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EXECUTIVE SUMMARY

This is the final report describing a long term basic research program in nonimaging optics that has led to major advances in important areas, including solar energy, fiber optics, illumination techniques, light detectors, and a great many other applications. The term "nonimaging optics" refers to the optics of extended sources in systems for which image forming is not important, but effective and efficient collection, concentration, transport, and distribution of light energy is. Although some of the most widely known developments of the early concepts have been in the field of solar energy, a broad variety of other uses have emerged. Most important, under the auspices of this program in fundamental research in nonimaging optics established at the University of Chicago with support from the Office of Basic Energy Sciences at the Department of Energy, the field has become very dynamic, with new ideas and concepts continuing to develop, while applications of the early concepts continue to be pursued. While the subject began as part of classical geometrical optics, it has been extended subsequently to the wave optics domain. Particularly relevant to potential new research directions are recent developments in the formalism of statistical and wave optics, which may be important in understanding energy transport on the nanoscale.

Nonimaging optics permits the design of optical systems that achieve the maximum possible concentration allowed by physical conservation laws. The earliest designs were constructed by optimizing the collection of the extreme rays from a source to the desired target: the so-called "edge-ray" principle. Later, new concentrator types were generated by placing reflectors along the flow lines of the "vector flux" emanating from lambertian emitters in various geometries. A few years ago, a new development occurred with the discovery that making the design edge-ray a functional of some other system parameter permits the construction of whole new classes of devices with greatly expanded capabilities compared to conventional approaches. These "tailored edge-ray" designs have dramatically broadened the range of geometries in which nonimaging optics can provide a significant performance improvement. Considerable progress continues to be made in furthering the incorporation of nonimaging secondaries into practical high concentration and ultra-high concentration solar collector systems. In parallel with the continuing development of nonimaging geometrical optics, our group has been working to develop an understanding of certain fundamental physical optics concepts in the same context. In particular, our study of the behavior of classical radiance in nonimaging systems, has revealed some fundamentally important new understandings that we have pursued both theoretically and experimentally.

The field is still relatively new and is rapidly gaining widespread recognition because it fuels many industrial applications. Because of this, during the final years of the project, our group at Chicago has been working more closely with a team of industrial scientists from Science Applications International Corporation (SAIC) at first informally, and later more formally, beginning in 1998, under a formal program initiated by the Department of Energy and incrementally funded through this existing grant. This collaboration has been very fruitful and has led to new conceptual breakthroughs which have provided the foundation for further exciting growth. Many of these concepts are described in some detail in the report.

Topics that may continue to be of interest in future programs include: a) new tailored-edge ray designs, b) the use of micro-structured materials that can be used to decouple the local and global slope of reflector surfaces so as introduce new degrees-of-freedom in the design of

nonimaging elements and the behavior of such elements, c) efficient new methods for the numerical optimization of nonimaging concentrators, and d) continuing theoretical and experimental studies of classical radiance in an effort to develop better model for radiance which will be useful for nonimaging systems and transport of electromagnetic energy on the nanoscale.

1.0 Introduction

This is the final report for a basic research program that was established at the University of Chicago more than fifteen years ago to explore and develop the optical sub-discipline that has come to be known as "nonimaging optics". This program has been extremely fruitful, having both broadened the range of formalism available for workers in this field and led to the discovery of many new families of optical devices. These devices and techniques have applications wherever the efficient transport and transformation of light distributions are important, in particular in illumination, fiber optics, collection and concentration of sunlight, and the detection of faint light signals in physics and astrophysics. Over the past thirty years, Nonimaging Optics (Welford and Winston, 1989) has brought a fresh approach to the analysis of many problems in classical macro-scale optics. Through the application of phase-space concepts, statistical methods, thermodynamic arguments, etc., many previously established performance limits were able to be broken and many technical surprises with exciting practical applications were discovered. The most recent three-year phase of our long-term continuing program ended in late 2002 and emphasized extending our work in geometrical optics and expanding it to include some interesting questions in physical optics as well as in the new field of statistical optics. This report presents a survey of the basic history and concepts of nonimaging optics and reviews highlights and significant accomplishments over the past fifteen years. This is followed by a more detailed summary of recent research directions and accomplishments during the last three years. This most recent phase was marked by the broadening in scope to include a separate project involving a collaboration with an industrial partner, Science Applications International Corporation (SAIC). This effort was proposed and approved in 1998 and was incorporated into this project (September, 1998) with the required additional funding provided through this already existing grant.

2.0 Overview and Background

Nonimaging optics is a relatively new optical sub-discipline that has experienced dramatic growth since its inception more than 30 years ago. The term refers to the optics of extended sources in applications for which image forming is not important but for which effective and efficient manipulation of the spatial and directional distribution of light energy are. A comprehensive review of the background and developments in this field over the last twenty-five years was presented in our proposal for the next to the last three-year phase of this program (Winston and O'Gallagher, 1995) and will not be repeated here. However, for clarity and context, a brief review and outline of the basic concepts and history of nonimaging optics is given below.

2.1 Nonimaging Optics

Nonimaging optics was invented at The University of Chicago in the mid 1960's with the discovery that optical systems could be designed and built that approached the theoretical limit of light collection. The limit to which a beam of light can be concentrated (or diluted) is fundamentally connected to its angular divergence (characterized by a half-angle θ), by the well known sine law of concentration which can be simply stated as

$$C_{max} = \frac{1}{\sin^2\theta} . \qquad (2.1a)$$

There are a variety of derivations of Eqn. (2.1a), some based on conservation of the volume in phase space occupied by an ensemble of light rays and some based on the Second Law of Thermodynamics. One of the latter that is particularly appropriate here goes as follows. Imagine the sun itself as a spherically symmetric source of radiant energy. The flux falls of as the inverse square of the distance R from the center, as follows from the conservation or power through successive spheres of area $4\pi R^2$. Therefore the flux on the earth's surface, say is smaller than the solar surface flux by a factor $(r/R)^2$ where r is the radius of the sun, and R the distance from earth to sun. By simple geometry, $r/R = \sin\theta$, where θ is the angular subtense (half angle) of the sun. If we accept the premise that no terrestrial device can boost the flux above it's solar surface value (to do so would lead to a variety of perpetual motion machines) than the limit to concentration is just $(1/\sin^2\theta)$. We will call this limit the *sine law of concentration.* This relation may be reminiscent of the well-known Abbe' sine condition of optics, but the resemblance is only superficial. The Abbe' condition applies to well-corrected optical systems and is first order in the transverse dimensions of the image. There are no such limitations to the *sine law of concentration* which is correct and rigorous for any size receiver. There is an escape clause to this conclusion when the target is immersed in a medium with index of refraction (n). In this case one is allowed and extra factor of n^2 so that

$$C_{max} = \frac{n^2}{\sin^2\theta} . \qquad (2.1b)$$

Of course the limit we have derived is for concentration in both transverse dimensions, which we will refer to as 3-dimensional concentration (or 3-D concentration for short). For concentration in one transverse dimension which we will refer to as 2-dimensional concentration (or 2-D concentration for short), the limit is clearly $1/\sin\theta$. While the concept of concentration in our demonstration refers to solar flux, implicit in our discussion is good energy throughput. We generally deal with concentrators that throw away as little energy as possible. Good energy *conservation* is an essential attribute of a useful solar system.

These equations (2.1a and 2.1b) define the "Thermodynamic Limit" for any optical concentrating system, that is the maximum possible concentration consistent with physical conservation laws.

The techniques of nonimaging optics were first consciously employed in the context of developing an efficient Cerenkòv light collector in a high energy physics experiment (Hinterberger and Winston, 1966). In its early stages, it provided simple, yet elegant, design methods for the field optics of an infrared astronomical instrument and it yielded new insights in vision research. The most well known applications have been in the field of the collection and concentration of sunlight (Winston, 1974) and this provided the motivation for the detailed design of many specific devices which are by now well known, such as the Compound Parabolic Concentrator (CPC), which achieves moderate levels of solar concentration without the need for tracking the motion of the sun, and the Dielectric Totally Internally Reflecting Concentrator (DTIRC) (Winston, 1976, Ning, Winston, and O'Gallagher, 1987) which introduces both refracting and totally internally reflecting surfaces into the concentrating element. Moreover, this approach has found important uses in many other areas where the efficient transport or transformation of light energy plays a role. For example, nonimaging techniques have been used in the design of very sensitive astronomical detectors, fiber optics couplers, novel illumination systems, automotive lighting, computer back-lighting devices, and laser pumping configurations, just to name a few. Recently developed concepts have increased the power of the available formalism and it has become clear that the full potential for utilization of these methods has barely begun to be developed.

Nonimaging optics has proven to be powerful because it departs from the methods of traditional optical design and aims to maximize the collecting or transmitting power of concentrating or disseminating optical elements and systems of elements. This is accomplished in part by applying the concepts of Hamiltonian optics, manipulating the phase space representations of the light distributions being propagated, and very often, by applying thermodynamic arguments (e.g. Smestad, Ries, Winston, and Yablonovitch, 1990) or radiative transfer methods wherever appropriate. Nonimaging optics relies on such notions as "Hottel strings" (McAdams, 1964) and has more in common with radiative transfer than with conventional optical design. In considering extended sources, one is led to distributions in phase space and beyond these, inevitably to the Theory of Radiance which has been the subject of some of our very recent work. The flexibility provided by these approaches has led to many new insights in understanding the operation of light transport and concentration systems. A measure of the importance that the field has attained can be obtained by examining the Table of Contents of the more than 600 page volume on the subject covering the first 20 years of activity in this field and which appeared recently in the SPIE milestone series (Winston, 1995a). Up-to-date summaries of the most recent results in the field are also available (Winston, 1995b, 1997). Furthermore, it is by now well established that it is only through the use of appropriately designed nonimaging devices that one can achieve the ultra-high solar fluxes necessary for many applications. The optical designs for such systems and their experimental demonstration have been described in a recent comprehensive review (Jenkins, O'Gallagher, and Winston, 1997)

In its relative brief history as a new sub-discipline, nonimaging optics has shown that, by relaxing the constraints of established traditional approaches, new insights into old problems can be generated and some surprising new discoveries and accomplishments made. For instance, until the early 1970s it was conventional wisdom in solar energy that no useful concentration of solar energy could be achieved unless the concentrating optics was rotated about at least one axis to follow the motion of the sun. A wide variety of concentrators, belonging to the family of Compound Parabolic Concentrators (Winston, 1974) and designed according to the principles of nonimaging optics are now known to provide concentrations up to a factors of 2-4 with completely stationary optics (fixed throughout the year) and up to between 10 and 20 with seasonal adjustments. Until the late 1980s, the world record for the concentration of sunlight using was about 16,000 times the level of ambient sunlight. In 1988, using a nonimaging secondary concentrator and a paraboloidal primary, our group established a new world record of 56000 times the ambient sunlight. On the scale of wave optics, until very recently, the traditional formalisms for radiometry yielded have unphysical (negative) values in certain limits. Our approach, based on nonimaging optics using statistical descriptions of the wave-field and the introduction of the concept of the "instrument function", has provided a satisfactory description that has been confirmed by direct measurements (Sun, Winston, O'Gallagher, and Snail, 2001b). One very important result is that objects being observed in the diffraction limit are considerably closer than would be inferred based on simple geometrical optics.

2.2 The Limitations of Conventional Imaging Devices

If one were to ask the proverbial "man on the street" for a suggestion of how one might attain the highest possible level of concentration of, say solar flux a plausible response would be to use a good astronomical telescope, perhaps the 200 inch telescope on Mt. Palomar, or whatever one's favorite telescope might be. Of course such an experiment had better remain in the realm of "gedanken" experiments only, since beginning astronomers are admonished *never* to point their telescope at the sun or risk catastrophic consequences to the instrument. But following-up on this train of thought, the concentration limit of a telescope is readily shown to be $\sin^2 2\phi/4\sin^2\theta$ after an elementary calculation. Here we have introduced a new parameter, ϕ which is the rim angle of the telescope. The best one can do is make the numerator 1 for rim angle $\phi = 45^0$, so the best concentration achieved is $1/4\sin^2\theta$ which falls short of the fundamental limit by a factor 4!. Now factors of 4 are significant in technology (in the Principal Investigator's case it represented the difference between success and failure in doing a high energy particle physics experiment). It was the desire to bridge the gap between the levels of concentration achieved by common imaging devices, and the *sine law of concentration limit* that motivated the invention of nonimaging optics. Entirely similar considerations can be applied to 2-D or trough concentrators. A straightforward generalization to a strip absorber rather than a disk absorber gives a limit for say, a parabolic trough of $\sin 2\phi/2\sin\theta$ with a consequent upper limit of $1//2\sin\theta$ for rim angle $\phi = 45^0$. In either case, we fall significantly short of the *sine law of concentration limit*, this time by a factor 2.

These simple examples of imaging systems and their attendant shortfall in concentrating performance (we could have examined lenses and reached similar conclusions) suggest that the requirement that an optical concentrator form an *image* is unduly restrictive. After all, we are after *transport* of radiant energy. From this point of view, even taking a more empirical optimization approach, it is plausible that relaxing the imaging requirement has the potential of improving concentrating performance ie, one would expect to be able to trade-off one against the other. Approaching the subject in this way does lead to incremental improvements over various classical imaging designs such as parabolic reflectors. Our approach is to show methods that actually attain, or closely approach the theoretical *sine law* limit to concentration while maintaining high throughput; methods that bear little resemblance to classical imaging approaches. An analogy with fluid dynamics may be useful to bring this point home. In fluid dynamics as in optics, a useful representation is in "phase space". Phase space has twice the dimensions of ordinary space and consists of both the positions and momenta of elements of the fluid. In optics, the "momenta" are the directions of light rays multiplied by the index of refraction of the medium. In optics as in fluid dynamics, the volume in this phase space is conserved, a sort of incompressible fluid flowing in this space of twice the number of physical dimensions (workers in optics usually use the term "etendue" for phase space). Now consider an imaging problem, taking the simplest example of points on a line. An imaging system is required to map those points on another line, called the image, without scrambling the points. From the phase space perspective, each point becomes a vertical line and the system is required to faithfully map line onto line. That may appear quite demanding, but it is precisely what an imaging system is asked to perform. But suppose we consider only the boundary or edge of all the rays. Then all we require is that the boundary is transported from the source to the target. The interior rays will come along. They cannot "leak out" because were they to cross the boundary they would first become the boundary, and it is the boundary that is being transported. To complete the analogy, the volume of container of rays is unchanged in the process. This is the conservation of phase space volume. It is very much like transporting a container of an incompressible fluid, say water. The fact that elements inside the container mix or the container itself is deformed is of no consequence. To carry the analogy a bit further, suppose one were faced with the task of transporting a vessel (the volume in phase-space) filled with alphabet blocks spelling out a message. Then one would have to take care not to shake the container and thereby scramble the blocks. But if one merely needs to transport the blocks without regard to the message, the task is much easier. This is the key idea of nonimaging optics, and the notion of transporting the boundary or edge of the container of rays leads to one of the useful algorithms. We shall see that transporting the edges only, without regards to interior order allows attainment of the *sine law of concentration limit.*

Incidentally, the limit for sunlight at the orbit of the earth from Eqn. (1b) is approximately 46,000 n^2 in air. In experiments at The University of Chicago we achieved a solar concentration of 84,000 in a refractive medium, sapphire, which has a refractive index n = 1.76 (Cooke, et. al, 1990). In subsequent experiments at the High Flux Solar Furnace (HFSF) at the National Renewable Energy Laboratory with power levels in the kilowatt range, concentrations of 22,000 in air (O'Gallagher, Winston, Zmola, Benedict, Sagie, and Lewandowski, 1991) and over 50,000 in a refractive medium (Jenkins, Winston, O'Gallagher, Lewandowski, Bingham, and Pitts, 1996b) times the ambient sunlight intensity have been demonstrated. These are the highest solar flux concentrations ever attained and measured at these power levels. A thorough review of the devices, techniques and accomplishments using nonimaging optics to generate ultra-high solar fluxes is given in a recent review by our group (Jenkins, O'Gallagher, and Winston, 1997). Some potential applications for highly concentrated sunlight that we or others have investigated include solar-pumped solid-state lasers (Benmair, Kagan, Kalisky, Noter, Oren, Shimony, Yogev, 1990; Jenkins, 1996) , surface alteration of materials (Pitts, Tracy, Shinton, and Fields, 1993) , production of Hydrogen by water splitting (Tamaura, Steinfeld, Kuhn, and Ehrensberger, 1995) production of fullerenes (Kroto, Heath, O'Brien, Curl, and Smalley, 1985; Fields, Pitts, Hale, Bingham, Lewandowski, and King ,1993), and space-based applications (Brauch, Muckenschnabel, Opower, and Wittwer ,1991).

