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# OVERVIEW OF REFERENCE DISTRIBUTION REAL IMAGE FORMATION TECHNOLOGY

Greyson Gilson
Mulith Inc.
30 Chestnut Street #32
Nashua, NH 03060-3361

15 July 2010

## ABSTRACT

A semi-qualitative overview of RIF (Reference distribution real image formation) technology is presented. The physics that underlies RIF has been developed (elsewhere) from basic principles. As part of this development, the previously unknown result that *two illuminated object points are required to form light waves that contribute to real image formation* was identified. The physics of this cooperative phenomenon has been developed theoretically and demonstrated experimentally. Also, the phenomenon has been used to form real images with resolution that far exceeds the commonly accepted optical diffraction limit. RIF technology is a practical application of this science.

## INTRODUCTION

A new theory of optical real image formation has been developed[1]. This theory is based on solving the optical wave equation subject to boundary conditions. The imaging system and the subject that is being imaged both impose salient boundary conditions.

Previously, it was widely assumed that only one illuminated point (a mathematical point that is infinitely small) in the subject is needed to support image-forming light. However, in accord with the new theory, at least two separate illuminated points are needed to support image-forming light. The consequences of this discovery are far-reaching and profound.

Reference distribution real image formation[2,3] (RIF) technology arose as a practical application of the new theory. RIF is being developed to provide precise optical real images. These images are useful for both microscopy (observing arbitrarily small things) and nanolithography (constructing arbitrarily small things); other potential uses have also been identified.

Ordinarily, light that propagates away from a subject is used to form an aerial image of the subject. No other source of light is involved – light from the subject acts alone.

With RIF, light that propagates away from a reference distribution, in addition to light that propagates away from a subject, occurs. The reference distribution is usually (but not necessarily) separated physically from the subject. An aerial image of both the subject and the reference distribution is formed. When RIF is used, no known fundamental resolution limit exists.

## REAL IMAGE FORMATION

A return to first principles was used to develop the fundamental real image formation optics that underlies RIF[4]. Development of fundamental optics is ordinarily based upon the Huygens-Fresnel principle and various improvised approximations. This conventional approach differs substantially from the approach used to develop the theoretical underpinnings of RIF.

The Huygens-Fresnel principle is not a law of physics and is furthermore known to be problematic[5]. In addition, a series of *Ad hoc* approximations (such as initial approximations, the Fresnel approximations, the Fraunhofer approximation, etc.) are invoked in derivations that are based upon the Huygens-Fresnel principle. None of these derivations can be considered to be fundamentally correct.

Fundamental principles of optics are independent of the Huygens-Fresnel principle. Accordingly, the Huygens-Fresnel principle and its attendant approximations were avoided in the development of Reference distribution real image formation (RIF). Rather, the optical wave equation was solved subject to salient boundary conditions. RIF theory evolved as a consequence of this return to basics.

Real image formation is achieved by means of an image formation apparatus. Consider the simple image formation apparatus illustrated in Figure 1. A plane subject, shown as a small

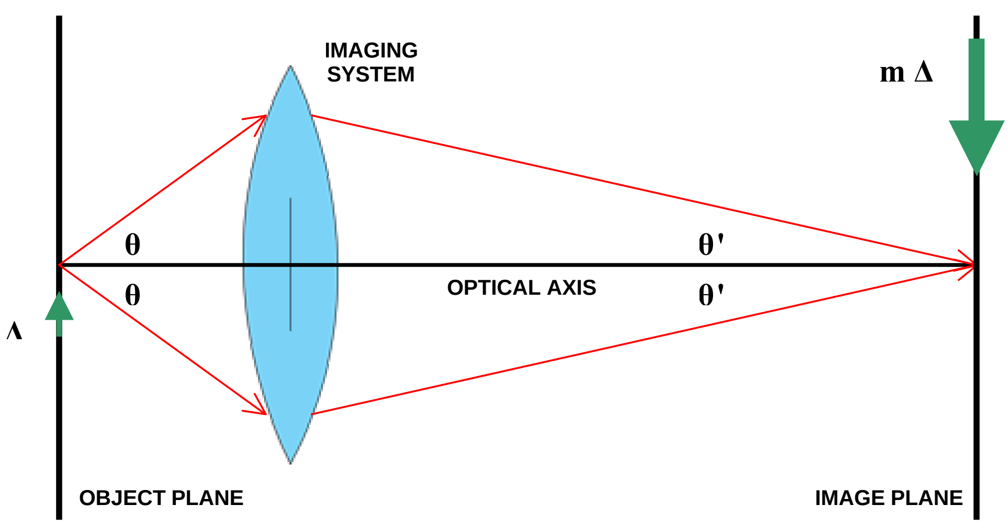



FIGURE 1. REAL IMAGE FORMATION APPARATUS

green arrow, exists in the object plane; an image of this subject, shown as a large green arrow, exists in the image plane. The image is formed by light that interacts with the subject, then propagates through the imaging system and ultimately arrives at the image plane. The image closely resembles an unchanged or resized and possibly inverted version of the subject.

