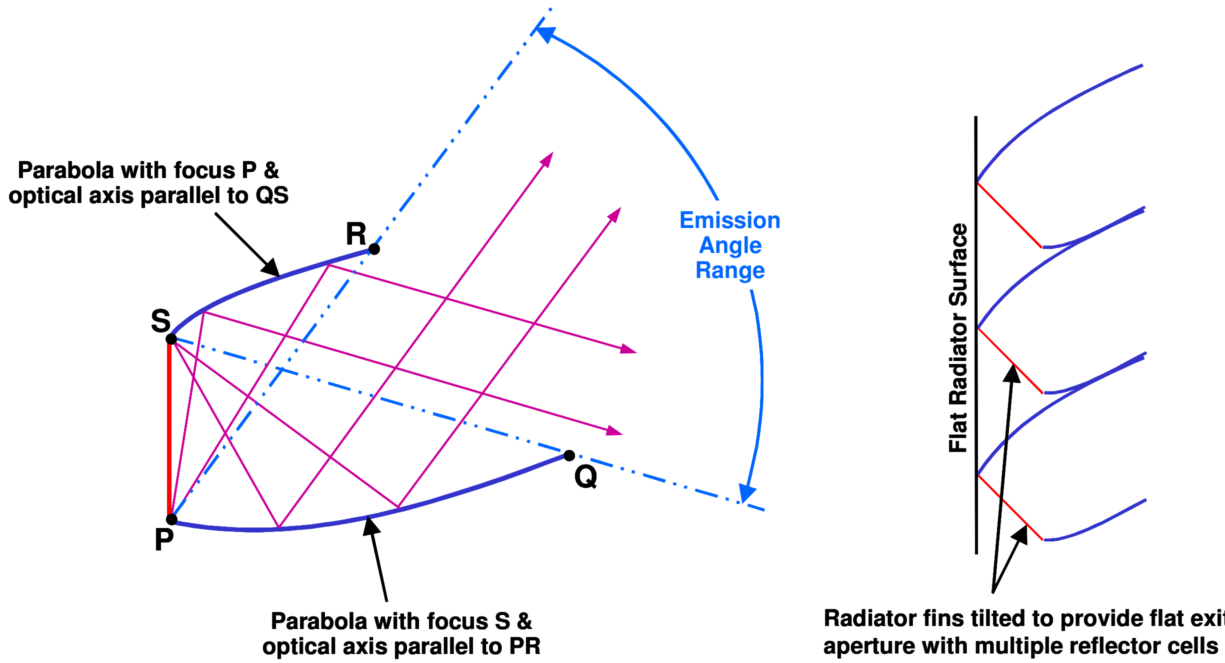


Figure 7: Skewed baffle design, using parabolas alone, does not allow close packing of multiple reflector cells into a low-depth assembly without use of tilted radiator fins

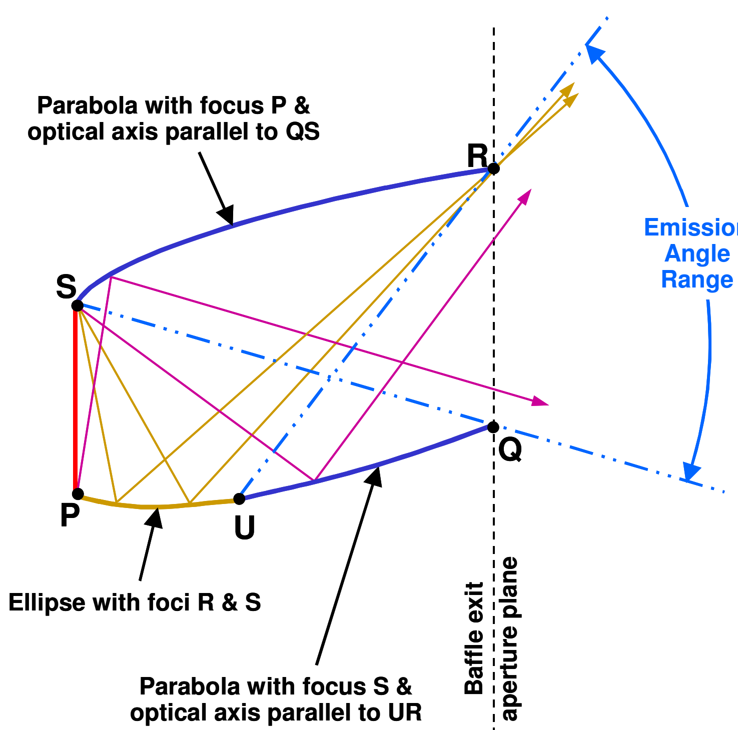


Figure 8: Addition of elliptical reflective surface shifts exit aperture plane parallel to radiator surface and allows close-packing of multiple reflector cells