2.3 Fundamentals of Nonimaging Optics

So far there have been three distinct phases in the development of the formalism used in nonimaging optical design. The earliest nonimaging designs were constructed by optimizing the collection of the extreme rays from the source to the target: employing the so-called "edge-ray" principle (Welford and Winston, 1978, 1989). See Figure 1. Later, new concentrator types were discovered by placing reflectors along the flow lines of the "vector flux" emanating from lambertian emitters of various geometries (Winston and Welford, 1979). Finally, a few years ago the discovery that making the design edge-ray a functional of some other system parameter (Winston and Ries, 1993, Jenkins and Winston, 1996).) permitted the construction of whole new classes of devices with heretofore unimagined capabilities. These "tailored edge-ray" designs (Friedman, Gordon, and Ries, 1993, Ries and Winston, 1994)) have dramatically broadened the range of geometries in which nonimaging optics can provide a significant performance improvement. Recently some symmetry breaking (Shatz, Bortz, Ries, and Winston, 1997) and global optimization(Shatz and Bortz, 1995) approaches, which are at the core of the newly initiated project with SAIC, show promis as the beginning of a fourth distinct phase. The first three of these are described briefly below.

2.3.1. The *edge ray* or *"string"* method.

To motivate the method we start with the remark that *all* of imaging optical design follows from a principle enunciated by the 17th century French natural philosopher and jurist, Pierre Fermat. The optical path length between object and image points are the same for all rays. This same principle applied to "strings" in stead of rays gives the edge-ray algorithm of nonimaging optical design. But we must first explain what strings are. This is best done by way of example. We will proceed to solve the problem of attaining the sine law limit of concentration for the simplest case, that of a flat absorber as illustrated in Figure 1. We loop one end of a "string" to a "rod" tilted at angle θ to the aperture AA' and tie the other end to the edge of the exit aperture B'. Holding the length fixed, we trace out a reflector profile as the string moves from C to A'. From simple geometry, the relation BB' = AA' $\sin\theta$ immediately follows This construction gives the 2-D compound parabolic concentrator or "CPC". Rotating the profile about the axis of symmetry gives the 3-D CPC with radius (a) at the entrance and (b) at the exit. The 2-D CPC is an ideal concentrator, i.e., it works perfectly for all rays within the acceptance angle θ. The 3-D CPC is very close to ideal For details, see Welford and Winston,1989. The flat absorber case is a natural candidate for rotating about the axis because the ratio of diameters ($\sin\theta$) agrees with the ratio of maximum skew invariant (again, for details see Welford and Winston,1989). Other absorber shapes such as circular cross-sections (cylinders in 2-D, spheres in 3-D) do not have this correspondence because the area of the sphere is $4\pi b^2$ while the entrance aperture area is πa^2. Notice that we have kept the *optical length* of the string fixed. For media with varying index of refraction (n), the physical length is multiplied by n. Of course we have not demonstrated that this construction actually works. One admittedly tongue-in-cheek approach is to state that anything this "neat" i.e., that satisfies the conservation laws in a natural way, *has to work*. Perhaps a more serious "proof" is to notice that the 2-D CPC rejects all stray radiation and therefore must be ideal by conservation of phase-space (Winston, 1970, Ries and Rabl 1994). The string construction is very versatile and can be applied to *any* convex (or at least non-concave) source and absorber.

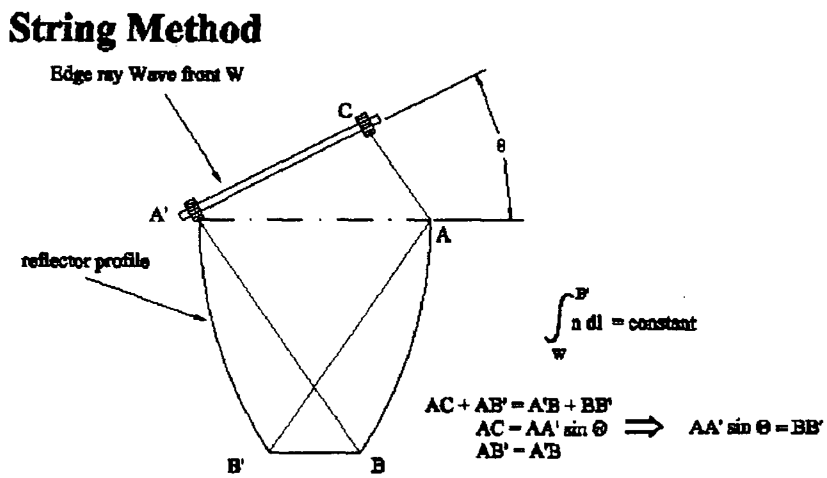


Fig 1. The "Edge Ray Principle" or "string" method.

The string construction for a tubular absorber (Figure 2) would be appropriate for a solar thermal concentrator(Winston, Hinterberger 1975). This particular construction, or its variants has been successfully applied to thermal collectors. The configuration for a vertical fin absorber has been applied to bi-facial solar cells by the Polytechnic University of Madrid Group (Luque,1989; Minano, 1985).

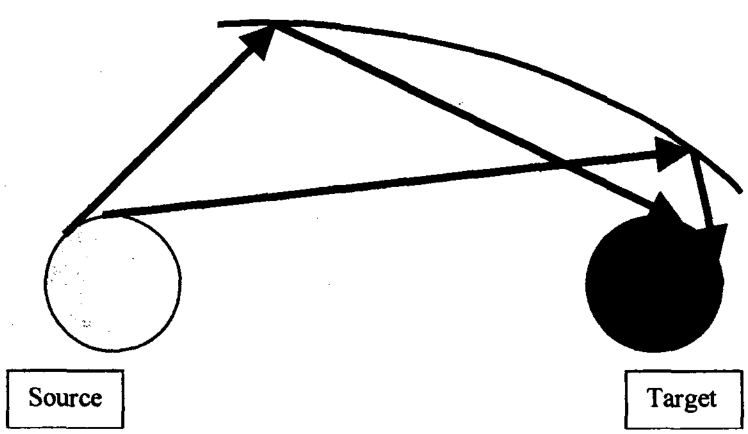
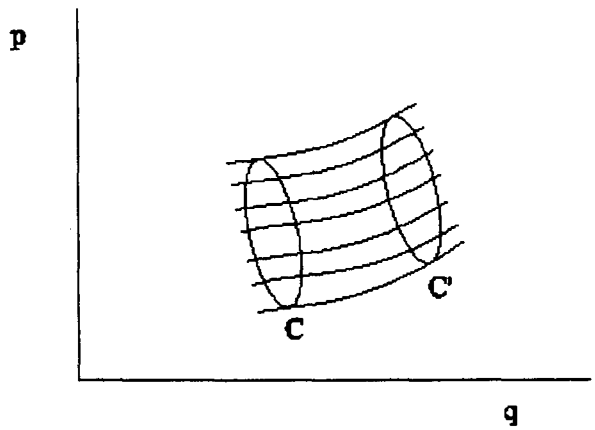


Fig 2. Alternative representation of the "string method", here for convex source and absorber

Phase Space Invariants



$$n\,ds = \sum_i p_i\,dq_i$$

1. $\oint p_i\,dx_i$

2. $\sum_{i \neq j} \int^{(4)} dp_i\,dp_j\,dx_i\,dx_j$ [important for nonimaging optics]

3. $\int^{(6)} dp_1\,dp_2\,dp_3\,dx_1\,dx_2\,dx_3$ [important for Liouville's Theorem]

Fig. 3. The vector flux or flow-line formalism is based on treating light as an incompressible fluid.

construct for calculating radiative transfer between lambertian surfaces. See McAdams, 1964). This approach was particularly useful for the design of wide-angle solar concentrators. It may be succinctly characterized as:

$$\int n(l)dl = \text{constant} \tag{2}$$

along a "string" stretched from the incident wavefront to the "edge" of the absorber. Here $n(l)$ is the index of refraction along the path length l and the integral is maintained constant from source to target along all rays characterizing a particular extreme or "edge" wavefront by appropriate shaping of the optical surfaces (e.g., reflectors). According to this, maximum concentration is achieved by ensuring that rays collected at the extreme angle for which the concentrator is designed are redirected, after at most one reflection, to form a caustic on the surface of an absorber. This defines a differential equation that can be solved either analytically or numerically as appropriate. Figure 1 (above) illustrates schematically how this method is used to design a basic Compound Parabolic Concentrator or CPC for an absorber of circular cross-section. The "string" is tied to the edge of the target and the length of string is held constant while the reflector shape is mapped out. This "edge ray" principle proved sufficiently elastic to accommodate most boundary conditions in two dimensions (i.e., linear geometry). In three dimensions, non-ideal but nevertheless very useful designs were generated, such as the CPC design for a plane target (or source). That is, the shape swept out by the fixed-length string is known to be an ideal concentrator in 2-d (Welford and Winston, 1989), while the 3-d axially symmetric concentrators formed by the rotation of a 2-d profile about its center vertical axis, while not truly ideal, are very close to ideal.

2.3.2 The Flow-line or Phase space method

In the early 80's, a second class of algorithms was found, motivated by the search for ideally perfect solutions in three dimensions (3-D) (The "string" solutions are ideal only in 2-D, and as figures of revolution in 3-D, they are only approximately ideal, though still very useful). This alternative method places reflectors along the lines of flow of a radiation field set up by a radiating lambertian source. In cases of high symmetry such as a sphere or disc, one obtains ideal solutions in *both* 2-D and 3-D. A conserved vector flux **J** is constructed from a fourth order invariant in phase space. It turns out that reflectors match the boundary conditions for the lines of flow of this vector flux. That is, by definition there is no energy flow across a reflector or a line of flow of **J**. Therefore placing reflectors along the lines of flow does not disturb the pattern and as a result produces ideal light collecting systems. Placing a reflector along the lines of flow "recreates" the entire source producing a nice optical illusion. For a planar source, which is most useful in optical devices, the lines of flow are confocal hyperbolas. The corresponding concentrator in 3-D has come to be called a "trumpet". This basic component can be combined with lenses at either entry of both entry and exit to produce collectors and/or enable transformers that are ideal. Note that the edge rays in a "trumpet" actually take an infinite number of reflections to reach the edge of the target absorber. Shapes of other fixed-angle acceptance concentrators can be found analytically using this method (Jenkins and Winston, 1996a)

We come back to our picture of light transport as the flow of an incompressible fluid in phase space (Figure 3). There is an analogy between the contour of the lines of flow of net flux (or vector flux) and reflectors. In both cases, the net flux is parallel to the contour. In fact, the boundary conditions of the vector flux is that it is tangential to a reflector and normal to a Lambertian emitter. This suggests (but does not prove) that placing reflectors along the lines of flow reconstructs the entire optical field. This is, in fact true in certain situations of high symmetry and is best illustrated by example. Consider a spherical, Lambertian source, very much like an idealized sun. The lines of flow are radial by symmetry (no calculation needed). Therefore. placing reflectors along the flow-lines, say a right circular cone, will reconstruct the field. This is correct in this case of high symmetry and produces a nice optical illusion, which the reader is encouraged to verify for themselves by constructing a model. It also produces an optical device, albeit not a particularly useful one for solar energy purposes. A useful concentrator is obtained by replacing the spherical source by a planar source. In this case, the flow lines are confocal hyperbolae (which *does* require a calculation (Winston, Welford 1979). Such designs have been used as second stage concentrators in parabolic dishes (O'Gallagher, Winston, Welford 1987). They are referred to as "trumpets" because of the resemblance to the musical instrument. An important step forward in this method came with the recognition by the University of Malaga and Polytechnic University of Madrid group of a formal analogy between the geometry of flow lines and three-dimensional *Lorentz* geometry. The full implications of this insight remain to be explored (Gutierrez, Minano, Vega, Benitez, 1995). Before leaving this discussion of the basic algorithms of nonimaging design, the following remark is useful. In selecting a design, we should compare the phase space (or etendue) of the source and target. In case there is a significant mismatch, then we know, from phase space conservation that an ideal, or close to ideal design is not possible. The details of the design are less critical, and often the imaging version is about as good as any. It is only when the source and target have equal phase space volumes, that the nonimaging design option can be implemented to good advantage. Alternatively, nonimaging designs can have imaging properties

2.3.3. Designs which are Functionals of the Acceptance Angle: ("Tailored Edge-ray Design" Method for Nonimaging Concentrators)

The third period of rapid development has taken place only in the past several years; its implications and consequences are still in the process of being worked out. The development of new techniques to "tailor" the design of concentrators has led to the solution of many new types of optical design problems. This came about as a result of an organized effort to address a wider class of problems in illumination that could not be solved by the old methods. When reversing the light ray paths, fixed acceptance nonimaging concentrators produce light distributions on distant screens that fall off as $\cos^2\varphi$ in 2-D and $\cos^4\varphi$ in 3-D (where φ is the angle between the normal to the screen and the direction to the light source). By making the acceptance angle collected variable along a reflector's surface (or "tailoring" the reflector shape to accommodate this varying acceptance angle) (Winston and Ries, 1993), unique and useful designs are attained for both illumination and solar concentrating systems.

Recent SPIE proceedings on nonimaging optics (Winston, Ed., 1995, 1997) provide an excellent summary of the new developments in the field made possible by tailoring. Other work (e.g., Winston and Ries, 1993) describes the new development of variable angular acceptance reflectors for illumination systems. The basic advance here is that nonimaging concentrators can be generalized beyond simple designs that accept only a fixed acceptance angular cone of rays. Using tailoring, edge-ray approaches yield designs that are more general. The additional flexibility introduces new degrees of freedom that make possible solutions for a whole range of new configurations. For instance in some cases, this will allow two-stage systems with short focal lengths to increase concentration above what had been previously thought possible, as shown for parabolic dish systems by Friedman, Gordon and Ries (1993). Their approach used methods developed by Gordon and Rabl (1992).

More recent developments (Jenkins and Winston, 1996) show how to use a general design method that involves numerical integration of a simple differential equation that can be used to generate most types of nonimaging concentrators including as a subset the already known solutions such as CPCs and "Trumpets." The design geometry for the reflector uses numerical integration of a simple differential equation given in polar coordinates by

$$\frac{d(\ln R)}{d\varphi} = \tan\alpha(R,\varphi), \qquad (2.4)$$

The solution is completely specified if α (the slope angle of the reflector) is known for all points (R, φ) in the plane of the reflector. The value of α depends on the incident flux distribution on the aperture of the concentrator and the target absorber's shape. For a flat absorber, shapes similar to CPCs are attained.

These concepts are so new that "tailored" nonimaging concentrators have not yet been employed in any actual devices. For instance all of the concentrator described in our review paper (Jenkins, O'Gallagher, and Winston, 1997) are based on the well established edge-ray designs for long focal length configurations. However, it should be kept in mind that the use of tailored designs may permit the design of solar furnaces with as yet undeveloped nonimaging secondaries that can approach the ideal limits of concentration in a short focal length configuration, thus significantly reducing the size of these systems. The use of fixed angle acceptance secondary concentrators in existing dishes and furnaces provides more phase space acceptance than is necessary for the optimum compensation for the aberrations induced by the imaging primary mirror. Optimizing the compensation for these aberrations by tailoring both the primary and secondary reflectors should result in a more compact two-stage concentrating systems. The future potential for solar furnaces configurations using these new design techniques remains to be explored. Issues associated with these new "tailored" designs and their implications for future work are described further below in Sections 3 and 4.

2.4 Advantages and Features of Two-Stage Concentrating Systems

An early impetus to the development of nonimaging optics was the realization that conventional imaging optics falls far short of the sine law limit. For example, a parabolic reflector achieves, at best, one quarter of the sine law limit. It is easily shown (Welford and Winston, 1989) that the concentration of a single stage paraboloid or any other conventional reflecting focussing primary falls well short of the limits of Equation 1. In particular, a primary with a convergence angle half-angle (or rim angle) ϕ, as schematically illustrated in Figure 1, can attain a geometrical concentration ratio of at most

$$C_{1,\max} = \frac{\cos^2\phi \sin^2\phi}{\sin^2(\theta_i)} \qquad (2.2)$$

and thus falls short of the maximum limit by a factor of $\frac{n^2}{\cos^2\varphi\sin^2\varphi}$. The maximum value of Equation 2.2 occurs at $\phi = 45^o$, and thus, even for this best single stage concentrator, the shortfall with respect to the limit of Equation 2.2 is at least a factor of 4 n^2. However with a suitable choice of a secondary concentrator deployed in the focal zone of the primary or "first stage", one can recover much of this loss in concentration.

