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SOME GEOMETRIC QUANTITIES USED IN MILITARY INFRARED TECHNOLOGY

AEROSPACE TARGETS BRANCH
AIR-TO-AIR MISSILES AND TARGETS DIVISION

TECHNICAL REPORT AFATL-TR-72-216

NOVEMBER 1972

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Some Geometric Quantities Used in Military Infrared Technology

Richard C. Burnett

FOREWORD

This technical report did not result from a specific Air Force project but is a general discussion of the geometric quantities associated with infrared technology. The information is intended as reference material for personnel involved in the development, test, and evaluation of infrared-sensitive weapon systems, as well as the development and test of infrared augmentation devices.

A significant portion of this material presented in this report was derived from the unpublished notes of Mr. Conrad M. Phillippi, former chief of the Applied Physics Branch at the Armament Development and Test Center, Eglin Air Force Base, Florida.

This technical report has been reviewed and is approved.

WILLIAM W. METZ, Chief
Air to Air Missiles and Targets Division

ABSTRACT

Infrared concepts and terminology are discussed with emphasis on spherical and plane surface radiators, steradians, radiant emittance, radiance, irradiance, and radiant intensity and on their relationships to each other. Although by no means a comprehensive treatment of these subjects or of military infrared in general, a better understanding of the geometric concepts outlined should be beneficial to personnel involved in infrared related programs.

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SECTION I

INTRODUCTION

Of the many disciplines involved in the development of air to air missiles and targets, infrared continues to maintain a rather dubious distinction of being considered the most closely associated with "black magic". This report defines some of the geometric quantities used in infrared technology. The addressed quantities include some of those used in describing, geometrically, the power radiated by a source and the energy density that could be used by infrared-sensitive ordnance some distance from that source.

Three radiation quantities will be initially described: radiant intensity, radiance, and irradiance. In laying the groundwork for a description of these items, it is necessary to define radiant power and steradian.

SECTION II

DEFINITION OF RADIANT POWER AND STERADIAN

Light and other electromagnetic radiation are described either as waves or particles (photons or quanta). There are several systems of units for describing this radiation quantitatively, but the one most widely used in radiometry is simply power expressed in watts. These radiant watts are the rate of flow of radiant energy since the photons, or waves, do carry electromagnetic energy through space. Thus the three radiometric quantities cited earlier (radiant intensity, radiance, and irradiance) are geometrical descriptions of radiant power for different purposes.

A steradian is a unit solid angle, just as a degree is a unit plane angle. Recall that a (plane) circle is divided into 360 degrees, or it can also be divided into 2π radians, that is, 6.28+ radians. Thus the radian equals approximately 57.3 degrees. The radian, although seemingly awkward, is convenient to use because an angle of one radian has an arc with the same length as its radius (Figure 1). The arc is the section of the circle which subtends the angle. Also, the chord is slightly shorter than its arc, but as the angle approaches zero, the chord approaches the arc length. Algebraically, $s=r\theta$ where s is the arc length, r is the radius of the circle, and θ is the angle in radians (NOT DEGREES). Also, s and r have the same units of distance whether measured in inches, meters, or miles. A steradian is nothing more than a square radian. Just as a square foot is a measure of area (length in two perpendicular directions), a steradian is a measure of a solid angle (angle in two perpendicular directions) (Figure 2). The point P is surrounded by an imaginary sphere of radius r. One radian of plane angle is drawn on the equatorial plane, and perpendicular to this plane, a solid angle 1 radian square is constructed with the point P at its apex. If A is the (curved) surface area of the spherical section (crosshatched in Figure 2), then $A = s^2 = r^2\theta^2$. The mensuration formulae show that the total surface area of a sphere $S = 4\pi r^2$. This is equivalent to saying that there are 4π steradians in a sphere, or that 4π steradians surround a point in space. Again, the square area enclosed by the chords approximates the curved surface area, and as the solid angle collapses, the approximation improves. A solid angle need not necessarily be "square" (i.e., have the same dimension on the sides); it might have a cross section that is rectangular, circular, or even irregular. Figure 2 was used merely for illustrating the basis for solid angles. In practice, a solid angle that is subtended by a surface at a point is calculated by dividing the area of the surface by the square of the distance between the surface and the point. For small areas or large distances, the flat area is a good approximation to the (exact) curved surface area. When the solid angle approaches a steradian, however, the exact curved equal-radius surface area should be used in the equation $\omega = A/r^2$.