Initially, light is reflected from or transmitted through the object plane. Light that interacts with various subjects in the object plane forms a configuration of light. This configuration of light – the subject distribution – exists on the side of the object plane nearest to the imaging system.

The length $\Delta$ of the small green arrow illustrated in Figure 1 separates two arbitrary illuminated points in the subject distribution. Two equi-amplitude plane waves that travel from the object plane to the image plane are linked to this pair of illuminated points. Referring to Figure 1, red arrows indicate the directions of propagation for these light waves. The directions of propagation change when the light passes through the imaging system.

The propagation direction and a wavefront that is perpendicular to the propagation direction are illustrated in Figure 2 for an individual plane wave component. The wavefront is an infinite plane that is perpendicular to the plane of the figure and that extends out of the plane; only the trace of the wavefront on the plane of the figure is shown in the figure. The propagation direction of the wave lies in the plane of the figure.

As shown in the new theory, the quantum amplitude spatial period associated with two illuminated points separated by the distance $\Delta$ in a distribution of light is given by

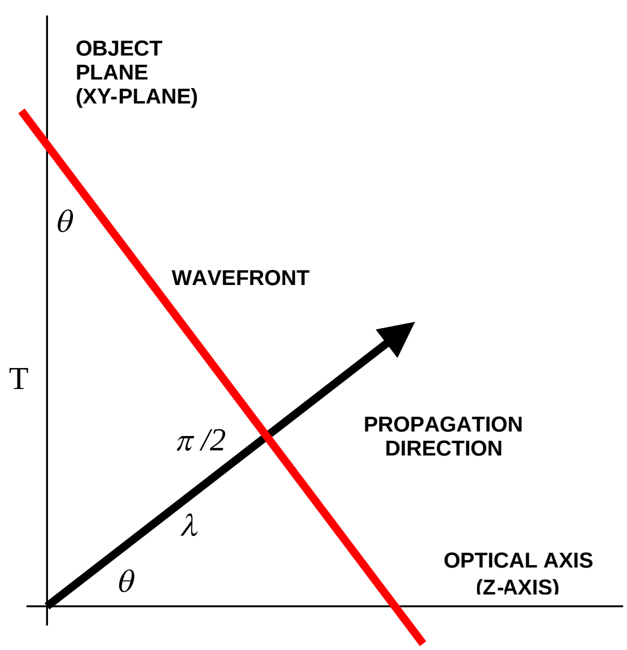



**FIGURE 2. PLANE WAVE PROPAGATION GEOMETRY**

$$T = \frac{\Delta}{2}$$

The quantum amplitude spatial period associated with two illuminated points in a distribution of light is illustrated in Figure 2 as the hypotenuse of a right triangle.

Referring to Figure 2, the direction of propagation and the optical axis define a propagation angle. In the region between the object plane and the imaging system, the object side propagation angle is given by

$$\theta = \sin^{-1}\left(\frac{2\lambda}{\Delta}\right)$$

where $\lambda$ is the wavelength of light involved. This relationship is illustrated graphically in Figure 3.

Small distances between points in a subject distribution are associated with large object side propagation angles. The minimum separation distance required for light to propagate away from the object plane exceeds two wavelengths of the light used, i.e.,