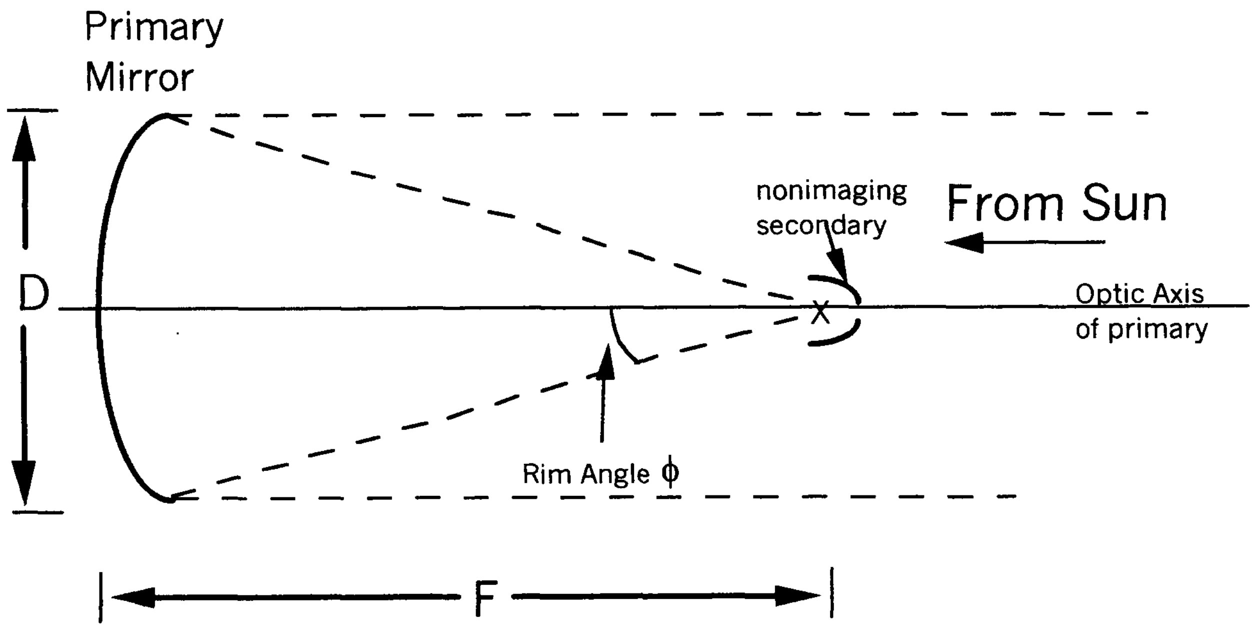


Figure 1. Schematic summary of configuration for a two-stage nonimaging concentrator.

There is a whole family of single -element nonimaging concentrators designed for relatively large acceptance angles and useful for achieving effective collection and concentration of light at moderate to intermediate levels, most notably the CPC. However for small design acceptances and corresponding large concentration ratios, these devices become extremely long and narrow and as such are not practical for attaining high concentration. The most effective designs (currently in use) for attaining very high concentrations and approaching the thermodynamic limit with a practical system are the so-called two-stage configurations comprised of a focusing first stage (or primary) and a nonimaging second stage (or secondary) deployed in the focal zone of the primary as indicated schematically in Figure 4. A nonimaging secondary can achieve a geometrical concentration factor of

$$C_{2,max} = \frac{n^2}{\sin^2\phi} \tag{5}$$

where ϕ is the rim angle of the primary. Combining this with the concentration of a single stage focusing primary we find that the practical geometric limit (with a fixed acceptance secondary) is

$$C_{2\text{-stage, max}} = C_1 \cdot C_2 = \frac{n^2\cos^2\phi}{\sin^2\theta_i} \quad . \tag{6}$$

It should be recognized that the single stage limit applies not only to paraboloids, but to *any concave focusing primary* (Welford and Winston, 1980). The two stage limit of Equation 6 comes close to the ideal limit for small ϕ, i.e., for large focal length to diameter (F/D) ratios. The rim angle ϕ is related to the focal ratio f = F/D by

$$\phi = \tan^{-1}\left[\frac{1}{(2f - 1/(8f))}\right] \qquad (7)$$

Here the maximum geometric concentrations for one and two stage concentrators, normalized to the Thermodynamic Limit, are compared as a function of the focal ratio of the primary. The highest concentration designs (with fixed acceptance secondaries) are those in which the primary has a large focal length to diameter ratio (F/D > 1), in which case the secondary can achieve very high concentration factors and the combined two-stage concentration readily exceeds 80% or 90% of the Thermodynamic Limit. This is in contrast to conventional systems which, if they are to maintain a respectable intercept factor, achieve a maximum concentration of < 25% of this limit at small focal ratios (F/D = 0.4-0.7) corresponding to ϕ near 45^{o}. Two stage configurations fall into two distinct focal length ranges, short (F/D = 0.4-0.7) or long (F/D = 1.5 - 2.5). An important near term application is the enhancement of the performance of previously existing dish designs which have been optimized as single stages and hence are characterized by shorter focal length configurations. In these "retrofit" cases, the nonimaging secondary still provides a significant boost (O'Gallagher and Winston, 1988), although it does not approach the ideal limit. All of the very high flux applications use a small rim angle, long focal ratio configurations since these are the only designs that provide a means of closely approaching the ideal limit with a fixed acceptance secondary. These large focal ratio nonimaging designs offer the opportunity for the incorporation of a number of additional built-in advantages. For instance, the primary concentrator can be a simple spherical mirror, since in a long focal length design, the image broadening due to spherical aberrations is negligible. Alternatively these designs encourage the use of faceted or segmented primary mirrors or reflectors formed from pressure stabilized metal or film membranes. The latter tend to form a sphere to a very good approximation. Finally we note that the off-axis aberrations are not as severe in the case of long focal length designs as they are in short focal length systems so that, with a secondary, even off-axis geometries can attain very respectable concentrations. This has important implications for the design of solar furnaces where fixed primary and target geometries are desirable and the motion of the sun is accommodated by a tracking heliostat directing the sun's rays to the primary.

3.0 Some Relatively Recent Accomplishments

3.1 Progress in "Tailoring" Methodology.

Tailored Edge-Ray Designs. The "tailored edge-ray" designs have dramatically broadened the range of geometries in which nonimaging optics can provide a significant performance improvement. Recent applications generated by the new approaches of these techniques are described Jenkins and Winston (1996) and Ries, Spirkl, and Winston (1998). The first concerns applications in illumination and while the second describes the potential for achieving higher concentrations than heretofore thought possible with fully stationary optics. This is still proving to be an extremely powerful design approach. However, our work in progress illustrates that the last word is not in. Depending on how one sets up the initial conditions, the solutions look quite different with differing advantages for applications. Much more work needs to be done to form a perspective on this general method and extend the domain of problems of interest. We are continuing these studies in collaboration with colleagues in Germany, Israel, France, and Spain.

3.2 Radiance and Measurement -- the Instrument Function

In parallel with the continuing development of nonimaging geometrical optics, our group has been working to develop an understanding of certain fundamental physical optics concepts in the same context, for instance the behavior of radiance in nonimaging systems, in particular near field boundaries. The present position in the theory of Generalized Radiance (i.e. radiance in the scalar wave model) seems unsatisfactory in that there are many possible definitions, none of which satisfies all the properties that radiance intuitively ought to have except possibly in relation to particular narrowly defined types of sources. Furthermore, radiance defined in these ways leads to details in the calculated values which are inherently impossible to observe, as we have shown (Littlejohn and Winston, 1993). Our group at Chicago has been collaborating with the University of California Berkeley group (Robert Littlejohn and Allan Kaufman) with the goal of developing a theory of radiance applicable to a wider range of optical systems including nonimaging optical systems. A way out of the difficulties posed by the theory of Generalized Radiance is to introduce an instrument function which is reciprocal to the wave field being measured (Littlejohn and Winston, 1995a and 1995b) Recently we have turned our attention to methods of calibrating the instrument function in an attempt to make the subject useful in practical radiometry.

Recently there have been several results from efforts devoted to unraveling the wave function through the use of phase space tomography. Most of these have been devoted to the study of the dependence of the atomic-beam wavefunction in the direction transverse to the propagation direction, (Janicke, and Wilkens, 1995; Kurtsiefer, Pfau, Mlynek, 1997) to the study of quantum states of an ion in a Paul trap, and to molecular quantum states (see Freyberger, Bardroff, Leichtle, Schrade, and Schleich (1997) for more references). The major outcome of this research front thus far has been the determination of the density matrix represented as a pseudo-probability density, the Wigner distribution, in phase space. We are attempting to fill in a missing piece in the picture of what appears to be an attempt of viewing quantum mechanics in the environment of phase space. This missing piece is the determination, either through measurement or through calculation, of the Wigner distribution of the operator corresponding to an instrument or an observable. We call this distribution the instrument function, I, first introduced by Littlejohn and Winston (1995a). This will allow us to complete the Dirac bra-ket in the phase space picture and allow us to compute various matrix elements. With the completion of the Dirac bra-ket, one can next interpret the outcome of various experiments in terms of the matrix elements.

We have shown that the theory of generalized radiance incorporating the idea of the instrument function has the same structure as the study of quantum mechanics in phase space. The idea of the instrument function corresponds to an observable having positive eigenvalues. Even though the foundation of radiometry, built upon the theory of partial coherence, is well constructed there still remain two thorny problems, that of negative radiance, negative probability in phase space, and the non-uniqueness of definition for generalized distributions.

Consider first negative probability. Negative probability is of course nonsense if we interpret it directly. What, then, are the intervening steps that are necessary for one to associate any physical meaning to generalized radiance? At present physical interpretation has been obtained by performing integration with respect to the x or k variables, the transverse position vector and the transverse wave-vector, to yield positive values which are interpreted as the radiant intensity and radiant emittance.

But in order to provide a firmer basis for the relationship with classical radiometry one need something more specific, since radiance in the framework of classical radiometry has physical meaning at a phase-space point. Of course effects due to finite wavelength entails bringing in the uncertainty principle which prohibits us from knowing the joint probability of position and wave-vector. However it is also precisely the uncertainty principle, which makes it legitimate for a distribution to have negative values, because the value at a point in phase space is not directly measurable. What is important is to have directly measurable quantities representing

Our work has shown how introducing the measurement process into the theory of radiance in a self-consistent way removes certain long-standing difficulties in the subject such as the fact that generalized radiance can take on negative values. This approach has so far been applied only to the simplest, most primitive kind of "radiometer". We believe it is important to extend these ideas to more realistic "radiometers" if the new concept is to have any impact on radiometry. Topics that we have studied are 1) The study of the eigenfunctions of the measurement operator in more detail, to see how well surrounding regions of phase space are rejected as the acceptance of the instrument is closed down and, 2) Development of a theory of phase space tomography for the measurement of an instrument function.

In parallel with the continuing development of nonimaging geometrical optics, our group has been working to develop an understanding of certain fundamental physical optics concepts in the same context, for instance the behavior of radiance in nonimaging systems, in particular near field boundaries. The present position in the theory of Generalized Radiance (i.e. radiance in the scalar wave model) seems unsatisfactory in that there are many possible definitions, none of which satisfies all the properties that radiance intuitively ought to have except possibly in relation to particular narrowly defined types of sources. Furthermore, radiance defined in these ways leads to details in the calculated values which are inherently impossible to observe, as we have shown (Littlejohn and Winston, 1993). Our group at Chicago has been collaborating with the University of California Berkeley group (Robert Littlejohn and Allan Kaufman) with the goal of developing a theory of radiance applicable to a wider range of optical systems including nonimaging optical systems. A way out of the difficulties posed by the theory of Generalized Radiance is to introduce an instrument function which is reciprocal to the wave field being measured (Littlejohn and Winston, 1995a and 1995b) Recently we have turned our attention to methods of calibrating the instrument function in an attempt to make the subject useful in practical radiometry.

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3.3. Two-stage dish concentrators for solar thermal energy

The concept of using a terminal nonimaging concentrating device in the focal plane of an imaging concentrator has been under development for nearly fifteen years (Ortabasi, Gray, and O'Gallagher, 1984, O'Gallagher and Winston, 1986). Properly designed nonimaging concentrators have the potential to increase the geometric concentration, C, of any optical system, so that it closely approaches the well known maximum physically allowed limit. In the case of solar concentrating systems, this limit depends, not only on the angular sun size but also on all sources of optical broadening of the solar image such as random slope errors on the primary reflecting surface, system alignment and tracking errors. If one tries to exceed the limit by making the target area too small the consequences will always be a loss in geometric throughput from intercept losses. Since a conventional focusing primary falls short of the limit by at least a factor of four, the attainment of high concentrations with only a primary concentrator employing practical, economic reflecting surfaces has proven to be a daunting problem. The use of a nonimaging secondary in combination with a focusing primary (Figure 1) permits in principle either the recovery of significant intercept losses ("spillage") while maintaining a fixed geometric concentration or substantial increases in geometric concentration while keeping intercept losses negligible. This can be done without requiring any improvement in the optical quality of the primary.

3.3.1 First Demonstration of a High Temperature Prototype

An experimental demonstration of a nonimaging secondary concentrator operating with a point focus dish and a cavity receiver high temperature has been carried out (O'Gallagher, Winston, Diver and Mahoney, 1996). These tests employed a "trumpet" type secondary (Winston and Welford, 1979) in combination with the Cummins Power Generation CPG-460 7.5 kWe concentrator system (Bean and Diver, 1993) and were the first such tests ever performed with a hot receiver. These tests and observations were reviewed in the context of a detailed thermal performance model for two-stage solar concentrator systems developed previously (O'Gallagher, and Winston, 1987; O'Gallagher and Winston, 1988). The characteristics of the primary concentrator and the procedures governing the optical, mechanical, and thermal design of the prototype secondary trumpet have been presented in some detail (see O'Gallagher, et. al., 1995a, and 1995b).

The basic objectives of these experiments were a) to demonstrate the practicality of the use of secondaries of this type with a high temperature thermal receiver and b) to measure quantitatively the effect of the secondary on both the optical and thermal performance of the receiver. In addition we investigated at high temperature a number of operational concerns including (i) the effectiveness of the active water cooling and (ii) the effectiveness of the thermal isolation of the trumpet from the hot receiver. The tests were performed in Abiline, Texas on one of four Cummins CPG 460 dishes maintained at the company's headquarters. The optical quality of the facets on this dish were known to have undergone some deterioration due to stretching and/or sagging after prolonged exposure to moisture. This fact is important in interpreting the results of the tests and did compromise the attainment of the quantitative objectives

3.3.2 Practical Performance Comparison of Different Nonimaging Secondary Concentrators

A comparison of the practical advantages and disadvantages of several different nonimaging approaches to the attainment of high levels of solar concentration has been carried out (O'Gallagher, 1997a). Some kind of nonimaging secondary concentrator is an absolute necessity if systems that lift attainable concentrations above the limits associated with single primary concentrator alone are to be achieved with high efficiency. The conventional CPC type and Trumpet designs are the most familiar and each has its advantages and disadvantages.

When compared with a trumpet, CPCs have many advantages. They can achieve the highest concentration at small rim angles (long focal ratio) and thus have geometrical concentrations in a two-stage configuration that can approach arbitrarily closely to the actual Thermodynamic Limit. Furthermore, CPCs have a compact design with minimal shading and are easily truncated. Some of their disadvantages are that CPCs have relatively high skew ray losses (~ 5%) and a relatively high average number of reflections. Thus with CPCs, there can be significant reflection losses in throughput and relatively high absorbed thermal loads unless surface reflectivity is high.

Some of the corresponding features of trumpets are that hey have about the same concentration as CPCs at high rim angles (short F/D) while they have *no skew ray losses*. Furthermore, they have a low average number of reflections leading to low reflection losses and small thermal loads. Trumpets provide a good match to contemporary dish designs. The trumpet's disadvantages are that it is not as compact as CPC (the "bell" extends well beyond the target aperture) and it cannot achieve high concentrations (trumpets are limited to ~ 2X since shading becomes prohibitive at long focal ratios).