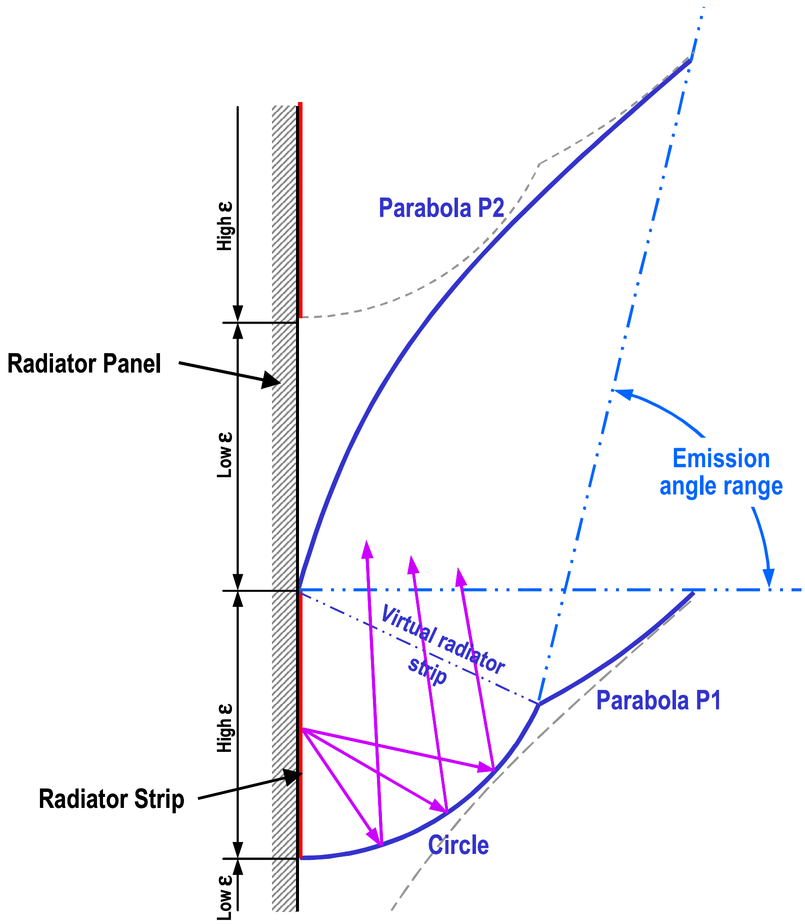


Figure 9: Addition of circular reflective surface to form a tilted virtual radiator surface