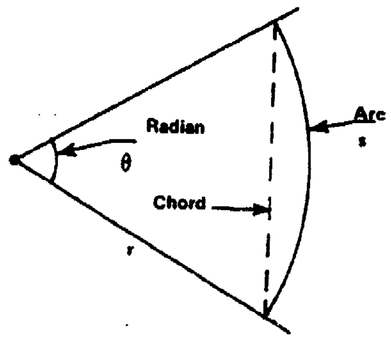

Figure 1. Definition of Radian

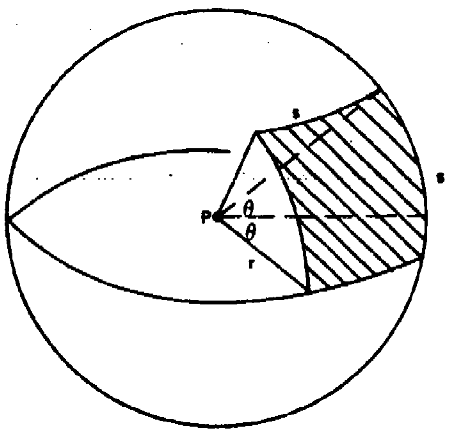

Figure 2. Definition of Steradian

SECTION III

DESCRIPTION OF IRRADIANCE

The derivation of the concept of solid angles (Section II) is further useful in forming the concept of the Inverse Square Law. Referring to Figure 2, the radius of the sphere selected for the illustration was arbitrary, and any sphere of radius R could have been used just as easily. If a radiation source emits 100 watts of radiant power uniformly into one steradian (Figure 2), then those 100 watts are spread uniformly over the surface area A, and the power density is 100/A watts per unit area at a distance r from the source. If the sphere had been twice as big, with a radius $R = 2r$, then the surface area would have been $A' = 1 \times R^2 = 4r^2$, and the power density on the more distant surface would be 100/4A watts per unit area or one fourth as great. This is the basis for the Inverse Square Law which states that the power density changes inversely as the square of the distance.

The power density referred to in the previous paragraph is the area concentration of radiant power expressed in watts/cm^2. This area concentration is known as irradiance and the location of the surface it refers to should be established. The irradiance can be falling on and being absorbed by a material surface, or it can be passing through a hypothetical area on its way from a source to a surface. Irradiance also has a direction associated with it, and the surface is ordinarily considered to be normal to (perpendicular to) the direction of irradiance. An exception to this would be a photographic lightmeter looking directly up at the overcast sky. Here, the surface is the sensitive area of the lightmeter, but since illumination (irradiance) comes from all parts of the overcast sky (all directions), only the zenith irradiance is generally incident on the area.

SECTION IV

DESCRIPTION OF RADIANT INTENSITY

A point source which radiates uniformly in all directions in space, such as a star, is called an isotropic radiator. Such an object is rare in military infrared technology because most targets radiate more intensely in some directions thar in others. Radiant intensity and radiance are terms used to describe how much a source radiates in various directions. Radiant intensity is the simpler concept and applies either to a point source or to a source which is angularly small. Radiant intensity is the number of watts of radiant power per unit solid angle, expressed in watts/steradian and accompanied by a directional statement unless the source is isotropic.

Thus, a jet aircraft might radiate 1000 watts into the steradian centered on the rearward axis of the engine, 100 watts into the steradian centered at right angles to the axis of the engine, and 10 watts into the foreward-directed steradian, where the targets radiant intensities would be 1000, 100, and 10 watts/steradian, respectively. A steradian is a far larger solid angle than is encountered in practice, and millisteradians or even microsteradians are more realistic (a one square foot surface 1000 feet away subtends a microsteradian); so, the measurement might actually be 1000, 100, or 10 microwatts of radiant power per microsteradian. It should be observed, however, that the radiant intensities are still the same. An isotropic radiator with a radiant intensity of 1 kilowatt/steradian would be dissipating 12.56 (4π) kilowatts of power into space.

SECTION V

DESCRIPTION OF RADIANCE

Before the concept of radiance can be developed, the concents of field of view, point sources, and extended sources must be established. The field of view of an instrument is merely the angular extent in two dimensions of its sensitivity. Thus, a particular infrared instrument might have a circular field of view of 1 milliradian in diameter. The milliradian, also known as the angular mil, is particularly convenient because it is simply one unit across in a thousand units out. A field of view could also be expressed as a solid angle; for example, the infrared instrument mentioned previously would have a field of view of 0.785 microsteradian. If it were placed 1000 feet away from a radiating source, as shown in Figure 3, it would be sensitive to radiation arising from any point within a 1 foot diameter circle in the plane of that source. If that source happened to be a candle flame with dimensions small compared to the 1 foot circle, that candle would be regarded as a point source. If that source happened to be a jet engine tailpipe 3 feet in diameter, which is large compared to the 1 foot circle, the tailpipe would be regarded as an extended source. A given source may be either point or extended depending on (1) its linear dimensions, (2) the separation between source and instrument, and (3) the field of view of the instrument. The terms "small compared to" and "large compared to" are not very explicit; a factor of 10 either way would be comfortable for assuring that the source is extended or is a point, but occasionally, a factor of 2 or 3 must be accepted. Here, too, the visual analog with infrared phenomena may break down because some combustion sources have different infrared and visible dimensions. Transition cases where the angular target dimensions approximate the field of view by radiant intensities or the extended source case described by radiances should be sought. Radiance then can be considered as the radiant intensity per unit area of an extended source expressed in watts per steradian per cm^2.