The techniques of edge-ray tailoring for two stage designs present by Friedman, Gordon and Ries (1993) provide powerful new optical techniques and have generated many new, previously unexplored, design options. However, when these tailored edge-ray designs (TEDs) are compared with conventional nonimaging secondaries, a number of other considerations become relevant. For very high concentration applications, long focal length configurations with CPC secondaries are probably the preferred secondary design. Trumpets and TEDs are not compact enough (prohibitive shading) and do not approach arbitrarily closely to the ideal limit. For shorter focal ratio geometries (F/D ≈ 0.5-0.7) the trumpet is probably the conservative choice. It provides significant boost in concentration with low optical losses and low thermal loads.

The TED provides the option of further increased concentration. It can provide an increase of ~ 25% with relatively compact design. Furthermore, the TED could provide an increase in concentration of as much as ~80 %. However this would require a larger secondary and perhaps require a new two-stage conceptual design. Finally note that since TEDs do interact with a large fraction of the concentrated flux it is apparent that having a high surface reflectivity will be very important for most its most effective utilization.

3.4. New Initiatives with Industrial Partner.

The field of nonimaging optics is still relatively new and is rapidly gaining widespread recognition because it fuels many industrial applications. Because of this, during the last phase of this project, our group at Chicago has been working more closely with members of the Advanced Technology division at Science Applications International Corporation (SAIC) in San Diego, California. This collaboration was at first informal but now, beginning this year (1998), it has been formalized under a program initiated by the Department of Energy and incrementally funded through this existing grant. This collaboration has been very fruitful and has led to new conceptual breakthroughs which have provided the foundation for further exciting growth. The group at SAIC has independently developed some new and very powerful techniques for the systematic design of nonimaging optical elements. It has been shown that the introduction of controlled symmetry breaking surfaces into axi-symmetric nonimaging designs has provided the ability to affect the brightness and skewness distributions of propagating bundles of light rays in heretofore unimagined ways. Furthermore, the application of global optimization algorithms to problems solved by "classical" nonimaging solutions such as the Compound Parabolic Concentrator (CPC), has shown that, for certain applications, there exist even better solutions. The application of both of these new approaches to several previously unexplored and challenging problems in nonimaging design has already generated devices with properties previously thought impossible and offers the promise of significant increases in system efficiency with important practical application. Many of these concepts are incorporated (see Section 4.5 below) into our proposed continuing effort.

In response to the Department of Energy Program Notice 97-15, a joint research project to explore and develop some new types of nonimaging optical devices with exciting properties was proposed. The problems proposed for investigation include: a) projection optics systems for rectangular receivers (such as liquid crystal diode display apertures), b) maximization of throughput and sharpness of angular cut-off for three-dimensional rotationally symmetric Dielectric Totally Internally Reflecting Concentrators (DTIRCs), c) efficient light coupling systems utilizing compact folded optics in nonimaging devices, and d) the design of a stationary concentrator with broken translational symmetry with the goal of generating three dimensional acceptance properties that will permit effective concentration of sunlight throughout the calendar year. Following the preparation and submission of a preapplication in response to the original solicitation, we were invited to submit a full proposal which was approved for funding.

Inverse Engineering Optimization. As is well known in this subject, exact three dimensional solutions are rare (e.g., flow-line solutions). Practical 3-D nonimaging designs are usually rotated 2-D solutions which fall short of theoretically maximum performance. An advance in the subject was recently presented by the group from Science Applications International Corporation (SAIC) who have introduced a novel numerical optimization method into nonimaging design (Shatz and Bortz, 1995). This is an inverse engineering topological-axiomatic approach which results in a variational principle for optimizing power transfer, beam shaping or irradiance distributions. While the gains in performance over conventional rotated 2-D designs so far demonstrated are small (< 1%), this represent a fundamental advance in nonimaging design methods. We have been working to apply the new and powerful methods of the SAIC group to a variety of problems that would benefit from this optimization. One example is the rotationally symmetric dielectric cone concentrator (or projector) developed by our group in the 1980's. This configuration has many applications both in light collection and illumination, and even a modest improvement in performance is well worth trying for. Other applications include non-axially symmetric designs which are important for both illumination and collection applications.

Symmetric system are limited by additional conservation law (Ries, et.al. 1997). Therefore even symmetric problems may require a-symmetric solutions (Shatz, Bortz, Ries, and Winston, 1997). The symmetry breaking needs not be on a global scale. Relatively small facets, that basically only break the symmetry with respect to their slope but not with respect to their overall shape suffice. This idea leads to microstructured materials, discussed further in Section 4 (Ries, et.al. 1999).

3.5. Other Highlights.

• Fourth Biennial Conference on Nonimaging Optics-- 27-28, July, 1997, San Diego, CA

As part of its annual meeting, the Society of Photo-Optical Instrumentation Engineers (SPIE) sponsored the fourth in its series of international conferences on nonimaging optics. The growth of the field that was founded here at Chicago and its intellectual vitality is dramatically demonstrated by the variety and depth of the contributions to this conference. A total of 28 papers representing the work of 60 different authors was presented during the two day conference. The proceedings of this conference have been published (Winston, 1997). These covered several very exiting new developments in theory, some innovative devices, and a variety of solar energy applications. In association with the conference, a short course in nonimaging optics (that was very well attended and well received) was also presented by the principal investigator on this grant (RW).

Several of the major areas of our group's work were presented in contributions to the conference. In particular, our work on radiance and the instrument function (Littlejohn, Sun, and Winston, 1997) describes significant progress in nonimaging applications in the physical optics domain and will be described briefly in somewhat more detail below. In addition, a dramatic example of the power of innovative thinking in overcoming some limits imposed by strict geometric optics considerations was given in Shatz, Bortz, Ries, and Winston (1997).

• Fifth Biennial Conference on Nonimaging Optics— SPIE Conference and Workshop 2-5 August, 2001, San Diego, and La Jolla CA

As part of its annual meeting, the Society of Photo-Optical Instrumentation Engineers (SPIE) sponsored the sixth in its series of international conferences on nonimaging optics. The growth of the field that was founded here at Chicago and its intellectual vitality is dramatically demonstrated by the variety and depth of the contributions to this conference. A total of 33 papers representing the work of 63 different authors was presented during the two day conference. The proceedings of this conference have been published (Winston, 2001). These covered several very exiting new developments in theory, some innovative devices, and a variety of solar energy applications. In association with the conference, a short course in nonimaging optics (that was very well attended and well received) was also presented by the principal investigator on this proposal (RW). Following the SPIE Conference, on August 4, 5, 2001, a special International Workshop on Nonimaging Optics was held in La Jolla, California. Specialists in the field presented their most up-to-date but as yet unpublished research.

Several of the major areas of our group's work were presented in contributions to the SPIE conference. In particular, our most recent work on measuring radiance and the instrument function (Sun, Winston, O'Gallagher, and Snail, 2001) describes significant progress in incorporating wave-effects into a consistent formalism in Liouville space, the Hilbert space of operators. In addition, a dramatic example of the power of innovative thinking in understanding the limits imposed by various geometric invariants was given in "Performance Limitations of Translationally Symmetric Nonimaging Devices" (Bortz, Shatz, and Winston, 2001). We also presented a remarkable analogy between the measurement of radiance and the well-known van Cittert-Zernike Theorem (Winston, Sun, and Littlejohn, 2001). Finally results on design of a new secondary concentrator capable of producing near uniform illumination of a rectangular target were presented (O'Gallagher , Winston, and Gee, 2001).

4.0. Some Remaining Questions.

Many interesting but general problems in nonimaging optics are as yet unsolved. We are just beginning to understand the breadth of possibilities. Given an input radiation distribution and a specified optical system, composed of reflecting and refracting elements, it is easy to calculate the resulting output radiation distribution by ray-tracing. However, the usual problem encountered is somewhat different. Instead, for a given input radiation distribution one wants to find an optical system which will transforms this radiation into a specified desired output distribution. This problem is much more difficult. There is no general solution to this inverse problem. Even the conditions for the existence of solutions are only rudimentarily known. There has been some progress toward solving this problem when the rays are in two-dimensional space. This situation is of practical interest because it applies to systems with translational symmetry. Furthermore, rotated 2-D solutions are often very useful (the oldest one, a rotated CPC is an example). However, one cannot prove that rotating a 2D solution will lead to rigorous solution in three-dimensional space. In fact in some cases symmetry involves additional conservation laws which limit the performance (Ries, et. al, 1997). And it may be useful to explicitly look for non-symmetric solutions even if the problem itself is symmetric (Shatz, Bortz, Ries, and Winston, 1997). It would be interesting to identify the constraints that define whether or not a particular problem is solvable and developing some powerful new tools to apply to those problems that are.

4.1 Tailoring

One of the most useful tools in nonimaging design is the edge-ray principle, which is based on the idea that a continuously curved optical element transforms radiation in a topological, (continuous) manner. This means that all rays situated on the border of the incoming set of rays will end up at the border of the output set. This simple situation is complicated by the possibility of multiple reflections, which introduce discontinuities. Previous work established an equivalence to a continuous map of the first reflection only. In addition, it introduces an auxiliary set of rays (Ries and Rabl, 1994) such that the union of source and auxiliary set needs to be transferred by the first reflection map to the union of target and auxiliary set. Consequently one does not need to analyze multiple reflections and one may apply the simple edge-ray principle to this first reflection map.

A constructive procedure has been found for designing an optical element such that a set of edge-rays is mapped onto another desired edge ray set. In this way, a reflector can be tailored to solve a specific problem. (Ries and Winston, 1994, Gordon and Ries, 1993). Normally, for any given location in two-dimensional space there are two edge rays to a given contiguous source. Tailoring can be applied to only one of them. If the reflector starts adjacent to the source we need to be concerned only about one edge ray. This procedure cannot easily be generalized to three dimensions because for each point in space there is now an infinite one-dimensional manifold of edge rays. On the other hand, we have only two degrees of freedom in specifying the orientation of the surface of reflector element at that point. Therefore, matching the edge rays of source and target with one reflector is in general over-defined.

There are several options to solve this problem, which we propose to study in more detail.

a) We may hope that the introduction of the auxiliary set can mitigate this difficulty. The freedom to choose the auxiliary set may then constitute the needed additional degrees of freedom.

b) Another possibility is to use multiple stages, which then must be designed simultaneously.

c) The third possibility is to use microstructured materials, in particular Fresnel reflectors and lenses, which also offer more degrees of freedom.

Most important for the beginning is a thorough understanding of the type of problems, that can be solved, at least in principle, depending on the systems used. For example, as we go from single stage reflectors, to multistage reflectors, constant index lenses gradient index lenses, etc. Each of these systems offer a higher number of degrees of freedom which can be used to meet the edge ray principle.

In illumination problems, the irradiance in one location depends on the projected solid angle of the source as seen from that location. The exact contour is irrelevant. Therefore in this context tailoring a reflector for a specific irradiation is not an over-defined problem and seems to be feasible even for non-symmetric 3-dimensional settings.

It would be interesting to develop a procedure in the spirit of the tailoring algorithm to determine the shape of a reflector in 3 dimensions which produces a desired, not necessarily symmetric irradiance distribution on a given target by specifying a differential equation. This differential equation is then to be solved analytically or numerically.

4.2 Micro-structured materials

4.2.1 Fresnel Optics (General Properties - Global slope and local slope decoupled)

Conventional concentrators for nonimaging optics are built from specular reflectors or lenses. Such materials have surfaces that are smooth on all scales larger than the wavelength of light. Recently, however, a variety of microstructured materials has become available. These have facets much larger than the wavelength of light, yet much smaller that the overall dimensions of typical optical systems. Thus these microstructured materials in effect decouple the local slope of the surface which is responsible for redirecting the radiation from the global slope which is dictated by the shape of the system. Obviously this represents a new degree of freedom which can be used for specific designs.

The best known examples of using this property to redirect the light independently of the overall shape of the optical system are Fresnel optics, such as Fresnel lenses and heliostats. The decoupling of global and local slope is unfortunately not only a blessing. Fresnel reflectors have specific problems due to the fact that incoming radiation pencils and the corresponding redirected pencils do not automatically have equal phase space volumes. If the outgoing radiation has larger phase space volume, then this amounts to dilution. On a microscopic scale of the individual facets, regions phase space filled with radiation alternate with domains that contain no radiation. Thus the maximum concentration ratio which can subsequently be achieved for example by appropriate secondary concentrators, is reduced accordingly.

If the outgoing pencil of rays in the desired direction offers less phase space, then due to the overall conservation law for the étendue, part of the radiation is lost. It will typically undergo more reflections and be redirected into completely different directions eventually exiting as stray light in Fresnel lenses. In Fresnel reflectors the radiation lost due to this effect typically hits the back-side of a reflector, which is called blocking.

The specific problems of Fresnel reflectors have been recognized in previous work (Karni, and Ries, 1994). We propose to analyze in detail analogous effects in Fresnel lenses. Fresnel lenses have an additional complication in the fact that the angle of a narrow pencil of light may be changed as it is redirected by a Fresnel lens, in the same way as it changes when passing through a regular lens. It may be possible to improve the performance of Fresnel lenses by adequately distributing the grooves between the two sides and possibly by appropriately designing the overall shape of the lens.

4.2.2 Perpendicular facets ("cats eye")

Another example of microstructured materials are cat-eye reflectors. These consist of groups of facets which are perpendicular to each other. As a result, on a global scale, these reflectors appear to feature nonstandard reflection laws: If the facets resemble the corner of a cube alternating between all three spatial directions, then these reflectors invert all components of the direction of a ray effectively turning it back to where it originated. This is a true cat eye reflector. If the facets are V-grooves extending in on direction of the global surface, then the reflector conserves the component of the radiation direction along the grooves and inverts both direction components perpendicular to it. These "partial" cats-eye reflectors seem particularly useful for the design of nonimaging concentrators.

It would be interesting to study the utilizability of such reflectors for nonimaging devices. We expect two major advantages using these materials. First a better reflectivity achieved at low cost because the reflection at the facets may be total internal reflection which is essentially loss-free. A second advantage may be the possibility to design novel nonimaging devices based on the specific reflection law inherent to these materials.

It is easily seen that rotational reflectors if constructed from a "partial" cat-eye material where the groove direction is in the plane of the optical axis, are from a geometric point of view precisely equivalent to the same devices built from conventional specular reflectors.

4.2.3 Polygonal apertures (tesselation)

State of the art nonimaging devices, which are at the theoretical limit in 2 D, i.e. in a trough configuration, are known, as are devices, which are perfect or very close to being perfect in a rotational configuration. However, one frequently would prefer concentrators with rectangular or hexagonal aperture because of the possibility to tile larger areas with a number of smaller apertures and to approach nonisothermal absorbers in this manner (Ries, Kribus, and

Karni, 1995; Timinger, et. al., 1998). Another application is photovoltaic cells for concentrated radiation, which are typically available in rectangular shape.

One would naively think that combining two or three 2D devices in a crossed configuration would lead to a satisfactory concentrator with a rectangular or hexagonal aperture. However, unfortunately this is not true. In crossed 2D devices rays which are only reflected between facing surfaces observe the edge ray principle and consequently none of these rays are lost. But rays, which are reflected in adjacent sides do not. A part of these rays may therefore be lost.

Due to the particular reflection in "partial" cat eye reflectors it still may be possible to be able to design reflectors where the rays are predominantly reflected in pairs of facing reflectors and thus to find better concentrators for polygonal apertures.

4.3 Stochastic Optimization --"simulated annealing"

The present state of the art in nonimaging optics is unfortunately insufficient to either solve any optical problem or prove that it is impossible. Therefore ultimately one often still has to resort to stochastic optimization procedures based on Monte-Carlo type techniques.

There is an extensive amount of work on the general problem of finding the minimum value of a scalar function in many-dimensional space. The most important difficulty is finding the global extreme value rather than a local one. This is addressed by concepts borrowed from thermodynamics. A thermodynamic system eventually settles in the global minimum energy configuration if the temperature is reduced sufficiently slowly. Similarly in optimization a parameter analogous to temperature is introduced which controls the probability that an uphill step is nevertheless accepted. The rationale for this is to be able to cross ridges into other valleys which may be deeper. This approach is known as stochastic annealing and is presently one of the most powerful tools in global optimization.

On the other hand this approach is extremely wasteful in terms of computing time because large numbers of rays are traced through many far from optimal optical systems. Therefore an area of intense research is the annealing schedule, that is how exactly the pseudo-temperature should be decreased in the course of the computation such as to find the global minimum efficiently in terms of computation time. Again concepts from thermodynamics can be borrowed: the computing time is treated as the heat extracted from the system, whereas the optimal values found so far are regarded as a measure of the temperature of the system (Salamon, et. al., 1988; Ruppeiner, 1983; Ruppeiner, Pedersen, and Salamon, 1991). In this framework finding the global optimum is equivalent to cooling a system by contacting it with an external heat sink. The system has a temperature dependent heat capacity and coupling to the driving reservoir. Recent advances in finite time thermodynamics yield a solution to this general problem in the framework of Euler-Lagrange Equations (Spirkle and Ries, 1995).