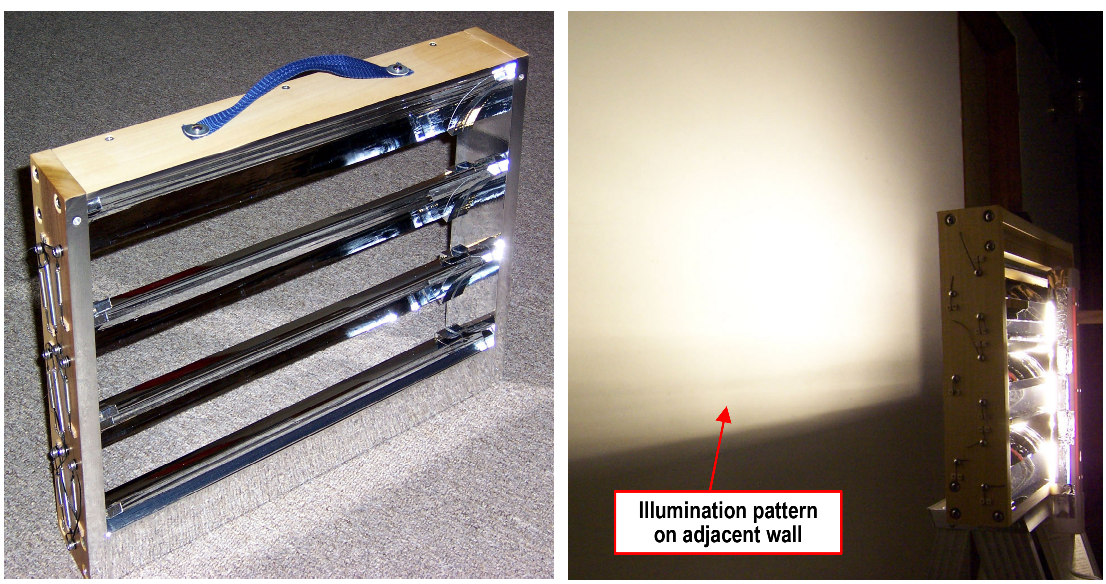


Figure 10: Photos of proof-of-concept model with three reflector cells utilizing circular reflector surface. Illumination pattern on wall demonstrates 0-90º emission range.

LIMITATIONS ON DIRECTIONAL BAFFLE PERFORMANCE

Why not design the IEC directional baffles to have an emission range that completely misses the sunshield? The answer is that there is a relationship between emission angle range and the ratio of entrance to exit areas that arises from the second law of thermodynamics. Called the Lagrange invariant, or étendue, this relationship can be considered to govern the amount of light that can be transmitted through an aperture. While the calculation of étendue can be complicated in some cases, for the case of 2D, i.e., linear or trough-like, baffles working in an environment with a fixed index of refraction, the governing relationship is simply

$$\frac{\text{Entrance area}}{\text{Exit area}} = \frac{\text{Entrance height}}{\text{Exit height}} = \frac{\sin\beta_1 + \sin\beta_2}{2} \tag{1}$$

where the meaning of the variables is shown in Figure 11. Reducing the emission angle range $\beta_1 + \beta_2$ requires increasing the exit-to-entrance-area ratio. However, the exit area is limited by the size constraints of the IEC (Figure 4), and the entrance area can only be reduced if the operating temperature of the radiator is increased as the amount of heat that needs to be dissipated is fixed. Consequently, there is a fundamental limit on the amount of control that can be applied to the emission angle range.

In addition to the above fundamental limit, there are the following additional factors that degrade directional baffle performance.

- The area of whatever structure used to support the reflector surfaces—a perimeter frame in the case of the IEC baffles—detracts from the available entrance and exit areas.
- The skewed shape of the reflectors results in the exit aperture being offset from the entrance aperture. This offset reduces the available entrance and exit areas.
- The reflector surfaces are not perfect mirrors. Surface defects and contamination act to scatter energy in undesired directions.

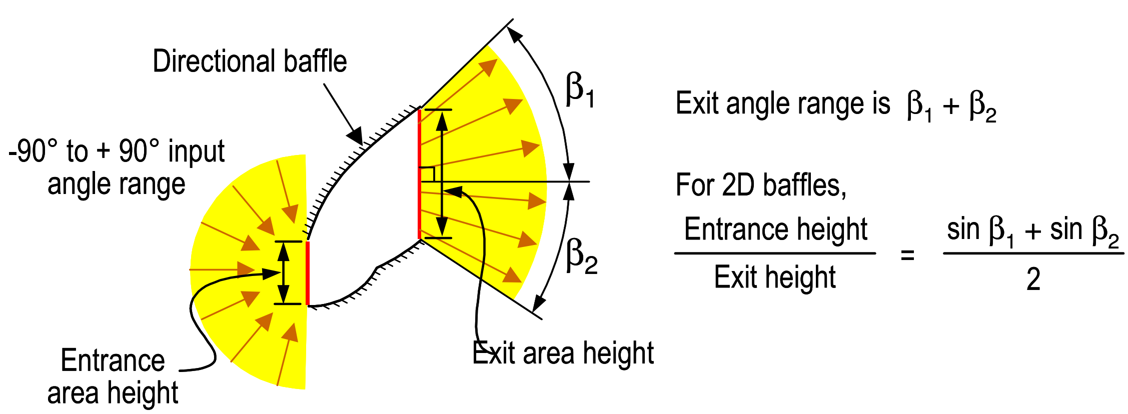


Figure 11: Illustration showing étendue relationship between entrance and exit aperture areas and emission angle range