$$\Delta_{min} = 2\lambda$$

**Two illuminated points in the object are required to form light waves that contribute to real image formation.**

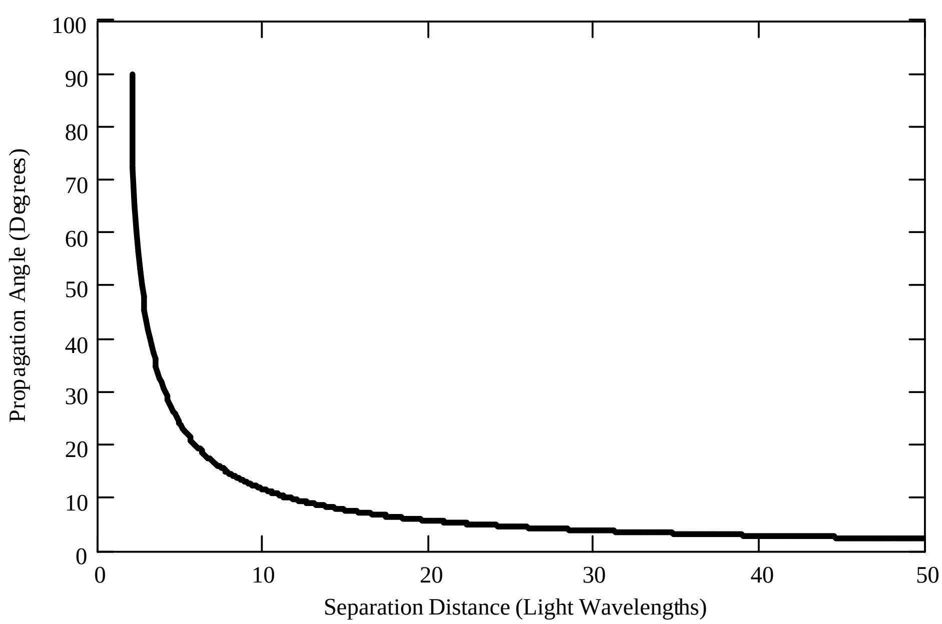



**FIGURE 3. OBJECT SIDE PROPAGATION ANGLE Θ AS A FUNCTION OF THE SEPARATION DISTANCE Δ BETWEEN TWO POINTS IN THE OBJECT**

In the region between the imaging system and the image plane, the image side propagation angle is given by

$$\theta ' = \sin^{-1}\left(\frac{2\lambda}{m\Delta}\right)$$

where $m$ is the magnification achieved by the image formation apparatus. The magnification $m$ is related to the angles $\theta$ and $\theta '$ in accord with the equation

$$m = \frac{\sin\theta}{\sin\theta '}$$

The foregoing relationship is known as the optical invariant.

At the image plane, the component light waves add together to form a configuration of light. This configuration of light closely approximates a magnified (enlarged, reduced or unchanged and possibly, but not necessarily, inverted) version of the initial configuration of light associated with the subject. Consequently,

$$\Delta ' = m\Delta$$

is the length of the large green arrow shown in Figure 1.

## RIF

RIF is achieved by means of two distributions of light – a subject distribution and a reference distribution. These distributions of light can be thought of as a single distribution of light that is separated into two bright regions by a dark region. An image of both distributions of light is formed. An image of the reference distribution may or may not be desired. An image of the subject distribution is desired.

A configuration of light that is suitable for achieving RIF is illustrated in Figure 4. The configuration of light exists on the side of the object plane nearest to the imaging system and is confined to the interiors of the circles shown in the figure. Light throughout the configuration is coherent or partially coherent. All points in both the subject distribution and the reference distribution are in the same area of coherence.

As indicated in Figure 4, the subject distribution exists inside a circular area of diameter $D_S$ while the reference distribution exists inside a circular area of diameter $D_R$. In addition, the minimum distance $S$ separates the reference distribution from the subject distribution. Ideal RIF occurs when the criteria

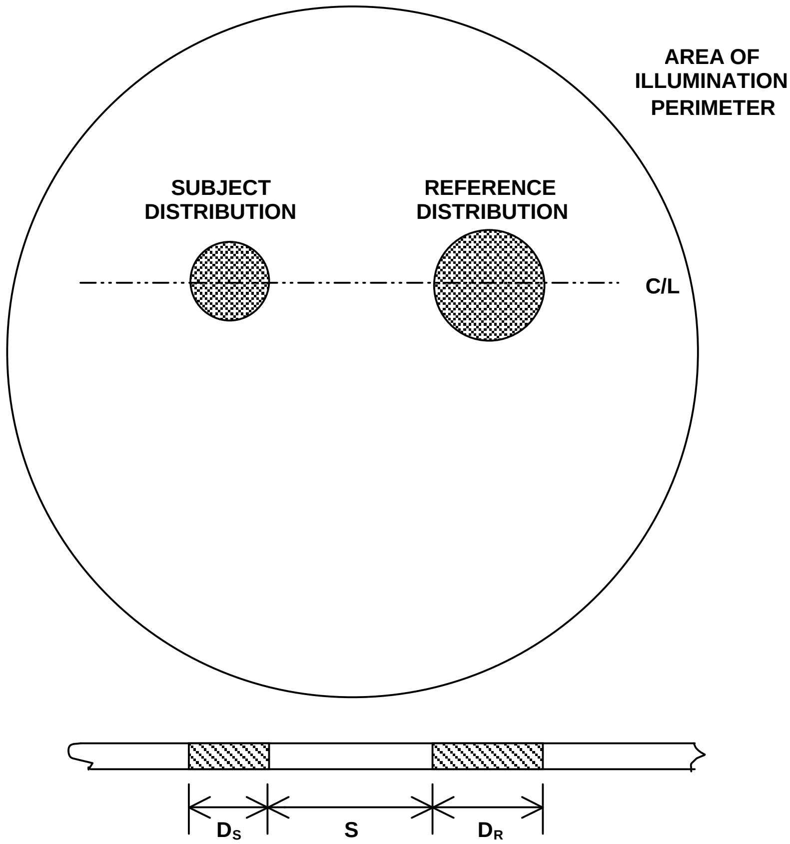



**FIGURE 4. RIF OBJECT PLANE CONFIGURATION: PLAN AND FRONT ELEVATION VIEWS**

$$S \geq \Delta_{\min}, \; D_S < \Delta_{\min} \text{ and } D_R < \Delta_{\min}$$

are realized physically. Noisy RIF occurs when either $D_S$ or $D_R$ or both $D_S$ and $D_R$ do not satisfy the foregoing inequalities.