We investigated the possibility of adapting this formalism to the specific features of objective functions derived from raytracing. Conventional objective functions for which the state of the art optimization algorithms are developed yield an essentially exact value for the price of a possibly lengthy but unchanged computational effort. In contrast, if the performance of an optical system is assessed by ray-tracing, then the value of the objective function can never be determined precisely. The more rays are traced, the more precise the result will be. Thus in addition to the decision of where to evaluate the objective function next, the optimization algorithm in the case of stochastic objective functions should specify the precision with which the objective function should be evaluated there, or equivalently the number of rays to be traced. Even more powerful is the option of deciding when to exit raytracing of a particular configuration based on the results accumulated so far. Because it makes no sense to determine the performance of a poor configuration more precisely that needed just to determine that it is not optimal, this may speed up the computation significantly.

It may yet be possible to develop an information theoretical approach for efficient Monte-Carlo optimization of optical systems, which not only will allow to attack a wider range of optical design problems but also represent a step forward in information theory and statistical physics.

4.4 Non-Classical Radiance and Measurement

4.4.1 Theory: Context and Choice of Formalism

Even though the foundation of radiometry, built upon the theory of partial coherence, is well, there still remain two vexing problems, that of negative radiance, negative probability in phase space, and the non-uniqueness of definition for generalized distributions.

Consider first negative probability. Negative probability is of course non-physical if we interpret it directly. What, then, are the intervening steps that are necessary for one to associate any physical meaning to generalized radiance? At present physical interpretation has been obtained by performing integration with respect to the **x** or **k** variables, the transverse position vector and the transverse wave-vector, to yield positive values which are interpreted as the radiant intensity and radiant emittance. But in order to provide a firmer basis for the relationship with classical radiometry one need something more specific, since radiance in the framework of classical radiometry has physical meaning at a phase-space point. Of course effects due to finite wavelength entails bringing in the uncertainty principle which prohibits us from knowing the joint probability of position and wave-vector. However it is also precisely the uncertainty principle which makes it legitimate for a distribution to have negative values, because the value at a point in phase space is not directly measurable. What is important is to have directly measurable quantities representing probabilities take on positive values. Integration with respect to the **x** or **k** variables yield measurable quantities which are positive. To probe the generalized distributions in more detail we will need to do integration in a region in phase space that is comparable to one cell, which has a volume of $(2\pi)^n$ where n is the dimension of the phase space, weighted with respect to some function.

Next consider the problem of non-uniqueness of definition for generalized distributions in phase space. This problem appears to be related to the negative probability problem. Various generalized distributions in phase space depend for their definitions on the second order correlations of the field. If for a particular choice of definition, and second order correlation, negative radiance is a strong feature of the calculated generalized distribution, then if we use another definition we find that the calculated distribution for it differ markedly from the previous one. Using the usual interpretation that the negative values and oscillations of the distributions are consequences of coherence and finite wavelength, different distributions would lead to apparently different coherence properties when viewed in the same phase space. The situation gets worse when we compare the evolution of the distributions upon z-propagation (Littlejohn and Winston, 1993).

Because of the ties between these two problems, one would thus expect that a rigorous theory which has a mechanism for resolving one of these problems should also resolve the other one using the same mechanism. We belief that we have such a mechanism as embodied in the idea of the instrument function. The mechanism fits into the existing theory of generalized radiance as follows. One would view the distributions as forming half the story. To complete the story, the generalized distributions will have to be convolved with another distribution in phase space characterizing the instrument, forming an expectation value, in order to arrive at a result that can be compared with experiment. This idea allows one to associate the signal coming out of a radiometer with the expectation value between two generalized distributions, corresponding to the transverse wavefield and the observable, the flux entering the radiometer in this case.

How does this idea solve the problem of negative probability and at the same time unify the various definitions of generalized radiance? To answer that question, we need to bring in the formalism that associates operators in Hilbert space and distributions in phase space.

We give here a brief synopsis of the formalism base on the papers by Balazs and Jennings (1984), Royer (1977), and Littlejohn (1986), and discuss how it fits into the problems of non-uniqueness of definition and negative radiance. The summary will be on the case of 1-dim transverse position. Our phase space is then a 2-dimensional x-k space where k is the transverse wavenumber. The cases of higher dimensionality are easily generalizable. Since the definitions of generalized distributions in phase space are not unique we will refer to them as representations in phase space. Attention will be confined to the two definitions of radiance introduced by Walther (1968,1973), since other representations can be handled in the same manner.

We make a distinction between generalized radiances and generalized distributions in phase space. Generalized radiances are defined as

$$B(x,k) = c \cos\theta \left(\frac{k_o}{2\pi}\right)^2 D(x,k), \tag{4.1}$$

where D(x,k) is the generalized distribution in a particular representation, θ is the angle between the wavevector and the longitudinal direction, the z-axis, k_o is the free-space wavenumber, and c is the speed of light in vacuum. Walther's first definition of radiance (Walther, 1968), is defined using the Wigner function as the representation for the distribution, and Walther's second definition (Walther,1973), is defined using the real part of the Kirkwood function as the representation for the distribution. The Wigner and the Kirkwood functions were first introduced to deal with functions of non-commuting observables in the context of quantum mechanics in phase space and its association with classical Hamiltonian mechanics and are defined in Balazs and Jennings (1984). We will concentrate our studies on generalized distributions but not on generalized radiances. The reasons will become clear later.

Let $\hat{\Gamma}$ be the operator corresponding to the cross-correlation function

$$<x|\,\hat{\Gamma}\,|x'> = \Gamma(x,x') \tag{4.2}$$

$\hat{\Gamma}$ is the analog of the density matrix in quantum mechanics and has exactly the same properties. If we write the expressions out in terms of wave-functions they become indistinguishable.

The Wigner function and the Kirkwood function, in the operator formalism, are given by:

$$W(x, k) = \mathrm{Tr}(\hat{\Delta}(x, k)\,\hat{\Gamma}) \tag{4.3}$$

for the Wigner function, and

$$A^{+}(x, k) = \mathrm{Tr}(\hat{\Delta}_{\bar{K}}(x, k)\,\hat{\Gamma}) \tag{4.4}$$

for the Kirkwood function. The operators $\hat{\Delta}(x,k)$ and $\hat{\Delta}_{\bar{K}}(x, k)$ are given by:

$$\hat{\Delta}(x,k) = 2T(x,k)\;\Pi\,T^{\dagger}(x,k) \tag{4.5}$$

$$\hat{\Delta}_{\bar{K}}(x,k) = (2\pi)T(x,k)\,\delta(\hat{x})\delta(\hat{k})\,T^{\dagger}(x,k) \tag{4.6}$$

where T(x,k) is the translation operator in phase space, and Π is the parity operator. We will call the operators, $\hat{\Delta}(x,k)$ the basis in the Wigner representation. It is clear that the Wigner function is a real function and that the Kirkwood function is a complex function with respect to (x,k).

One can express $\hat{\Gamma}$ in terms of W(x,k) as

$$\hat{\Gamma} = \frac{1}{2\pi}\int dx\,dk\,W(x,k)\,\hat{\Delta}(x,k) \tag{4.7}$$

This follows from equation (4.3) and the fact that the operator $\hat{\Delta}(x,k)$ is its own inverse basis. By this we mean that

$$\mathrm{Tr}(\,\hat{\Delta}(x,k)\;\hat{\Delta}(x',k')\,) = (2\pi)\delta(x-x')\delta(k-k') \tag{4.8}$$

One can also express $\hat{\Gamma}$ in terms of $A^{+}(x, k)$ as

$$\hat{\Gamma} = \frac{1}{2\pi}\int dxdk\;\; A^{+}(x,k)\hat{\Delta}_{K}^{+}(x,k), \tag{4.9}$$

where $\hat{\Delta}_{K}^{+}$ (x, k) is the Hermitian conjugate of $\hat{\Delta}_{\bar{K}}$ (x,k) and is its inverse basis,

$$\mathrm{Tr}(\,\hat{\Delta}_{K}^{+}(x,k)\;\hat{\Delta}_{K}^{+}(x',k')\,) = (2\pi)\delta(x-x')\delta(k-k') \tag{4.10}$$

We will call the operators $\hat{\Delta}_{\underset{K}{+}}(x,k)$ the basis in the Kirkwood representation. Another way of writing $\hat{\Gamma}$ is

$$\hat{\Gamma} = \frac{1}{2\pi}\int dxdk\;\; A^{-}(x,k)\hat{\Delta}_{K}^{-}(x,k), \tag{4.11}$$

where $A^{-}(x, k)$ is the complex conjugate of $A^{+}(x, k)$. Any operator in Hilbert space can be expanded as in equations (4.7) , (4.9), and (4.11).

The value of the Wigner function at the point (x,k) is the expectation value of the Hermitian operator, $\hat{\Delta}(x,k)$, which is parameterized by x and k through the translation operator. Different x and k gives rise to a different operator. We write the Wigner function in the form of equation (3) for the following reason. From equation (7) we see that the points (x,k) are to be interpreted as labels. For a given (x,k), W(x,k) is the expansion coefficient corresponding to the operator $\hat{\Delta}(x,k)$ for the operator $\hat{\Gamma}$. The points (x,k) constitute a "mock" phase space, (Balazs and Jennings,1984), in the Wigner representation. This phase space does not have, as of yet, any geometrical structure unlike classical phase space which has a symplectic geometry. Any geometrical structure that this phase space might possess must be endowed by the unitary transformations in Hilbert space. The same can be said of the Kirkwood function. It thus makes no sense to compare generalized distributions corresponding to different representations.

From (4.7) and (4.8), the expectation value of an operator $\hat{M}$ is given by

$$\mathrm{Tr}(\hat{\Gamma}\hat{M}) = \frac{1}{2\pi}\int dxdk W(x,k)\, M_W(x,k) \tag{4.12}$$

in the basis of the Wigner representation. From (4.9) and (4.10), the expectation value of $\hat{M}$ in the basis of the Kirkwood representation is given by

$$\mathrm{Tr}(\hat{\Gamma}\hat{M}) = \frac{1}{2\pi}\int dxdk A^{+}(x,k) M_{\bar{K}}(x,k) = \frac{1}{2\pi}\int dxdk A^{-}(x,k) M_{\underline{K}}(x,k) \tag{4.13}$$

We now come to the reason of why we chose to discuss the Kirkwood function instead of the real part of it, sometimes known as Rivier ordering, which is associated with Walther's second definition of radiance. It is given by,

$$R(x,k) = \mathrm{Tr}[\frac{1}{2}\,(\hat{\Delta}_{\underline{K}}(x,k) + \hat{\Delta}_{\bar{K}}(x,k))\,\hat{\Gamma}] \tag{4.14}$$

The operator appearing beside $\hat{\Gamma}$ in the trace is the easiest way of writing an operator corresponding to a shifted delta function in phase space. Unfortunately, it does not have an inverse basis so that a trace between two operators can not be written as an expectation value between two distribution functions in phase space.

Different representations can be related to each other. In particular the Wigner distribution and the Kirkwood distribution are related as

$$A^{+}(x,k) = \exp[\frac{i}{2}\,\hat{D}]\,W(x,k) \tag{4.15}$$

and

$$W(x,k) = \exp[-\frac{i}{2}\,\hat{D}]\,A^{+}(x,k) \tag{4.16}$$

where

$$\hat{D} = \frac{\partial^2}{\partial k \partial x} \tag{4.17}$$

is a differential operator in phase space.

If we want to maintain the meaning of the overlap integral in phase space as a representation independent expectation value then changing the representation in phase space of the distribution for the transverse wavefield from Wigner to Kirkwood necessitates changing the distribution for the instrument from the Wigner representation to the Kirkwood representation by applying equation (4.15). This is analogous to the case in quantum mechanics where we change from one representation to another via an unitary transformation keeping matrix elements the same. The analog of the unitary transformation would be the transform equations(15) and(16). Letting $\hat{M}$ be the operator corresponding to the instrument, we then have the output signal of the instrument,

$$Q = \mathrm{Tr}(\hat{\Gamma}\hat{M}) \tag{4.18}$$

being the representation independent expectation value. The idea of the instrument function corresponds to an observable having positive eigenvalues; thus radiance measurement, as follows from this theory, will be positive. By taking into account the measurement process, each representation yields the same answer making the decision of which representation to use a matter of convenience or a matter of appeal when making contact with classical radiometry, a subject based on geometrical optics in phase space.

Having gathered all the mathematical tools, we will now furnish an explanation as to why the discussion has been concentrated on generalized distributions rather than on generalized radiances. We will begin by saying that our perspective of and approach to the subject are fundamentally different from the hitherto taken course in the study of this subject. We ask the question of how the concept of radiance fits into the theory of partial coherence instead of how partial coherence can be used to extend the concept of radiance from its native environment of geometrical optics to wave optics. In our perspective, the main physical entities are $\hat{\Gamma}$ and $\hat{O}$, which stands for any physical observable, and any physical measurement or quantity is to be represented by an operator corresponding to it. For example, the operator corresponding to the z-component of the energy flux is given by

$$\hat{J}_z(x) = \frac{c}{2k_o}(|x><x|\hat{H} + \hat{H}|x><x|) \tag{4.19}$$

where $\hat{H}$ is the ray Hamiltonian,

$$\hat{H} = -\sqrt{k_{o^2} - \hat{k}^2} \tag{4.20}$$

The operator corresponding to the $\perp$-component of the energy flux is given by

$$\hat{J}_\perp(x) = \frac{c}{2k_o}(|x><x|\hat{k} + \hat{k}|x><x|)\,. \tag{4.21}$$

The cosine factor which relates the generalized radiance to generalized distribution can in certain circumstances, depending on the specific representation employed, on $\hat{\Gamma}$, and on the physical observable being considered, be compensated for by the operator corresponding to the physical observable. The z-component of the energy flux serves to illustrate this point.

The z-component of the energy flux is

$$J_z(x) = \mathrm{Tr}(\hat{J}_z(x)\,\hat{\Gamma}). \tag{4.22}$$

This expression agrees, as shown in Littlejohn and Winston (1993) , with the fundamental expression for the flux

$$J_z(x) = \frac{c}{k_o}\ \mathrm{Im}\ \frac{\partial\psi(x)}{\partial z}\psi^*(x) \tag{4.23}$$

It also agrees with the z-component of the energy flux as obtained using Walther's second definition of radiance,

$$J_z(x) = \int(\cos\theta)B(x,k)dW \tag{4.24}$$

with B(x,k) given by

$$B(x,k) = c\cos\theta\left(\frac{k}{2\pi}\right)^2 \mathrm{Re}(A^+(x,k)) \tag{4.25}$$

But as we already remarked, there is no inverse basis for Rivier ordering. Therefore, even though Walther's second definition of radiance gives the right result for the flux, it still has the problem of negative radiance. Also because Rivier ordering does not have an inverse basis, there is no transformation which can convert it to other representations (Balazs and Jennings, 1984). On the other hand, if one had used Walther's first definition of radiance, using the Wigner representation for the distribution,

$$J_z(x) = \int(\cos\theta)B(x,k)d\Omega$$

with B(x,k) given by

$$B(x,k) = c\cos\theta\left(\frac{k}{2\pi}\right)^2 W(x,k) \tag{4.26}$$

the result would be in conflict with the fundamental expression (4.23), (Littlejohn and Winston, 1993) . This serves as an example of the difficulty one encounters when emphasis is placed on generalized radiances and not on generalized distributions. Different physical results are obtained for different definitions. One can say that this approach is representation dependent. All definitions, however, agree when one consider quasi-homogenous sources. For the case of the ⊥-component of the flux, all the above definitions agree as well.

The theory of non-classical radiance, when emphasis is placed on generalized distributions and incorporating the idea of associating an operator for a physical observable or a measurement, shares the same structure as the study of quantum mechanics in phase space. Another motivation for choosing generalized distributions as the object to be studied is that generalized distributions have the aforementioned transformation properties relating different representations. There does not appear to be one for generalized radiances. This comes back to the point that generalized radiance is a representation dependent concept.