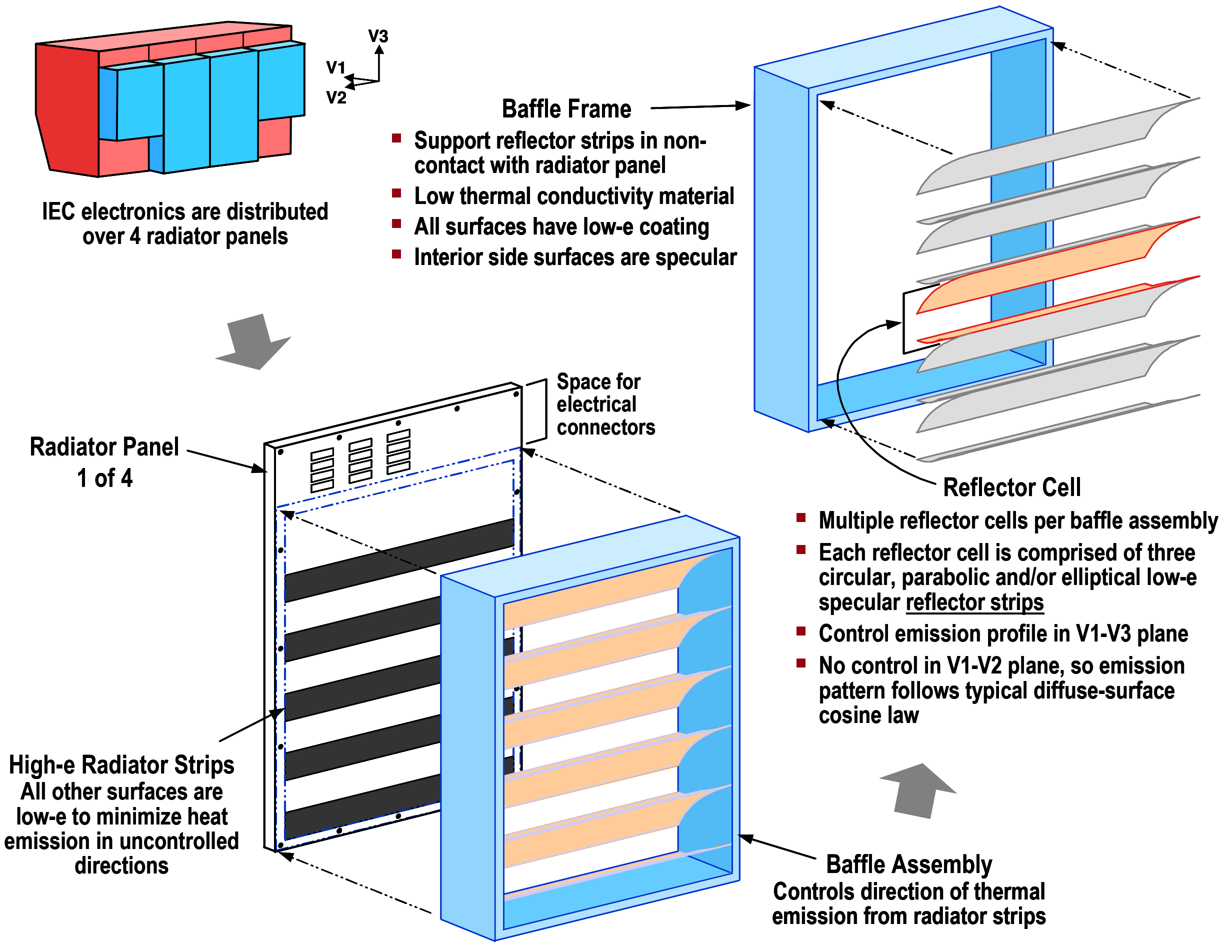
- Thermal emissions from the reflector surfaces and the structure used to support the reflectors general go in undesired directions. For the IEC directional baffles, this effect is minimized by fabricating the baffle housings from low thermal conductivity materials, mounting the baffle assemblies to the radiator panels using insulating inserts or washers, and covering the housing with a low-emittance coating.

BAFFLE ANALYSIS & PERFORMANCE

Directional baffle design for JWST utilizes a spreadsheet program and an iterative solution approach to develop a family of reflector cell designs. Each reflector cell design is then evaluated over a range of scale factors (a few large cells to many small cells) to determine how well multiple cells grouped into a baffle assembly package within the allowable dimensional constraints. Figure 12 illustrates the directional baffle design concept developed for JWST and provides summary design data on the current (May-06) design. Because there is a significant difference in the required-to-available-radiator-area ratios between the inner and outer radiator panels, the inner and outer panels require different baffle designs, each with different emission angle ranges. Note the reduction in actual emission angle range achieved in comparison to the theoretical range given by Equation 1.