Consider the conceptual illustration of transmission RIF provided in Figure 5. Initially, light is incident (from the left) upon an opaque screen with two apertures in it. The side of the screen nearest to the imaging system (shown as a lens) serves as an object plane.

Coherent or partially coherent light passes through the apertures to form two distributions of light on the object plane. These distributions of light are, ideally, the same size and shape as the apertures. The distributions of light are designated as the subject distribution and the reference distribution.

Taken separately, the propagation angles of the light that travels away from either of the two distributions of light are larger than the acceptance angle of the imaging system. Such light does not pass through the imaging system and consequently does not contribute to image formation.

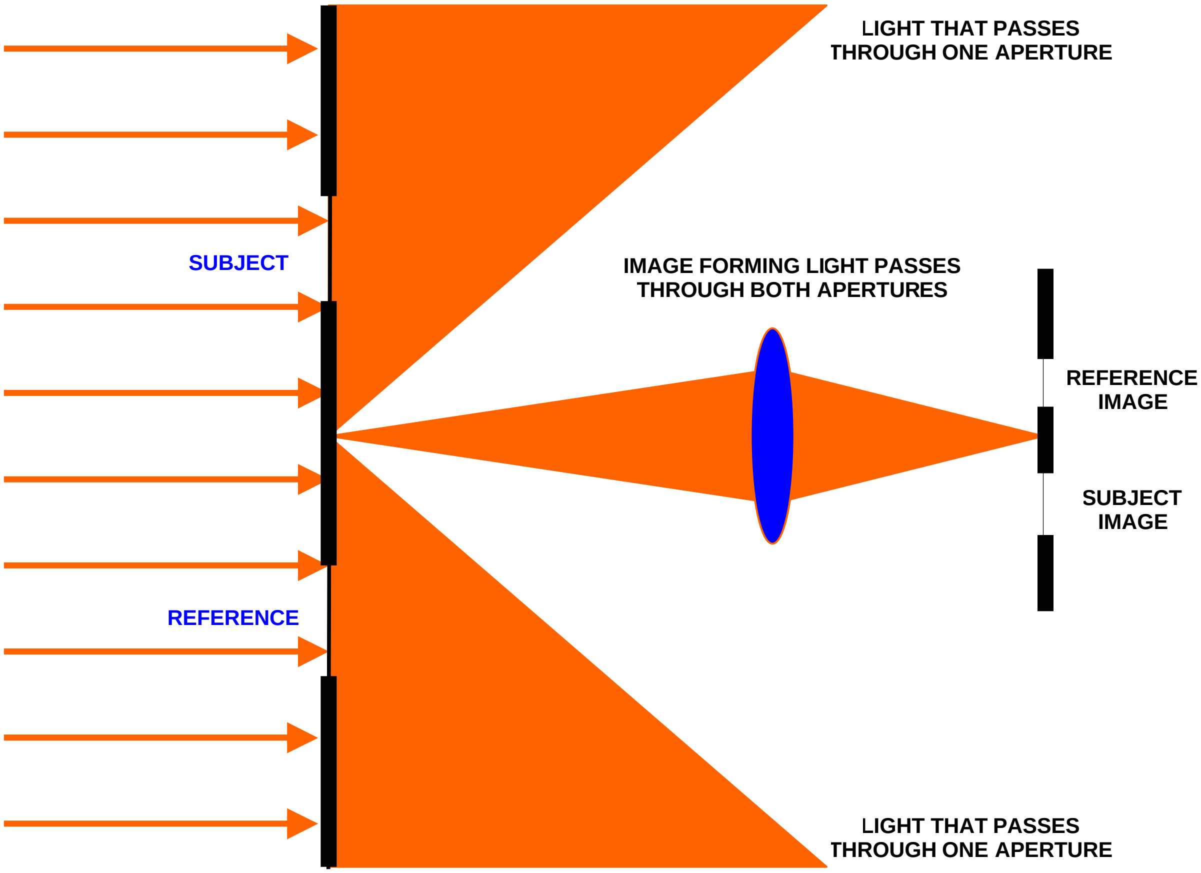



**FIGURE 5. CONCEPTUAL RIF PROCESS**

Taken together, the propagation angles of the light that travels away from the combined distributions of light are smaller than the acceptance angle of the imaging system. This light defines a finite bandwidth and is transferred, without amplitude or phase distortion, through the imaging system. Consequently, light that propagates away from the combined distributions of light contributes to undistorted image formation.