Having expounded that our approach is representation independent, we next ask: Of the two phase-space representations under study which one possesses a geometrical structure closer to that of geometrical optics. As already mentioned, geometrical optics in phase space has a symplectic geometry. We want a representation such that transformations of distributions base upon geometrical optics in phase-space (classical Hamiltonian mechanics) would serve as a good approximation. The incentives are that there is more intuitive appeal as well as ease of calculation. In the paper by Littlejohn and Winston (1993), it is shown that the Wigner function is much more conserved along rays than the Kirkwood function. This implies that the "mock" phase space of the Wigner representation retains more of the geometrical structure of classical phase space.

In fact there is an interesting group of unitary operators, *Mp(2N)*, the metaplectic group, which are parameterized by linear symplectic matrices, *Sp(2N)*, such that when an element of it acts on a state, $|\psi\rangle$, which represents the transverse wavefield, it gives rise to a fresnel optic type expression that is associated with the particular linear symplectic transformation of geometrical optic parameterizing that element of the metaplectic operator (Guillemin and Sternberg, 1984). What is even more interesting is that the Wigner distribution corresponding to the correlation function of the resulting wavefield is that which would have been obtained had we simply evolve the original Wigner distribution according to the rules of geometrical optic by the linear symplectic matrix. The Wigner function retains its functional form under metaplectic transformation of the wavefunction, and the result is the same as would be obtained had we used Gaussian optics for a classical radiance distribution.

The approximations implicit in the metaplectic operators when they act on a state $|\psi\rangle$, are the same as those contained in fresnel optic. This geometrical structure of the "mock" phase space of the Wigner representation will be important when we test our theory of non-classical radiance to cases where diffraction effects become important.

4.4.2 Experimental Test

The introduction of the "instrument function-" serves to describe the characteristics of the measuring instrument in a manner which is symmetric to the radiance function. Measuring radiance is represented as the integral of the product. It is a basic property of these functions that the result is non-negative definite, a physically appealing property not share by radiance alone. The most recent work on this topic has just been reported (Littlejohn and Winston, 1997)). In particular, this will allow us to have a firm fix on the concept of radiance in terms of partial coherence. It is known that partial coherence can be directly related to the density matrix of the scalar wavefield. We interpret the measured radiance as the trace between the density matrix of the radiation field and the operator corresponding to the instrument.

The scheme we are proposing is to first measure the instrument function, perform a calculation of the Wigner function of the radiation field, do the overlap integral in phase space between the two functions, and check with the experimental result. The type of the experiment we will first try, once the theory of measuring the instrument function is worked out and checked on a computer simulation, is a scanning experiment. We will scan the edge of a semi-infinite blackbody source using a radiometer, whose instrument function will be measured, and measure the radiance. The edge of the semi-infinite blackbody source is known to be untreatable by a quasi-homogenous calculation. A preliminary version of this experiment was performed by Winston and Welford and documented in an unpublished paper. The experimental result that they obtained clearly disagrees with the present theories of radiance defined in terms of partial coherence. It is interesting to note that this scanning experiment (of Winston and Welford) is reminiscent of a near-field experiment, thus it appears possible to extend the concept of the instrument function to a rigorous method of calibrating a near-field probe operating in the dual collection-source mode.

Measuring the Density Matrix of Wavefield vs. Measuring the Instrument Function: The general method of measuring the density matrix or Wigner function of a wavefield is discussed in Janicke, and Wilkens, (1995); Kurtsiefer, Pfau, Mlynek, (1997); Freyberger, Bardroff, Leichtle, Schrade, and Schleich (1997)) and Raymer, Beck, and McAlister (1994). There are several distinctive features separating the methods of measuring the Wigner function corresponding to the density matrix of a wave field and measuring the Wigner function of an operator corresponding to an instrument. The measurements for the case of the wavefield utilize the rotation of the Wigner function of the wave field with the axis of the phase space remaining fix and then projecting the resulting distribution on to the position axis. For the case of the instrument, it is the distribution corresponding to the operator that remains fixed, but the axes are rotated. The rotation of an axis is performed by first introducing a new axis. This is accomplished by sending in a plane wave, which has a Wigner distribution with support along a horizontal line, taken to be the new axis. The plane wave is then sent through the same optical setup used in the measurement of the phase-space distribution of the wavefield resulting in a rotation of the new axis. The inverse Radon transformation algorithms can then be employed to obtain the distribution corresponding to the instrument.

The methods of Metaplectic operators and symplectic matrices are useful in understanding rotations of distributions in phase space, and therefore very useful in the theory of Radon transforms. Metaplectic operators, with the symplectic matrices taken to be the optical element matrices, when used to find the evolution of the wave field, gives the same result as the fresnel integrals for the cases of free space propagation and propagating through a lens. Its a lot faster method when one does not care about transforming the resulting distribution back to the position-space representation.

It's important to point out that calibration of an instrument using plane waves is insufficient in unraveling the operator corresponding to it for the reason of not being able to acquire the off diagonal matrix elements when the operator is written in the representation of plane waves. The pressing problem at this stage is to find the right parameters for an optical beam that will serve as a good approximation for a delta function when performing tomography on a phase-space distribution in the theory of Radon transformations.

We have just begun a project to test these ideas experimentally in collaboration with optical scientists at The Naval Research Laboratory (NRL). In the theory side we will use a simple model for the operator corresponding to the instrument (Littlejohn and Winston, 1995), and taking the generalized distribution for the transverse wavefield to be that of a blackbody source restricted by a slit, a decidedly non-quasi-homogenous source. We will use the sinc correlation, obtainable from Quantum Electrodynamics, to calculate the Wigner distribution of the blackbody source restricted by an adjustable slit. On the experimental side we will use a blackbody source and a continuous variable filter to select a wavelength of 12μm. We have an adjustable slit whose width can be determined to an accuracy of 10μm. We will use an infrared radiometer as our instrument. Since the acceptance angle of a radiometer is very small, 1 mrad, one can use the metaplectic operators to evolve the wavefield along the optic axis. Some preliminary data from very recent measurements at NRL and a photograph of the apparatus is attached in Appendix III.

4.5 Collaboration with Industrial Partner (SAIC)

In response to the Department of Energy Program Notice 97-15, in early 1998 our group submitted a proposal in collaboration with Science Applications International Corporation that described a three year research project to explore and develop some new types of nonimaging optical devices with exciting properties. These devices, expected to be able to provide substantial improvements in energy throughput in a broad variety of radiant energy transfer applications, including illumination systems, projection optics, fiber optics and solar concentrators. Following review of that proposal, the project was approved and initially funded for one year through our current grant.

This effort was carried out in collaboration with members of the Advanced Technology division at Science Applications International Corporation (SAIC) in San Diego, California, who have independently developed some new and very powerful techniques for the systematic design of nonimaging optical elements. In particular, it has recently been discovered that the introduction of controlled symmetry breaking surfaces into baseline structures, that would be fully symmetric under the usual "classical" nonimaging design principles, has resulted in the ability to affect the brightness and skewness distributions of propagating bundles of light rays in heretofore unimagined ways, resulting in devices with properties previously thought impossible. Also the application of global optimization algorithms to problems solved by "classical" nonimaging solutions such as the Compound Parabolic Concentrator (CPC), has shown that, for certain applications, there exist even better solutions. The application of these new approaches to several previously unexplored and challenging problems in nonimaging design offers the promise of significant increases in system efficiency with important practical application.

4.5.1 Background and Scope.

These new research efforts aim to apply the new developed techniques of

1) the introduction of controlled, graduated symmetry breaking surfaces, and
2) global optimization algorithms

to the following specific problems.

a) Extension of the concepts similar to those in the projection optics systems described below (with symmetry breaking star-shaped cross-section) to rectangular receivers (such as liquid crystal diode display apertures). This important application to projection optics requires that we must now consider the added complication whereby not only are the optics nonrotationally symmetric but the target is also nonrotationally symmetric.

b) The optimization of three-dimensional rotationally symmetric Dielectric Totally Internally Reflecting Concentrators (DTIRCs) (Winston, 1991) to maximize throughput and sharpness of angular cut-off.

c) Investigation of the properties of compact folded optics in nonimaging devices (Benitez and Minano, 1995) for efficient light coupling systems.

d) The design of a trough-like concentrator with broken translational symmetry with the goal of generating three dimensional acceptance properties that will permit more effective stationary concentration of sunlight throughout the calendar year than is possible with current designs.

4.5.1.1 Controlled Symmetry Breaking.

The introduction of controlled, graduated symmetry breaking was first described by Shatz, Bortz, Ries, Winston (1997). The key idea was to remove the constraint of rotational invariance. The challenge was to solve a classic problem in nonimaging optics: transforming a spherical source into a beam. Although both source and beam are rotationally symmetric, a rotationally symmetric design imposes mutually incompatible constraints. From étendue conservation, $r \sin ø = 2R$, where r is the beam radius, R the source radius and ø the beam divergence (the factor 2 comes from comparing the sphere area with the beam area). From skew invariance, $r \sin ø = R$ (no factor 2!) so that there is an incompatibility. The solution is to break rotational symmetry.

4.5.1.2 Global Optimization Algorithms.

Global optimization algorithms were first described by Shatz and Bortz (1995). The algorithms used differ from the traditional methods of nonimaging optics in that they are non-local. The traditional design methods employ a differential equation to match, say the edge ray of the source to the edge ray of the target. The global optimization algorithms vary all coordinates of the design simultaneously. Although the method is inherently numerical, not analytic, the approach can lead to attaining higher levels of performance. The above reference showed a small improvement over the rotational compound parabolic concentrator (CPC), the most classic of all nonimaging designs.

The method is based on an inverse engineering topological-axiomatic approach applicable to nonimaging optical design. The reflective and/or refractive surfaces of the optics are sequentially modified within a given parameterization scheme and a constraint set until performance objective global optimality, evaluated upon a system radiometric model, is achieved. This formalism permits study of non-concave, reentrant, and piecewise continuous reflector and lens configurations that can constructively exploit multiple reflections for maximal energy transfer, beam shaping, or irradiance redistribution. A new variational principle was derived for constructing axially symmetric reflector forms that maximizes energy transfer . This principle operates under a single-reflection approximation and can be extended to provide optimal beam shaping. The derivation accounts for generally shaped sources with arbitrary radiance distributions and for reflection losses.

The performance of known edge-ray designs was compared with our solutions showing that the 3D CPC concentrator and the 3D involute CPC reflector (operated in reverse as a projector) can be improved upon. A projective design, employing a spherical source, was presented, which makes use of source reenergization through retroreflection. This design achieves a beam radiance greater than that of the (naked) source and requires a reentrant component, if a requirement for continuity of the reflective surface is imposed. While it was recognized from the start that that rotational version of the ideal 2-D compound parabolic concentrator was not ideal, its performance was so close to ideal that it remained unaltered for the 30 years since its invention. Now, thanks to global optimization, this design has been improved. The global optimization method promises to improve on other nonimaging designs as well. In some cases by much larger margins than was demonstrated in the 3-D rotational CPC.

4.5.2. Potential Applications.

4.5.2.1 Projection Optics Systems for Rectangular Apertures

The primary goal of many nonimaging optical design problems is to transfer as much radiant flux as possible from a source to a specified target. In the past, it has been common practice to restrict solutions to nonimaging optical systems which possess a high degree of symmetry, such as rotational symmetry. The use of symmetrical forms simplifies the design process and can in some cases produce solutions that provably achieve optimality. However, it has recently been demonstrated by researchers at the University of Chicago, working in collaboration with SAIC, that in other important cases of practical interest this imposed symmetry may severely limit the achievable power-transfer efficiency.

The recent achievement by the U of Chicago - SAIC team has been the discovery of the benefits of symmetry breaking for projection optics (Shatz, Bortz, Ries, and Winston, 1997). It has been shown that by incorporating reflectors having a novel star-shaped cross section in projection optics the efficiency may be almost doubled. These results were achieved for a circular receiver. In practice many receivers, such as film gates and liquid crystal diode display units, are rectangular in shape. Therefore, in order to further capitalize upon this result it is important to extend this concept to rectangular receivers. This means that we must now consider the added complication whereby not only are the optics nonrotationally symmetric but the target is also nonrotationally symmetric.

<u>Optimization of 3D reflectors for use with spherical sources</u>

We first turned our attention to the problem of designing an optimal reflector for projection of energy from a spherical Lambertian source into an emergent conical beam. The 2D involute CPC is an edge-ray solution capable of collecting the light incident over a given input acceptance angle and ideally transferring it onto a circular absorber. Consequently, the 3D involute CPC, operated in reverse, constitutes the edge-ray solution for the projection of energy from a spherical source into an emergent conical beam. We investigated the performance of the 3D involute CPC and provide comparisons with designs obtained through global optimization.

Two separate problems were addressed. The first was to determine the profile of a rotationally symmetric optimized spline reflector (OSR) which maximizes energy transfer from a 1-cm-radius spherical Lambertian source into an emergent conical beam subtending a 10° half angle, under the constraint that the exit-aperture area of the OSR equals that of a 3D involute CPC with a design acceptance angle of 10°. The second problem was to determine the OSR profile which maximizes energy transfer from the same source into an emergent conical beam subtending a 6.35° half angle, with the same constraint on aperture size as in the first problem. The particular significance of the 6.35° beam half angle chosen for the second problem will become apparent later in this section. For both problems we assumed a loss-free, specular, axially symmetric continuously differentiable reflector

Our problem statement is as follows: Determine the profile of a rotationally symmetrical 3D optimized spline concentrator (OSC) that maximizes the energy transfer within a given acceptance angle, and that has an entrance aperture diameter of 10 cm and an exit aperture diameter that corresponds to the maximum theoretical 3D concentration ratio for that acceptance angle. The shape profile of the 3D OSR design optimized for a 10°-half-angle beam was determined using the methods developed in Shatz and Bortz (1995). The difference between the shape profile of the 3D OSR and that of a 3D involute CPC small but significant. Plots of the far-field intensity versus angle off-axis for both the 3D OSR and the 3D involute CPC were generated. The 3D OSR maintains a higher beam intensity than the 3D involute CPC, from an off-axis angle of 0° all the way out to 8.4°, and transmits 99.54% of the energy into the 10°-half-angle beam, as compared to 98.87% for the 3D involute CPC. This improvement represents 59% of the residual energy projected by the 3D involute CPC outside the desired 10° zone.

We next turned to the second problem, beginning with an explanation of the rationale behind the decision to maximize the energy transfer into a 6.35°-half-angle beam. In accordance with the conservation of phase-space volume, an ideal 2D nonimaging projector is one which transmits 100% of the rays emitted by a 2D Lambertian source into an emergent fan of half angle θ_{2D}. Similarly, an ideal 3D projector is one which transmits 100% of the rays emitted by a 3D Lambertian source into an emergent conical beam of half angle θ_{3D} where θ_{3D} is referred to as the ideal 3D half angle. The CPC is an ideal 2D projector because it maps 100% of the input phase space to a region of output phase space having an angular half width equal to the ideal 2D half angle $\theta_{2D}=\theta_i$. However, the CPC is *not* an ideal 3D projector because some of the skew rays fall outside the ideal 3D half angle $\theta_{3D}=\theta_i$. Nevertheless, the 3D CPC is nearly ideal due to the fact that the ideal 3D half angle θ_{3D} equals the CPC's design acceptance angle θ_i. Because the 2D CPC is ideal, all of the meridional rays projected by the 3D CPC must fall within an emergent conical beam of half angle θ_{3D}.

For the involute CPC, the situation is different. Like the CPC, the involute CPC is an ideal 2D projector having an ideal 2D half angle equal to its design acceptance angle . In three dimensions the involute CPC is non-ideal, as is the ordinary CPC. However, the involute CPC is non-ideal in a much less benign way than is the ordinary CPC. For the ideal 3D half angle does not equal the design acceptance angle, as it does for the ordinary CPC. This means that, in three dimensions, the involute CPC *does not achieve ideal performance even for the meridional rays*, since the involute CPC projects the meridional rays into a half angle of q_i, which is always greater than the ideal 3D half angle θ_{3D}.

A projector design utilizing source reenergization

It is possible to reduce the volume of the output phase space through the constructive use of reentrant sections and source reenergization through retroreflection. This mechanism can in some cases be used to increase beam intensity for projector designs. However, the introduction of reentrant components into a projection system may have the deleterious effect of diminishing the exit area, thereby decreasing the system's concentration ratio. It also increases the frequency of multiple reflections and reflection losses. However, the concomitant increase in apparent source radiance may more than offset all such losses. This is true only when the physical nature of the source permits efficient recovery and reuse of the energy that is incident upon it.