The spreadsheet design and analysis program only considers radiator emission range and packaging issues. To better determine the performance of a directional baffle design, including the effects of scattered energy and thermal emissions, TSS and SINDA/G models are used. Due to the limitations of TSS, the parabolic sections of the baffles are represented by piece-wise cylindrical arcs with a maximum angular error 2º. Figure 13 shows TSS analysis results for a complete set of four directional baffles installed on the IEC. These results are only for emissions coming from the radiator panels—no emissions from the reflectors or baffle housings are included. Due to the non-zero height of the baffle assemblies and the overlapping emission patterns, the angular emission pattern varies with distance. At larger distances, the emission pattern of a baffle assembly begins to approach that of a single reflector cell.

The performance adequacy of the directional baffles is ultimately evaluated against their impact on telescope and ISIM temperatures. Two issues arise with system-level analyses. First, performing a thermal analysis with the full-up JWST thermal model requires considerable computer processing time. Second, radiant energy exchange between the IEC and the telescope and ISIM is strongly dependent upon the shape—both general shape and wrinkling—of the highly reflective sunshield. In order to simplify the evaluation of the directional baffles and decouple their development from a still-changing sunshield design, a simplified thermal model is used. This model consists of an IEC with baffles and a fixed representative-geometry model for the sunshield and bottom of the ISIM. The sunshield is divided into five zones and a sixth zone represents the bottom of the ISIM. All six zones have 100% emittance and thus measure the incident flux. Maximum allowable heat loads from the –V1 surface of the IEC are specified for each zone as the requirement against which baffle performance is evaluated. The representative surfaces are illustrated along with the predicted and specified maximum allowable heat loads in Figure 14. The predicted heat flow to all zones is currently within specification.



Parameter	Units	Inner Baffles	Outer Baffles
Overall height of baffle frame	m	0.824	0.595
Overall width of baffle frame	m	0.579	0.579
Overall area covered by baffle frame	m^2	0.477	0.345
Baffle frame thickness	m	0.015	0.015
Interior height of baffle frame	m	0.794	0.565
Interior width of baffle	m	0.549	0.549
Interior area of baffle	m^2	0.436	0.310
Required radiator area	m^2	0.200	0.091
Ratio of required-to-available radiator areas	-	0.459	0.293
Upper emission angle limit β_1	deg	67	67
Ideal lower emission angle limit β_2	deg	-0.1	-19.5
Actual lower emission angle limit β_2	deg	+6.5	-12.0
Number of reflector cells	-	7	5

Notes: 1. Emission angle limit signs are per Figure 11.

2. The difference between the ideal and actual lower emission angle limits results from the skewed geometry of the reflector strips, the finite thickness of the reflector strips, and allowances made for baffle-to-radiator misalignment.