SECTION VI

DISCUSSION

As derived in this report, irradiance is a field quantity while radiant intensity and radiance are source quantities. A field quantity is a description of the radiation field surrounding a source. The cm^2 factor in irradiance and radiance applies to different areas; in irradiance it refers to a surface in the radiation field surrounding a source, and in radiance it applies to the radiating surface.

One objective in performing an infrared radiometric measurement is to describe a target's radiation emission characteristics, such as radiant intensity, with the aid of a radiometer. Strictly speaking, the radiometer does not measure the source but rather responds to the irradiance falling on it at a distance from the source. Thus, the radiometer measures irradiance which is a field quantity. This field quantity is then converted to a source quantity through radiometer calibration factors and source-radiometer physical relationships at the time of the measurement. If radiant intensity is desired, a knowledge of the slant range separating the source and the radiometer is essential; if radiance of a uniform extended source is desired, the slant range is not necessary. Figure 4 illustrates this effect. As the slant range is increased, the irradiance indeed decreases as the square of the distance; but the total radiating area of the source within the field of view increases as the square of the distance, and the two distance factors cancel out. The relationships discussed so far can be reduced to a few simple algebraic equations. Let:

P = Radiant power under consideration in watts

H = Irradiance on a surface in watts/cm^2

J = Radiant intensity of a point source in watts/ster.

N = Radiance of an extended source in watts/ster. cm^2

A = The emitting area of an extended source under consideration in cm^2

a = The collecting area of a distant radiometer, cm^2

R = The slant range separation, cm^2

Ω = The solid angular field of view of the radiometer, steradians

ω = The solid angle a source radiates into which is under consideration, steradians.

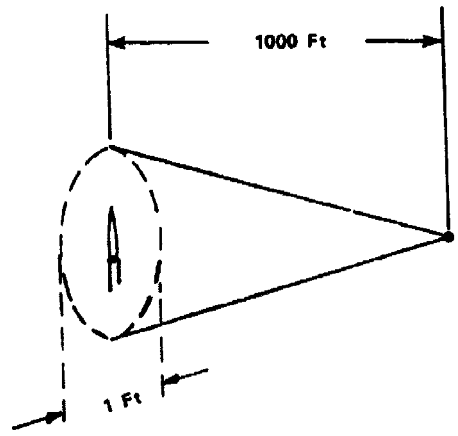

Figure 3. Definition of Field Of View

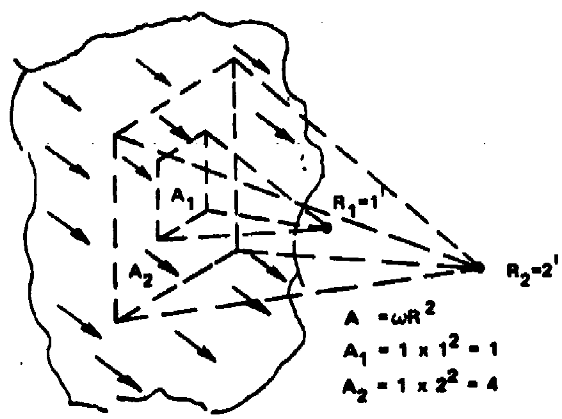

Figure 4. Radiance of Uniform Extended Source

The solid angles and areas are related by the equations $\Omega = A/R^2$. and $\omega = a/R^2$. If the source is a point with radiant intensity J, the irradiance at a distance R is $H = J/R^2$. Conversely, if an irradiance H is measured at a distance R with radiometer collector subtending a solid angle ω at the source, the power $P = Ha$ received is that emitted by the source into a solid angle ω. Alternatively, the source can be considered to be radiating P watts per ω steradians or Ha watts/aR^{-2} steradians or the radiant intensity $J = HR^2$ as derived previously. If the source is extended with a radiance N, of which a partial area A falls within the field of view of a radiometer, then the "radiant intensity" of that partial area is $J = NA$ and the irradiance on a radiometer collector $H = NA/R^2 = NR^2\Omega/R^2 = N\Omega$; thus, irradiance is independent of slant range.