We next modified the problem statement of the previous section to achieve maximal energy transfer from a 1-cm-radius spherical Lambertian source into a conical beam subtending a 2∞ half angle and introduce source reenergization into the problem. We postulate a reenergization mechanism which assumes that 100% of the rays incident on the source are diffusely reflected back from it. In order to implement the reenergization process we further truncate the 3D involute CPC to an exit-aperture radius of 11.80 cm and attach a reentrant multi-faceted retroreflector which occupies the annular region between 11.80 cm and 12.00 cm relative to the axis of symmetry of the involute CPC. The purpose of the faceted retroreflector is to capture a portion of the rays which would otherwise escape into the halo and return them to the source. This is done by means of a series of annular facets of spherical shape, having their centers of curvature coincident with the center of the source. These annular facets are connected to each other and to the truncated involute CPC by means of a series of annular facets of conical shape. Besides connecting the annular facets, the conical facets serve the purpose of preventing rays from escaping by passing between adjacent spherical facets. The hybrid design achieves an energy-transfer efficiency of 5.68%, which is 29.7% higher than the non-reenergized result.

By demonstrating the existence of designs which improve upon the 3D CPC concentrator and the 3D involute CPC reflector (operated in reverse as a projector), we have shown that the edge-ray method does not guarantee maximal energy transfer in three dimensions. We have also demonstrated a projective design which achieves a beam radiance significantly greater than that of the naked source by constructively exploiting source reenergization.

Introduction of rotational symmetry breaking

Theoretical upper limits on measures of flux-transfer performance due to skewness conservation in rotationally symmetric nonimaging optical systems have recently been discovered and quantified. These limits can have an adverse impact on the performance of projection or coupling optics which collect light from three-dimensional sources. In previous work (Shatz, et. al, 1997) we have shown that these limits can be exceeded by employing nonrotationally symmetric configurations.

A formalism allowing one to compute the upper limit on flux-transfer performance due to skewness conservation in rotationally symmetric nonimaging optical systems was derived. It has been shown that when the target and the source have different skewness distributions, the performance of rotationally symmetric systems can be severely limited in comparison to the upper limits imposed by the conservation of étendue alone. This may adversely impact the performance of projection optics and light coupling devices which rely on the collection of light from three-dimensional sources such as incandescent filaments, high intensity discharge (HID) plasma arcs, etc.

In this work we began to investigate forms designed to break the rotational symmetry, thereby overcoming the aforementioned limitations. As a practical matter we are interested in reflector geometries which on a global scale are close to being rotationally symmetric yet on a local scale possess distinct features which enable them to actively modify the skewness of the reflected rays. The skewness of a ray is proportional to the tangential component of its direction. Therefore the crucial new design feature is the inclination of the local surface normal at a given point on the reflector with respect to a plane which contains both that point and the optical axis. This inclination modifies the skewness of an impacting ray. With this in mind, we consider reflectors for which cross-sections perpendicular to the optical axis are essentially star-shaped. A ray which is reflected has its skewness either increased or decreased by a given amount depending upon which side of the lobe it intersects. For comparison we refer the reader to an analogous problem in which polygonal cross-sections were used for extracting rays from a waveguide. The inclination of the star lobes is primarily responsible for the change in skewness, the dimension of the individual lobes being of secondary importance. In fact, one could investigate the limit in which these lobes are much smaller than the overall dimension of the reflector, yet large enough compared to the wavelength of light that diffraction effects are negligible. In this limit the overall shape of the reflector maintains its rotational symmetry, while its reflective characteristics do not. From a purely probabilistic point of view, such a reflector will tend to spread out the skewness distribution in a way that is analogous to the effect of diffuse scattering on a beam of light. In terms of the skewness distribution, the star-shaped reflector mixes portions of different skewnesses with each other, thereby bringing about a broadening of the distribution. Consequently, when the target has a broader skewness distribution than that of the source, the system performance will benefit from this broadening effect.

We next briefly review the key factors affecting the flux-transfer performance of nonimaging optical designs--such as collection, projection or coupling optics--that utilize three-dimensional sources and/or targets. We list a series of performance limits associated with étendue matching, skewness matching, source and target inhomogeneities, design constraints, design goals and nonidealities. The ultimate performance of the nonimaging system will be driven by some combination of these performance-limiting factors.

Étendue matching. Étendue matching is the single most important consideration in the design of a nonimaging optical system. We define the target-to-source étendue ratio (TSER) as the total target étendue divided by the total source étendue. If the target étendue is smaller than that of the source, then a corresponding fraction of the flux will not go through. If the target étendue is greater than that of the source, then the target phase space will be diluted. As a practical matter, the étendue of the source should be computed based upon an integration of experimental measurements or a valid source model, whereas the étendue of the target can usually be computed using an analytical integration.

Skewness matching. A skewness mismatch between the source and target may cause severe performance losses. In particular, it has been demonstrated that designs based upon classical 2D edge-ray constructions which have been rotated to generate a 3D reflector can fall far short of even the theoretical performance limit of rotationally symmetric optics. A comparison of skewness mismatch between candidate sources and the target can be useful during the design selection process--e.g., a common dilemma is whether to select an on-axis or a transverse filament orientation. Losses due to skewness mismatch may be recovered to a large extent by employing an optimized nonrotationally symmetric design which actively attempts to match the skewness of the source to that of the target.

Source and target inhomogeneities. Source and target inhomogeneities will affect the performance limits. In order to assess these limits, weight functions need to be calculated based upon the source's specific spatial and angular radiance distributions and the target's preferential characteristics.

Design constraints. Real world designs are often subject to constraints. If constraints are active at the optimal design point, then the performance of the system will be adversely affected. Typical design constraints may include minimum source-to-reflector clearance, reflector diameter and length constraints.

Design examples: star concentrators for a spherical and cylindrical sources

We begin by considering a rotationally symmetric reflector. To generate this reflector shape we define a two-dimensional profile, which is then rotated about an axis of symmetry. Many nonimaging optical solutions start with an involute at the apex. The rationale for this is to reflect rays emitted backwards into a forward direction. In phase space these rays are placed adjacent to the region occupied by the source itself such as to appear as a contiguous region to the forward parts of the reflector. The crucial new design feature is the inclination of the local surface normal at a given point on the reflector with respect to a plane which contains both that point and the optical axis. This inclination modifies the skewness of an impacting ray. With this in mind, we consider reflectors for which cross-sections perpendicular to the optical axis are essentially star-shaped. The star-shaped reflector also attempts to place the reflected rays adjacent to the source but at different skewness values. A ray which is reflected has its skewness either increased or decreased by a given amount depending upon which side of the lobe it intersects.

In Shatz, et. al., (1997)) we developed a new parameterization scheme for such star shaped concentrators. By incorporating this parameterization into the global numerical optimization procedures and by considering the problems of maximizing flux transfer from both a homogeneous spherical source and a homogeneous cylindrical source to a homogeneous disk-shaped target of equal étendue, we found that the performance limits due to skewness conservation for these problems can be overcome by numerically optimized reflectors possessing a nonrotationally symmetric star-like cross-section.

Many high-end nonimaging systems such as projection optics and light coupling devices rely upon the ability to efficiently collect light from three-dimensional sources such as incandescent filaments, high intensity discharge plasma arcs, etc. Conventional concentrators perform the function of collecting and concentrating the light. We have introduced a new class of concentrators which also actively modify the skewness of the source to better match that of the target. Examples show that with such nonrotationally symmetric designs it may be possible to double the efficiency of designs generated by rotating 2D classical edge-ray profiles. It is of particular interest to note that even though we have considered cases where both source and target are rotationally symmetrical, it is through the breaking of symmetry that we have achieved the performance gain. Extension of the techniques introduced in this contribution to nonrotationally symmetrical targets such as rectangular apertures will be the focus of this component of the proposed research project.

4.5.2.2 Throughput and Sharpness Of Angular Cut-Off For DTIRC's

As is well known in this field, exact three dimensional solutions are rare (e.g., flow-line solutions). Practical 3-D nonimaging designs are usually rotated 2-D solutions which fall short of providing theoretically maximum performance. An advance in the subject was recently presented by SAIC who have introduced a novel numerical optimization method into nonimaging design (Shatz and Bortz, 1995). The behavior of nonimaging optical systems has recently been developed in terms of properties of mappings and an inverse engineering formalism which provides a framework within which nonimaging optical designs can be optimized was presented. A new variational principle for use in the optimization of nonimaging systems was also introduced . This is an inverse engineering topological-axiomatic approach which employs a variational principle and numerical optimization for optimizing power transfer, beam shaping or irradiance redistribution. This represents a fundamental advance in nonimaging design methods.

<u>Mappings In Nonimaging Optics</u>

In the geometrical optics approximation, the behavior of a nonimaging optical system can be formulated and studied as a mapping g: $S^{2n} \varnothing S^{2n}$ from input phase space to output phase space, where S is an even-dimensional piecewise differentiable manifold and n is the number of generalized coordinates. The starting point for this formulation is the generalization of Fermat's variational principle, which states that a ray of light propagates through an optical system in such a manner that the time required for it to travel from one point to another is stationary.

Let g be a differentiable mapping. The mapping g is called canonical[1] if g preserves the differential 2-form $w^2 = \Sigma\, dp_i \wedge dq_i$, i=1..n, where q is the generalized coordinate and p is the generalized momentum. Applying the Euler-Lagrange necessary condition to Fermat's principle and also the Legendre transformation, we obtain a canonical Hamiltonian system which defines a vector field on a symplectic manifold (a closed nondegenerate differential 2-form). Now, a vector field on a manifold determines a phase flow, i.e., a one-parameter group of diffeomorphisms (transformations which are differentiable and also possess a differentiable inverse). The phase flow of a Hamiltonian vector field on a symplectic manifold preserves the symplectic structure of phase space and consequently is canonical.

The properties of these mappings can be summarized as follows:

1) The mappings from input phase space to output phase space are piecewise diffeomorphic. Consequently they are one-to-one and onto.

2) The transformation of phase space induced by the phase flow is canonical, i.e., it preserves the differential 2-form.

3) The mappings preserve the integral invariants, known as the Poincaré-Cartan invariants. Geometrically, these invariants are the sums of the oriented volumes of the projections onto the coordinate planes.

4) The mappings preserve the phase-space volume element. The volume of gD is equal to the volume of D, for any region D.

In certain cases, the optical system may cause a section of the input phase space to map onto another section of the input phase space. When that happens, and as a direct consequence of property (4), the volume of the output phase space becomes *smaller* than the volume of the original input phase space. Consequently, depending upon the physical nature of the source (represented by the input phase space) and the extent of the reflective losses, the radiance of the output may become *greater* than that of the original input.

The inverse engineering formalism and global optimization

Suppose one wishes to design an engineering system to achieve certain objectives. The basic axiom of inverse engineering can now be stated as follows: An engineering design problem on a physical system, for which there exist ideal computational models $M_i=P_i$, can be reduced to a set of objectives and a set of constraints. In our experience, the solution topology for a broad range of nonimaging optical design problems has been found to be multi-modal. Consequently, the use of local optimization techniques to accomplish nonimaging optical system design is not advisable. Over the past decade, a branch of optimization has emerged which has come to be known as global optimization. Global optimization algorithms[2-4] can find, under certain regularity conditions, the locations of global optima in multi-modal topologies. Such techniques are therefore generally useful for engineering design, and their use in this context has engendered the term inverse engineering.

The global optimization problem can be formally stated as follows: Minimize $f(d_j,x_n)$, x_n □ R^N subject to the constraint set $h_q(d_j,x_n)$=TRUE, assuming that f is piecewise continuous and exists almost everywhere and that the h_q are piecewise continuous. The problem is to find the global minimum f*, which may not be unique. In other words,

$$f^* = f(d_j,x_n^*) \leq f(d_j,x_n) \quad \text{for all } x_n \;\square\; R_\varepsilon \,, \tag{4.27}$$

where R_ε, for any positive ε, is given by

$$R_\varepsilon(x_n^*) = \{x_n \mid h_q(d_j,x_n) = \text{TRUE}, \| x_n - x_n^* \| \leq \varepsilon, x_n \;\square\; R^N\} \,. \tag{4.28}$$

In the context of nonimaging optical design, the mathematical entities P_i, M_i, d_j, h_q, and x_n take on the following meanings:

□ The P_i represent one or more radiometric or photometric quantities to be optimized, such as transmitted flux incident on a target or a measure of the difference between a delivered irradiance distribution and a required irradiance distribution.

□ The M_i represent the computational models available for calculating the corresponding functions P_i. The functions M_i differ from the P_i in the sense that the M_i can only approximate the physics (e.g., the geometrical optics approximation), and typically are computed using numerical techniques (e.g., a quadrature employing a finite number of rays) which introduce a variance into the calculation of each M_i. This causes the solution topologies to become stochastic.

□ The d_j are problem-specific inputs describing known characteristics of the optical system, such as surface reflectance, the spatial and angular radiance distributions of the radiation source, etc.

□ The h_q are system design constraints, such as length and diameter limitations on the optics, or more complex requirements such as a restriction of the solution to concave or non-reentrant optical forms, etc.

□ The x_n are the independent parameters describing the design of the optical system, such as reflector shape parameters, source location relative to the optical system, choice of material for a refractive component, etc.

<u>A variational principle for reflector design</u>

The first step has been taken towards developing an analytical theory for reflector design. The goal is similar to that of Winston and Ries (1993), but the method is different. The idea is based upon the observation that the interaction of the source with the reflector takes the form of a convolution. The intent is to express the objective function (OF) in the form of an integral, without requiring a ray-trace model, and then to solve for the shape of the reflector by means of variational techniques. There is then derived--under a single-reflection approximation, for generally shaped sources with arbitrary radiance distributions, and accounting for reflection losses--a functional form stating the expression for the energy transferred from a source into a beam.

This technique can also be extended to the beam-shaping problem. Due to the single-reflection assumption, this technique produces approximate solutions. These solutions can be helpful in developing coordinate systems for the parameterization schemes required by global optimization. The global optimization technique used to obtain the results presented in this paper employs an exact ray tracing model which allows multiple reflections.

We propose to apply these new and powerful methods developed by the SAIC group to a variety of problems that would benefit from this approach. The specific example which would have great practical importance and which we have already begun to discuss with the SAIC group is the rotationally symmetric dielectric cone concentrator (or projector) developed by our group in the 1980's. This configuration has many applications both in light collection and illumination, and even a modest improvement in performance is well worth trying for. Other applications include nonrotationally symmetric designs which are important for both illumination and collection applications.

4.5.2.3 Efficient Coupling with Compact Folded Nonimaging Optics

Using a combination of refractive and reflective surfaces, J. C. Minano and his colleagues at the Polytechnic University of Madrid have designed and built very compact illuminators and concentrators (Benitez and Minano, 1995). We will explore applications to light emitting diodes as well as sensors which are very attractive.

4.5.2.4 Stationary Concentrator with Broken Translational Symmetry

The problem of trough concentrators has been of great interest since the original CPC was proposed. The standard CPC achieves at best a geometrical concentration of 1.7X. A recent solution found that higher concentrations can be achieved but one must be willing to sacrifice throughput (Ries, Winston, and Spirkl, 1997). Introduction of symmetry breaking in the longitudinal axis could result in significant improvement.

4.5.3 Potential for Further Development.

This research is expected to lead to the development of several new types of nonimaging optical devices with previously unattainable properties that will result in practical improvements in light transfer efficiency. These devices are expected to be able to provide substantial improvements in energy throughput in a broad variety of radiant energy transfer applications, including illumination systems, projection optics, fiber optics and solar concentrators. The application of these new approaches to several previously unexplored and challenging problems in nonimaging design offers the promise of significant increases in system efficiency with important practical applications. In particular, among other innovations, we hope to be able to achieve increases in projection optics efficiency for rectangular sources and receivers comparable to those already attained for the circular case in which the throughput was almost doubled and also to develop solid dielectric totally internally reflecting solutions whose performance is closer to the thermodynamic limit than has previously been attained. These will be very important for both illumination and collection applications.

4.5.4. Collateral Benefits.

An important benefit of collaborating with a company of the wide capabilities and stature of SAIC is the opportunity to interface with real-world technology challenges that would normally be outside the scope of our academic interactions. One example is the application of nonimaging optics to ultra-fast focal plane arrays. Typical focal plane arrays have numerical aperture (N.A.) of 0.5 or less. Nonimaging designs can have N.A. of n-squared, where n is the index of refraction of the detectors. In the infra-red, where high N.A. is at a great premium, the index of refraction, n is >> 1, possibly 3 to 4. Since the sensitivity of the detection is proportional to N.A. squared, a nonimaging focal plane array can increase sensitivity by orders of magnitude. Detectors are often cryogenically cooled to improve signal/noise. An important consequence is reducing cooling requirements by reducing detector size, hence noise for the same signal. This advantage has been exploited to some extent in far-infrared focal plane arrays for Astronomy, but never really pushed to the theoretical limit. The ultimate benefit would be light-weight, portable infra-red viewers that would not require cryogenic cooling. Another example would be in infra-red jammers for countermeasures. Nonimaging optics has already been demonstrated to enhance the performance (Proc. Nonimaging Optics: Maximum Efficiency Light Transfer). SAIC has also contributed to this area, as described in Appendix 2. Collaboration in this area was a natural extension of our earlier work and contacts.