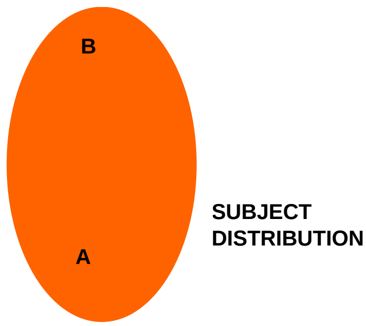
No two points in either the subject distribution or the reference distribution are sufficiently separated to contribute to image formation. Every pair of points such that one point is in the subject distribution and one point is in the reference distribution is sufficiently separated to contribute to image formation.

## RIF RESOLUTION

Coherent or partially coherent light and a quite ordinary diffraction limited optical system can be used to achieve RIF.

Referring to Figure 6, points A and B in an ordinary object are too close together (a special case) to be resolved by conventional real image formation. A fundamental resolution limit exists and the images of points A and B merge together.

Introduction of a reference distribution changes the situation profoundly.




**FGURE 6. ORDINARY OBJECT (SUBJECT DISTRIBUTION)**

Coherent or partially coherent light is transmitted through or reflected from certain areas in the object to form a subject distribution and a reference distribution. Both distributions of light are inside the same area of coherence.

Referring to Figure 7, points A and R are sufficiently far apart to be imaged together as two separate points.

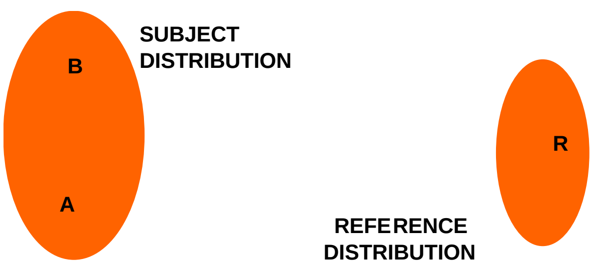



**FIGURE 7. RIF OBJECT (SUBJECT DISTRIBUTION & REFERENCE DISTRIBUTION)**

Points B and R are sufficiently far apart to be imaged together as two separate points.

Points A and R define one side of a triangle, points B and R define another side of a triangle, and $\angle ARB$ defines the angle between the two sides.

An image of points A, B, and R is formed without amplitude or phase distortion.

No minimum separation of points A and B exists and no fundamental resolution limit exists when RIF (Reference distribution real image formation) is used.

Resolution is complete.

## CONVENTIONAL IMAGE DISTORTION

Most imaging systems are circular. Although non-circular imaging systems exist, little would be gained by considering them in the present context. Henceforth, attention will be restricted to circular imaging systems. In addition, the terms *imaging system* and *circular imaging system* will be used interchangeably.

Circular imaging systems are endowed with a definite diameter. Accordingly, an imaging system restricts the propagation angles of the light that can pass through it to a maximum allowed value, $\theta_{\max}$. As a consequence, some of the light that propagates away from the object plane does not pass through the imaging system. The propagation angle $\theta_{\max}$ is known as the acceptance angle of the imaging system.

The numerical aperture, defined as

$$\mathrm{NA} = \sin\theta_{\max}$$

is often used to characterize an imaging system. Indeed, the fundamental limits of performance for a circular imaging system are often expressed in terms of its numerical aperture. The minimum separation distance between object points that can be imaged by a specific image formation apparatus is given by

$$D_{\min} = \frac{2\lambda}{\mathrm{NA}}$$

where, as before, $\lambda$ is the wavelength of light used.

Figure 8 illustrates the real image that is formed by a circular imaging system when it is illuminated by a plane wave propagating along the optical axis. The image is known as an Airy pattern. As shown in the figure, this image consists of a central bright region that is surrounded by a number of much fainter rings. The exposure associated with the central bright region is very much greater than that associated with any other region in the image. The central bright region is known as the Airy disk produced by the imaging system.

The diameter of the Airy disk produced by an imaging system is given by

$$\delta = \frac{1.22\lambda}{\mathrm{NA}}$$

where $\lambda$ is the wavelength of light used. The diameter of the Airy disk is often referred to as the imaging system's spot size.