SECTION VII

APPLICATION

The preceding sections have briefly defined radiation concepts and terminology, which are used, with variations, to describe the emission characteristics of radiating bodies. From the discussion of radians, steradians, chords, and arcs (Section II), it was observed that the plane projected area was a good approximation of the exact curved projected area of a spherical body, provided that the solid angle under consideration remained considerably less than 1 steradian. Because a steradian is a far larger solid angle than is obtained from actual radiometric measurements (i.e., radiometer collecting aperture area much larger than source area), the approximation of the exact surved projected surface area by the flat (plane) projected surface area remains valid for the computations of irradiance (watts/cm^2). Assume that the power density (irradiance, H) computed for a distance R from a plane radiating body is a good approximation of the power density computed for the same distance and within the same steradian for a spherical body of like diameter. Since $J = HR^2$, in a non-absorbing atmosphere, it follows that the radiant intensity of a plane body is a good approximation of the radiant intensity (J) of a spherical body, provided that the projected radiating areas are the same. Point sources of radiation can therefore be considered as plane sources exhibiting various plane projected radiating areas as a function of the direction in which they are being observed.

An isotropic radiator radiates uniformly into 4π steradians and the projected plane radiating area in each of these solid angles is identical to the area of a plane circle of equal radius. However, when viewing a plane surface radiator from various directions the projected radiating area is not the same, and therefore, its radiant intensity will be a function of the direction in which it is being observed. If the surface substance is a perfectly diffuse radiator, as opposed to a specular or mirrorlike radiator, the emissivity (ε) and the radiant emittance (W) in watts/cm^2 as observed from a given incremental surface element (cm^2) will not vary as a function of viewing angle but will remain constant throughout the 2π steradians of the hemisphere into which it is radiating. The emission characteristics of such a "Lambert law" surface are illustrated in Figure 5 where the emissivity (ε) and the radiant emittance (W) are independent of the viewing angle (Θ) and the projected radiating area (A_p) and the radiant intensity (J) are a function of the cosine of the viewing angle Θ. A plane circular surface cannot radiate the total power of a spherical body of equal radius (r), emissivity, and temperature constant. As an example, assume that the emissivity and temperature of a radiating body are such as to produce a radiant emittance (W) of 1 watt/cm^2 of radiating area. If this body were spherical (Figure 6) with a radius (r) of 1 cm, the radiating surface area would be given by $4\pi r^2 = 4\pi = 12.56$ cm^2. The total power radiated into space (P) = WA = 1 watt/cm^2 x 12.56 cm^2 = 12.56 watts. The surface area of a plane surface of equal radius is given by $A = \pi r^2 = \pi(1)^2 = 3.14$ cm^2. The total radiant power from this surface = 3.14 watts or one fourth the radiant power emitted by a spherical radiator of equal radius. To compute the radiance (N) from a plane surface of this type, it is necessary to convert W (watts/cm^2) to N, or watts/steradian cm^2. To convert W to N for one steradian (ω), requires division by ω, $N = W/\omega$, where ω is equal to one unit solid angle. Since, by definition, $\omega = A/r^2$; the case of the steradian perpendicular to the plane surface (central steradian) becomes $\omega = 3.14\ cm^2/r^2 = 3.14/1^2 = \pi$. Therefore, the Lambertian expression for the central steradian (cosine Θ = 1 for 90° and $A = A_p$) becomes $N = W/\pi$. The radiant intensity of such a surface in watts/steradian is obtained by the formula $J = NA_p$ where A_p is defined as the projected area of the source (A) perpendicular to the given viewing angle Θ. Thus for the plane surface just discussed, the radiant intensity would simply be $J = NA_p = 1/\pi \times \pi = 1$ watt/steradian. This equation further illustrates that, of the total 3.14 watts of radiant power radiated into the hemisphere, 1 watt is radiated into the central steradian. In other words, $1/\pi$ of the total power is contained within the central steradian of any incremental Lambertian surface area irrespective of the shape of the total radiating body.

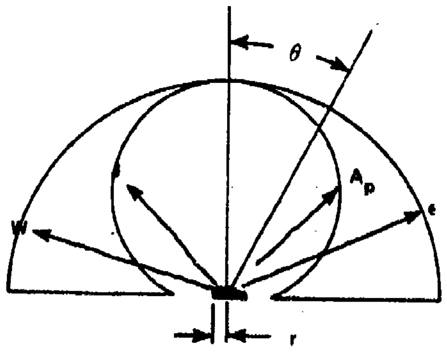

Figure 5. Emission Characteristics

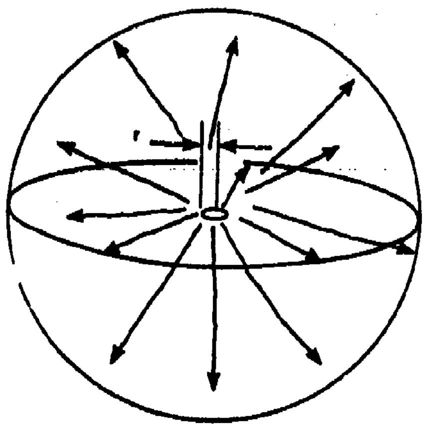

Figure 6. Spherical Radiating Body

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