Figure 12: Directional baffle design concept for IEC

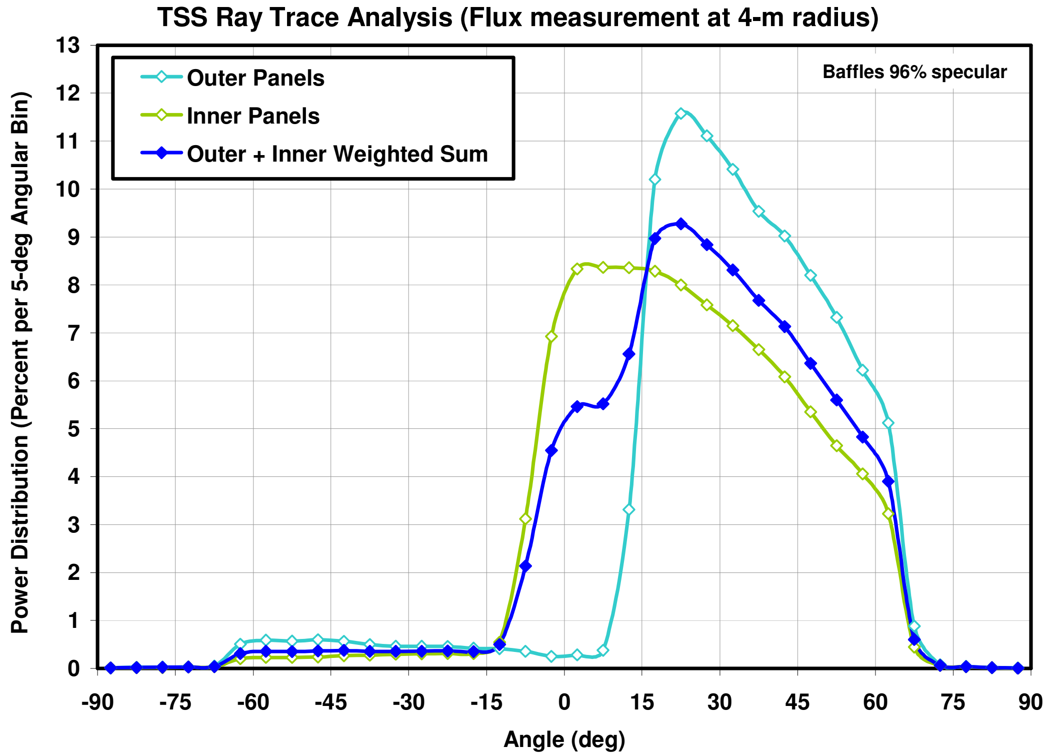
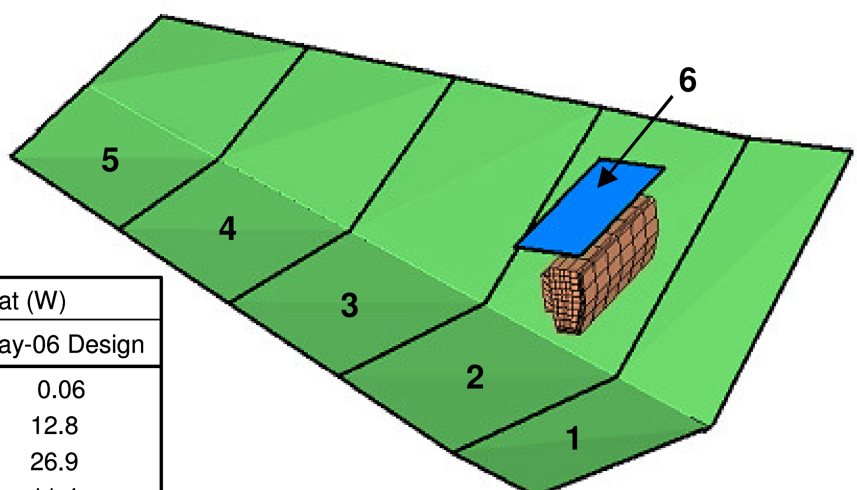


Figure 13: V1-V3 plane angular control plots for IEC directional baffles. Angle is measured from radiator normal with negative direction down towards sunshield.

Properties of Directional Baffle Reflector Surfaces

Emissivity = 0.04
Specularity = 0.96



Zone		Incident Heat (W)	
		Requirement	May-06 Design
Sunshield	1	0.2	0.06
	2	13.5	12.8
	3	31.5	26.9
	4	14.5	11.4
	5	4.5	3.3
ISIM	6	7.0	2.0

Figure 14: IEC heat flow requirements & results

CONCLUSIONS

The feasibility of using a directional baffle to laterally control thermal emissions has been demonstrated through preliminary design work, performance analysis, and a proof-of-concept model. The developed design is a new extension of the classic trough-type compound parabolic concentrator/shield. Through the addition of circular and/or elliptical curved surfaces, the design permits close packing of adjacent baffle cells and reduced baffle height—characteristics critical to area and volume limited applications.

As an application of this development, a preliminary directional baffle design has been developed for the JWST program that allows incorporation of an ambient temperature electronics compartment adjacent to cryogenic-temperature hardware with acceptably small thermal impact.

Emission direction control performance is considered very good, with control of energy emitted by the radiator approaching the theoretical maximum. Emission in undesired directions results primarily from energy conducted into or absorbed by the baffle assembly that is the radiated hemispherically. Additional design and analysis work is required to better limit these undesired emissions and to understand reflector surface shape and contamination control requirements.

ACKNOWLEDGEMENTS

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NOMENCLATURE, ACRONYMS, ABBREVIATIONS

CPC	Compound Parabolic Concentrator
IEC	ISIM Electronics Compartment
ISIM	Integrated Science Instrument Module
JWST	James Webb Space Telescope