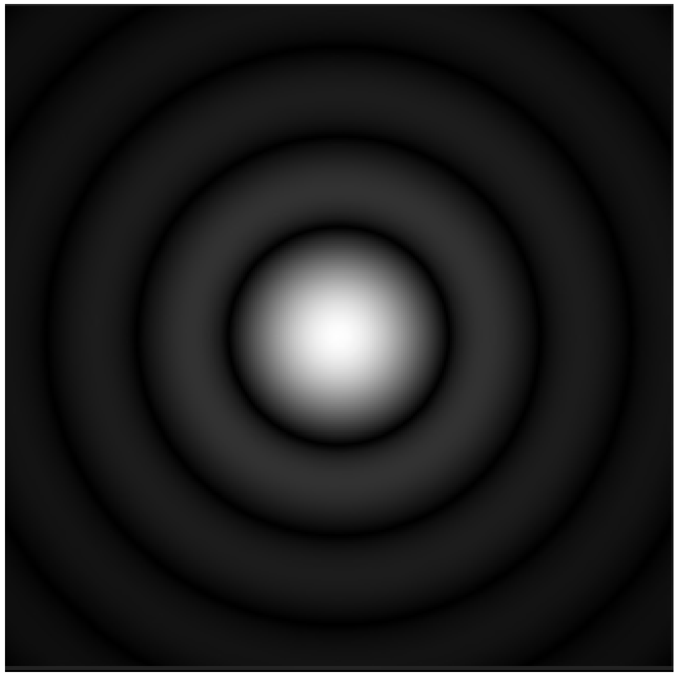


**FIGURE 8. AIRY PATTERN. SOURCE: WIKIPEDIA, *AIRY DISK***

Dimensions of image features that are formed by conventional means (not RIF) are larger than their geometrical size. As indicated in Figure 9, the linear dimensions of such an image feature are increased in size by an amount equivalent to the imaging system's spot size.

A minimum separation distance between two conventionally formed and distinguishable image features exists. The minimum separation distance such that the image of two features that are

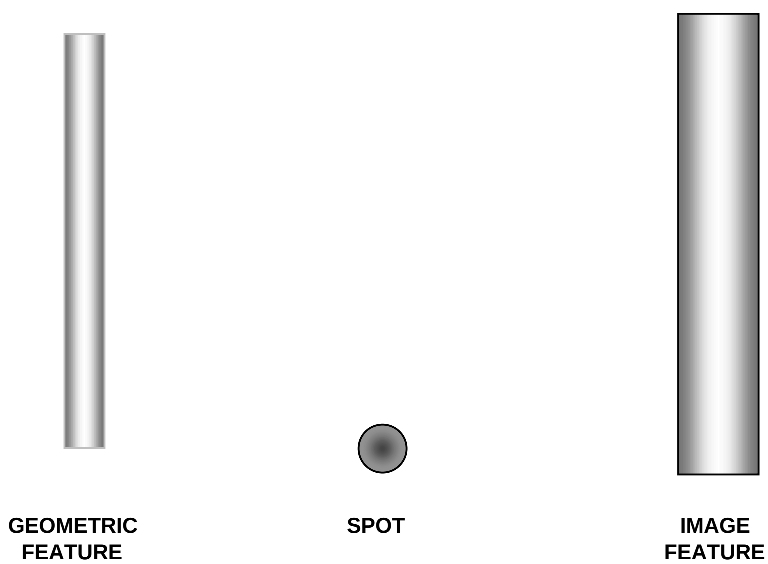



**FIGURE 9. GEOMETRIC FEATURE DIMENSIONS ARE INCREASED BY THE IMAGING SYSTEM SPOT DIAMETER**

distinguishable as two features is equivalent to the imaging system's spot size. Two image features that can be distinguished as two image features are said to be resolved.

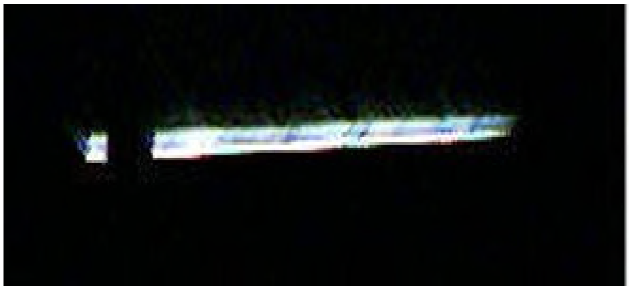
RIF is being developed to eliminate the adverse effects associated with an imaging system's spot size. This includes optical real image formation that has no resolution limit.

## RIF DEMONSTRATIONS

A versatile RIF demonstration unit[6] has been constructed and used to demonstrate Reference distribution real image formation (RIF). In addition, the unit has been used to demonstrate microscopy that is based on RIF technology. The unit can be and has been used as a reflection microscope and as a transmission microscope. A photograph of the RIF demonstration unit is shown in Figure 10. The RIF demonstration unit was designed, constructed, and used under the auspices of Mulith, Inc.

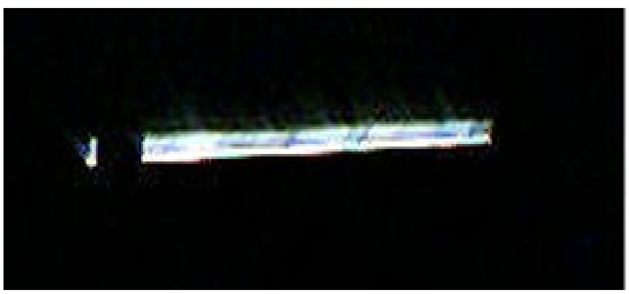
Primarily, the RIF demonstration unit was developed to provide a means for demonstrating RIF and serve as a RIF based microscope. In addition, a vigorous attempt was made to achieve design simplicity, ease of construction, and ease of operator use when the demonstration unit was being developed.