5.0 Recent Developments in Statistical Optics and Wave Effects in Radiative Transfer

Radiative transfer is an important subject with applications in astronomy and astrophysics, particle beam physics, medical physics, and machine vision. Yet, it is still grounded in geometrical optics. Central to the subject is the quantity radiance, sometimes referred to as the brightness, and the equation of transfer. The equation of transfer is an analogue of the Boltzmann equation in classical statistical mechanics with radiance serving as the distribution. The distribution, however, is a power distribution rather than a probability distribution. As a distribution radiance can used to calculate the energy density, the energy flux density, and the radiation pressure as a function of position.

Attempts have been made in constructing the foundation of radiative transfer by defining a generalized radiance based on the two-point correlation function of the wavefield. The equation of transfer, Boltzmann equation for light, would then result from Helmholtz equation and the definition for generalized radiance. Major contributions along this line of research have been made by A. Walther and E. Wolf. This program, however, is mired in questions about the choices of definitions for the generalized radiance.

In our work on radiative transfer including statistical optics we've shown the fruitfulness of using Liouville space, the Hilbert space of operators, as the formalism in connecting statistical optics with radiative transfer. The two-point correlation function of statistical optics, $\Gamma(\mathbf{r},\mathbf{r}',\omega)$, where ω is the angular frequency of the radiation field, can be thought of as an operator, an element of Liouville space. The formalism allowed us to circumvent questions regarding the correct choice of definition. It is able to include wave-effects and statistical optics into the subject in a consistent fashion, and retain much of the structure of geometrical optics in phase space. Other presentations of this material have already appeared (Sun, Winston, O'Gallagher, and Snail, 2001a, 2001b).

The formalism allows us to interpret radiance measurement in terms of the statistical properties of the radiation field. This basically results from choosing a phase space representation for the Liouville space, a procedure analogous to that in quantum mechanics where we choose a representation for the Hilbert space of wavefunctions to reveal a particular aspect of the problem under study. The phase space representation that most retains properties of geometrical optics is the Wigner representation. Radiance or brightness is the two-point correlation function in the Wigner representation. An important ingredient in the formalism for it to be consistent with experiment is measurement, despite the fact that this is still classical physics.

The output signal, Q, of a measuring apparatus is associated with the trace between the two-point correlation function of the incident radiation, viewed as an operator, and $\widehat{M}$, a nonnegative-definite Hermitian operator that characterizes the measuring apparatus.

$$Q = \mathrm{Tr}(\hat{\Gamma}\,\widehat{M}) \tag{8}$$

The trace operation is the inner product in Liouville space. The nonnegative-definite condition on $\widehat{M}$ guarantees that the measured signal will be positive. In the Wigner representation, a measurement is given by the overlap between two phase space distributions, one for the radiation field and another for the measuring apparatus.

$$Q = \int \frac{d^2\mathbf{r}_\perp d^2\mathbf{k}_\perp}{(2\pi)^2} \Gamma(\mathbf{r}_\perp,\mathbf{k}_\perp;\omega,z)\, M(\mathbf{r}_\perp,\mathbf{k}_\perp) \tag{9}$$

Here $\mathbf{r}_\perp$ is the transverse displacement vector, $\mathbf{k}_\perp$ is the transverse wave-vector, and z is the longitudinal displacement. Expressed in this form, the trace operation for the signal has the same form as in radiative transfer of geometrical optics. For thermal radiation, to an excellent approximation, $\Gamma(\mathbf{r}_\perp,\mathbf{k}_\perp;\omega,z)$ is equal to its classical distribution, a strip in phase space. Even though the Wigner representation retains much of geometrical optics in phase space, an important caveat is that the phase space distributions can have negative values.

Examples of this are shown in Fig.5 for the 2-d phase space distribution of $\widehat{M}$, the instrument function. In the figure, x is the transverse spatial dimension, k_x is the transverse wavenumber, a is the lens radius, $\kappa = \frac{2\pi\theta_o}{2\lambda}$, θ_o is the full acceptance angle, and N is,

$$N = \frac{d\theta_0 dk_0}{2\pi} = \frac{d\theta_0}{\lambda}; \qquad d = 2a. \tag{10}$$

N is the number of phase-space cells occupied by the instrument in 2-d phase space (a 2-d phase space cell has an area of 2π . The number of spatial modes the instrument projects out is approximately N^2.

Phase space parameters were also identified to characterize a measurement as well as indicating when the formalism will be useful, when we are not in the regime of geometrical optics or plane wave diffraction.

Experiments were performed to test the formalism. An infrared camera was used to scan square blackbody sources whose dimensions and distances from the camera were chosen for the appearance of partial coherence. The condition to be satisfied is for the transverse coherence length of the radiation field, l_s to be smaller than the diameter of the camera lens, d

$$l_s = \frac{\lambda}{\theta_s} <\approx d \ . \tag{11}$$

Here θ_s is the angle subtended by the source at the camera aperture,

$$\theta_s = \frac{D}{z} \tag{12}$$

and D is the linear source size. A phase space parameter characterizing this condition is

$$N_s = \frac{d\theta_s}{\lambda} >\approx 1 \tag{13}$$

Physically N^2 is approximately the number of spatial modes of the radiation reaching the camera aperture.

In comparing experiment with theory, a normalization was needed to circumvent the problem of obtaining absolute power levels. The normalization is the following: If the phase space domain of the instrument function lies entirely within the phase space domain of Γ, then the normalized signal, $Q = 1$. If the phase space domain of the instrument function lies entirely outside the phase space domain of Γ then $Q = 0$. This corresponds physically to the following procedure in processing the data. The value of the signal when the detector of the camera is flood illuminated by the blackbody radiation (corresponding to the instrument function been completely inside the phase space domain of Γ minus the value of the signal when the detector is flood illuminated by the background (corresponding to the instrument function been completely outside the phase space domain of Γ is the normalization.

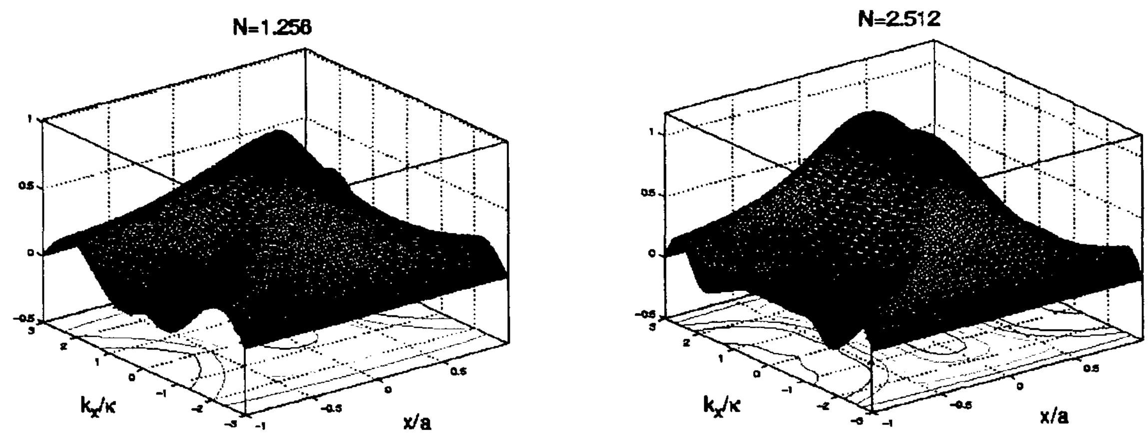

Fig 5. Instrument functions for N=1.256 and N=2.512 in 2-d phase space. Note that for N=1.256 there is one hump corresponding to approximately one state and two humps for N=2.512 corresponding to approximately two states. Both instrument functions have negative values and extend beyond the classical limits of $\left|\frac{k_x}{\kappa}\right| = 1$.

Data for a normalized scan of a $D = 9.53$ cm square blackbody source at $z = 18.3$ m plotted against theory for $N = 2.512$ is shown in Fig. 6. Data for the measurements of the peaks of the scans as a function of N_s are plotted with theory for $N = 2.512$ in Fig.7. For the larger N_s values, the source size was kept fixed at $D = 9.53$ cm while z was increased to reduce N_s.

In pinning down the smaller N_s values in Fig.7 we made measurements for cases where we are effectively at far field. For these measurements, the distance was kept fixed at z =38.2m, and the source size was varied from 1.27cm to 10.16cm.

If the peak measurements are utilized as means of measuring distance using a source of known size through measuring the signal strength, then the geometrical optics approximation always yield a longer distance at a given signal strength. Equivalently, for a known distance between source and instrument, the geometrical optics approximation yield a smaller source size compare with theory and experiment at a given signal strength.

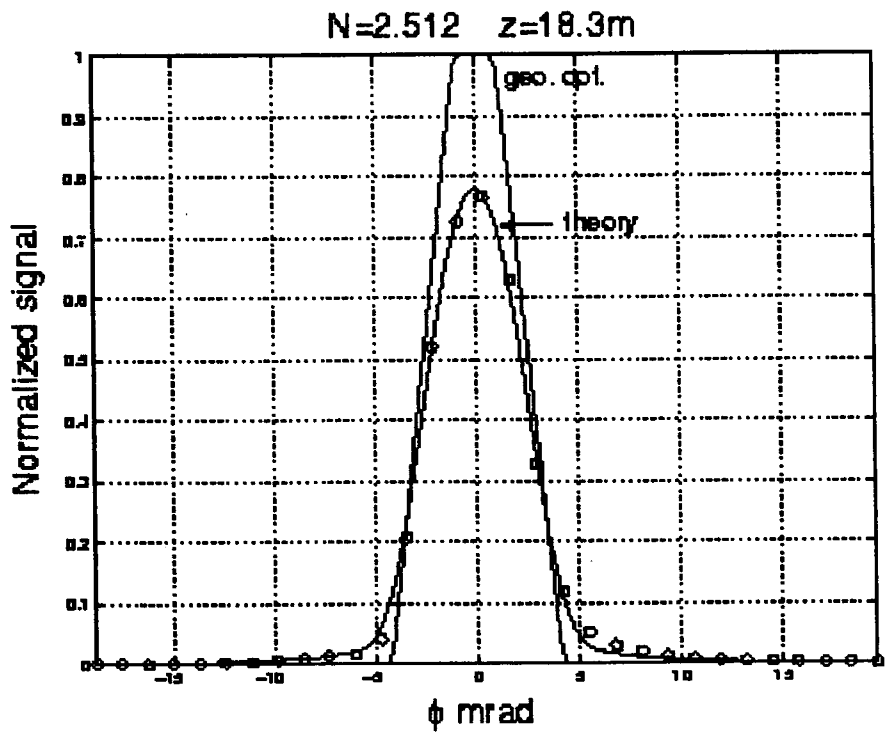

Fig. 6. Comparison of experiment with theory for the scan profile of a square blackbody source of dimension 9.53cm located at $z = 18.3$m away from a camera with $N = 2.512$. The camera has an acceptance angle of $\theta_0 = 3.2$mrad. Data points are open circles.

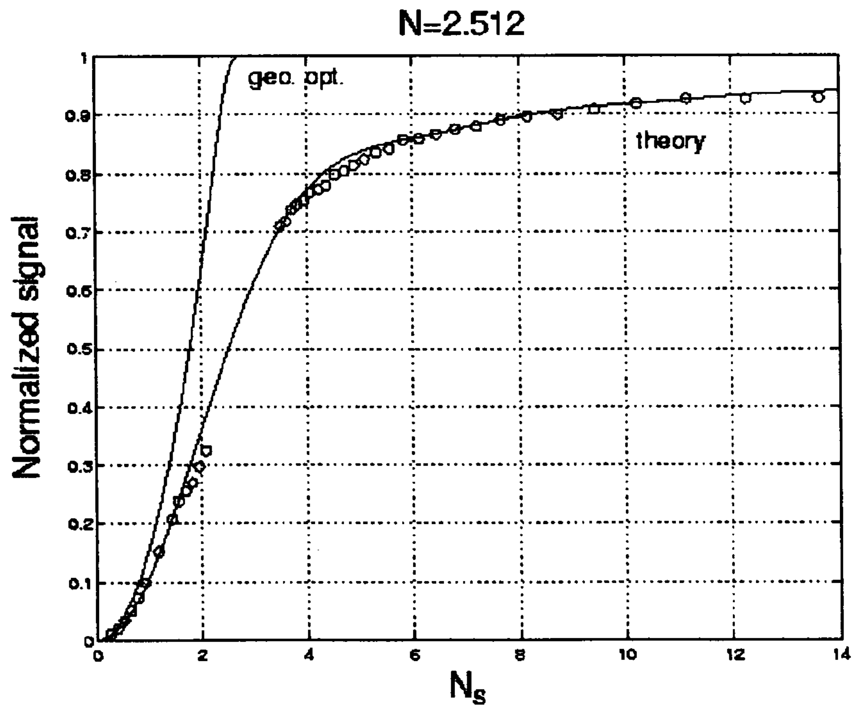

Fig. 7. Comparison of experiment with theory for the $N = 2.512$ far-field envelope. Open circles are data points.

The theoretical curves were calculated using an one-dimensional model for the instrument and squaring the result of Eq.(8). One difficulty in using Eq.(8)is that it may not be easy to compute **c** let alone its Wigner representation. Although the one-dimensional calculation was not too hard, we do not expect it to be easy to compute the instrument function for many realistic radiometers, which are two-dimensional in cross section and which may have complicated geometry.

There is, however, a physical interpretation of the instrument function which is similar to the van~Cittert-Zernike theorem that is useful in obtaining $\widehat{M}$. Knowing the importance of measurement in radiative transfer and signal detection led us to discover this remarkable analogy between the measurement of radiance and the well known van Cittert-Zernike Theorem. We exploited the symmetry between an incoherent source whose radiance is being measured, and the detector whose signal represents the measurement. In fact, the measured radiance is represented(up to an overall constant) by the double integral over the instrument aperture of the mutual intensity of the field and the mutual intensity of a delta correlated source the same size, shape and location as the detector. While we have expressed our results in the context of radiometry, one would go through a similar analysis in analyzing the detection of any partially coherent wave. The signal is represented by the double integral of twoo mutual coherence functions. One of these is for the incident wave, the other arising from the detector considered as a source. It is likely that entirely similar considerations may apply to other signal detection processes.

Working with our colleague, Dale Fixen, we are investigating the problem of optimizing microwave antennas and single mode optical couplers using a combination of principles: non-imaging optics, Feynman's path integral, phase space parameters to characterize a coupler or an antenna, and the symmetry between an incoherent source and a detector. Besides applications in communication systems, the results have some bearing to near-field optics. The problem there is to optimize the transfer of electromagnetic energy from a single mode fiber to a Bethe hole placed at the end of the fiber.

Near-field optics is of importance in coupling electromagnetic energy between single mode fibers and a nano-optical device. This is the research direction we are heading. In the broad picture, our research in radiative transfer has evolved from putting the problem in the framework of phase space, incorporating wave-effects into the framework, optimizing passive optical components based on the framework, and leading to the consideration of how these concepts apply to the regime where the dimensionality of the problem, d, is of order $d \leq \lambda/10$. In this regime, we have a transition from radiation to, essentially, static electromagnetic oscillations.

Our group at The University of Chicago has a tradition of distinguished visiting scientists who have made major contributions to the development of nonimaging optics. This started some 20 years ago with annual visits by the late Walter Welford of Imperial College. Our current visiting scientists include Robert G. Littlejohn, The University of California, Berkeley, and Dale Fixen of the Goddard Space Flight Center. With Littlejohn, our group has clarified the methodology of formulating and measuring phase space distributions (called "radiance" in optics) and we have been exploring a remarkable analogy between the measurement of radiance and the well-known van Cittert-Zernike Theorem. With Fixen, we are investigating the problem of optimizing microwave antennas and single mode optical couplers using a combination of principles: non-imaging optics, Feynman's path integral, phase space parameters to characterize a coupler or an antenna, and the symmetry between an incoherent source and a detector.

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