**FIGURE 10. RIF DEMONSTRATION UNIT**



(A) BOTH SEGMENTS OPEN

(B) RIGHT SEGMENT PARTIALLY CLOSED; LEFT SEGMENT NOT DIRECTLY CHANGED



(C) RIGHT SEGMENT REOPENED; LEFT SEGMENT NOT DIRECTLY CHANGED

**FIGURE 11. SLIT APERTURE SEPARATED INTO TWO SEGMENTS; THE DARK REGION THAT SEPARATES THE SEGMENTS IN (A) AND (C) IS THE SHADOW OF THE HAIR THAT SEPARATES THE SEGMENTS**

The RIF demonstration unit is an optical real image formation system. Ordinarily, real images of a subject are formed with light that propagates from the subject alone. With RIF, a distribution of light – a reference distribution – that is usually (but not necessarily) separated from the subject is introduced. A real image of both the subject and the reference distribution is formed on the image plane.

An iterative process was used to develop the RIF demonstration unit. RIF was demonstrated at various stages of the development process.

RIF was first demonstrated[7] on 12 July 2006. This simple demonstration was achieved by using optical transmission microscopy and a special microscope slide.

The microscope slide featured a slit aperture that was 2.5 micron wide by 25 micron long. The slit aperture was separated into two segments by means of a human hair.

Referring to Figure 11, the dark regions that separate the two bright regions in micrograms (A) and (C) are recordings of the hair's shadow.

A subject distribution (an object of interest) is defined by the slit segment that corresponds to the images shown on the left in micrograms (A) and (C). A reference distribution is defined by the slit segment that corresponds to the images shown on the right in micrograms (A) and (C). The image shown in microgram (B) is not an image of the subject distribution and is also not an image of a satisfactory reference distribution.

Using conventional optics, the slit segment on the left in the foregoing sequence of micrograms was too small to be imaged. However, when the slit segment on the right was extended sufficiently far from the hair (thus forming a satisfactory reference distribution), an image of the region on the left was formed. These facts are all directly observable without recourse to theoretical understanding.

The micrograms presented in Figure 11 are overexposed. As a result, distortion of feature dimensions that is attributable to the image recording process (not the image formation process) occurs. Consequently, any attempt to obtain quantitative dimensional information from the micrograms is inappropriate.

(A) BOTH APERTURES OPEN

(B) LEFT APERTURE PARTIALLY CLOSED; RIGHT APERTURE NOT DIRECTLY CHANGED

(C) LEFT APERTURE CLOSED; RIGHT APERTURE NOT DIRECTLY CHANGED

**FIGURE 12. TWO SEPARATED APERTURES**

White light was used with a 0.10 NA lens for the foregoing demonstration. The smallest wavelength of the light involved approximated 0.4 micron. The corresponding minimum separation of two points in the object that could be imaged by conventional means would be $20\lambda = 8$ micron, a distance that is far greater than any of the distances that exist inside the subject distribution in the foregoing demonstration.

A cooperative phenomenon such that reference distribution changes are linked to subject distribution changes occurs when RIF is used. This phenomenon has been demonstrated by using two circular apertures in a thin metal screen. When light was transmitted through the apertures, one aperture served as a subject distribution of light and the other aperture served as a reference distribution of light.

Micrograms of two separated circular apertures are shown in Figure 12. White light was used with a 0.10 NA lens to record these micrograms. The nominal diameters of the apertures approximate 10 micron; their effective diameters are unknown. Both apertures were completely open in microgram (A). In microgram (B), the aperture on the left was partially closed while the aperture on the right was not directly changed. In microgram (C), the aperture on the left was completely closed while the aperture on the right was not directly changed. This progression illustrates the cooperative phenomenon that occurs.

Gradual closure of the reference distribution was used to demonstrate the cooperative phenomenon.

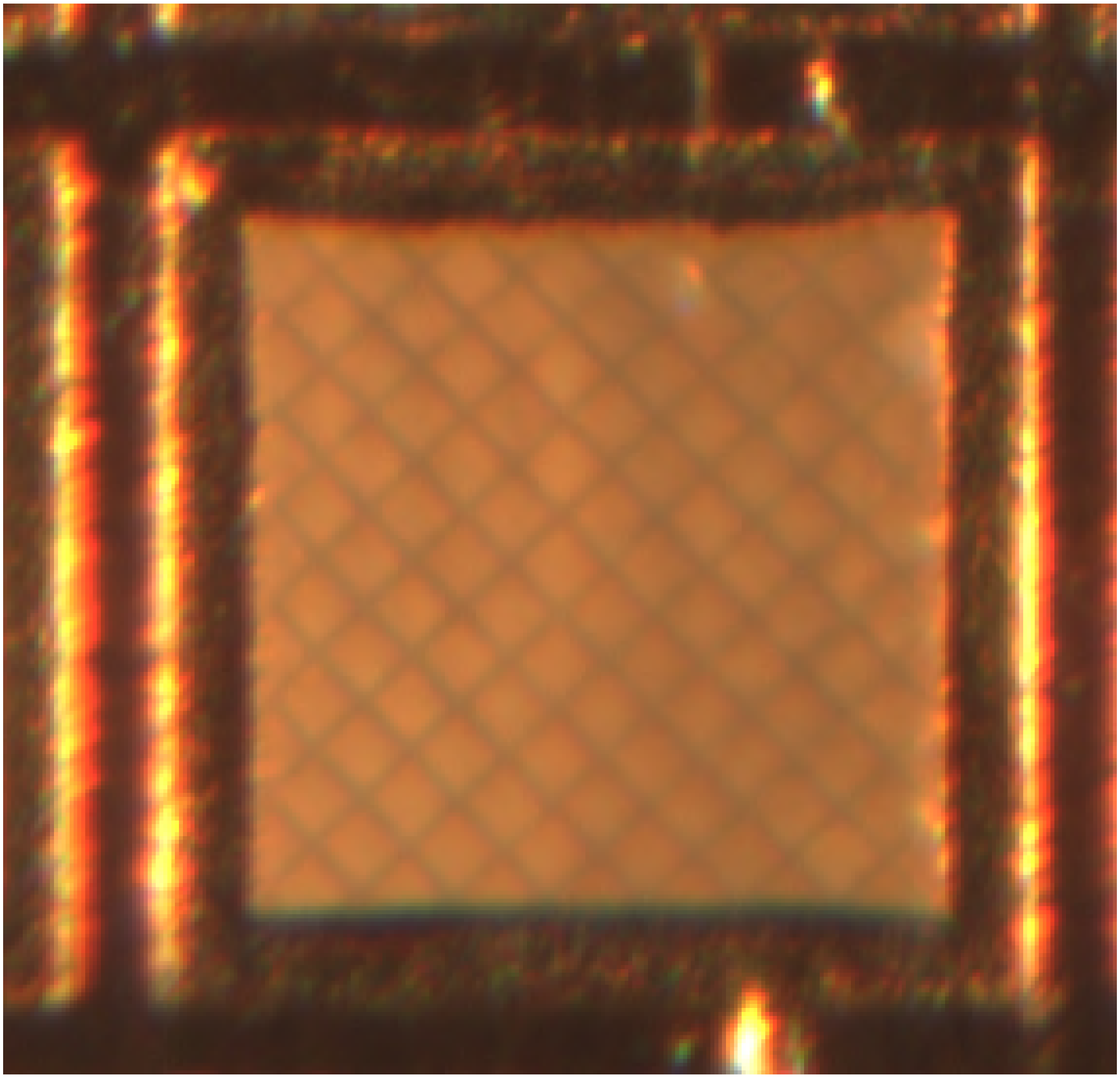


**FIGURE 13. QUANTIFOIL S7/2 MICROMACHINED SQUARE MESH HOLEY CARBON GRID**

Thus, the subject distribution of light was kept open and the reference distribution was partially closed in a progressive manner. Changes in the distribution of light associated with the subject distribution occurred when the distribution of light associated with the reference distribution was changed.

Consider the microgram of a Quantifoil S7/2 Micromachined Square Mesh Holey Carbon Grid on 200 Mesh Copper shown in Figure 13. The grid consists of 7 micron X 7 micron square holes that are separated by bars that are 2 microns wide; the repeat distance (pitch) is 9 micron. Typically, Quantifoil grids are used to support specimens for electron microscopy examination.

White light was used with a 0.25 NA lens to obtain the Quantifoil grid microgram shown in Figure 13. The smallest wavelength of the light involved approximated 0.4 micron.

In accord with conventional real image formation theory, the imaging system's spot size approximated 2 micron. Images of the bar widths would be increased from 2 micron (magnified) to 4 micron (magnified) while images of the distances between the bars would decrease from 7 micron (magnified) to 5 micron (magnified). This is clearly contraindicated by Figure 13.

Conventional optical real image formation theory does not support understanding the microgram in Figure 13. However, this image is easily understood as an example of noisy RIF. Images of the bars were created in accord with RIF; contrast was sacrificed because light from the spaces between the bars (optical noise) was present in the image.

## CONCLUSION

RIF (Reference distribution real image formation) technology is being developed to provide precise optical real images. These images are of practical importance to high-resolution microscopy, high-resolution nanolithography, and to passive ghost imaging.

## REFERENCES

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