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Two-beam laser illumination for shape classification: Feasibility study

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ABSTRACT. Techniques to generate iluminations for objects with no intrinsic signature are investigated. We propose two-laser beam illumination resulting in a straight-line interference pattern generated across a flat surface. The actual degree of fringe-deformation indicates the shape of the object, in particular, the amount of curvature across the object. This illumination method is applicable to an object such as a comet nucleus and an asteroid: it is cold, generates no light, and is too small or too far away from the Sun to receive an adequate amount of illumination from it. For the most effective utilization of laser power, the optimum separation of the illuminating apertures equals four aperture diameters.

RESUMEN. Se investigan técnicas para generar iluminación en objetos que no emiten radiación suficiente para revelar sus características morfológicas. Proponemos una técnica de iluminación utilizando dos haces de luz láser los cuales al interferir sobre una superficie plana generan lineas rectas. En un objeto con superficie irregular el grado de deformación de las franjas indica sus contornos, especialmente, la curvatura en cada uno de sus puntos. Este método de iluminación se puede aplicar a objetos celestes, tales como núcleos de cometas y asteroides: estos objetos son fríos, no generan luz, son muy pequeñas y se encuentran muy alejados del sol para poder percibir una adecuada cantidad de iluminación. Para la utilización de la potencia del láser la separación entre las aberturas de iluminación debe ser igual a cuatro veces su diámetro.

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1. INTRODUCTION

The celestial sources have been characterized in the visible, infrared, radio, and UV-spectral region in the recent years, due to the parallel, concurrent developments in the telescope fabrication techniques and the detector technology. Thus, we have developed a fairly good understanding of the star-formation throughout its life; we have obtained photos of nearly all the planets in our own solar system and a number of their moons [1].

There are other equally important objects, however, that continue to evade our abilities to study them, or even to capture them, despite the fact that the same imaging camera that views a planet may be used to study these mysterious objects: they are comet nuclei and asteroids. The comets have been fascinating humanity for a longer time than the stars themselves, because they move with respect to the night sky; yet we know practically nothing about them [2, 3].

Asteroids, that follow their own orbits around the Sun, most often within the region of space referred to as the asteroid belt, are cold rocks that were not able to participate in a planet formation or that resulted from an explosion of a planet or a moon. Their only source of energy is solar illumination, which is low for the orbits corresponding to the asteroid belt. They can be studied only upon a relatively close approach of the platform, because of their small size, and from the direction of the solar illumination [4]. They have no internal heat-generating mechanism, they are too small and too far away from the Sun to absorb adequate amounts of solar heat to offer an infrared representation. There exist a number of difficulties related to their investigation: for example, in 1991 the planetary probe Galileo, designed to study outer planets and their moons, also tried to capture an image of the asteroid Gasper, while cruising to its distant goal. The potato-like asteroid was indeed captured in several CCD camera frames [5]. However, the resolution and contrast were very poor due to the inadequate illumination conditions. Thus, the best description of the surface morphology that the scientists were able to propose was "irregularly shaped".

The comet nuclei are even more interesting than asteroids, because they are thought to be objects from outside the solar system. They potentially incorporate matter, that is different from that found in our solar system. They have undergone a different life cycle than the objects belonging to the solar system. Consequently, more effort has been made to study them; and, at the same time, we have encountered more difficulties in even seeing them. As the comet approaches the Sun in its elliptical trajectory, some volatile gases leave the frozen nucleus, forming its radiant coma and tail. The comet nucleus is generally invisible, because it is surrounded and shaded by ionized gases glowing in blue and red. The comet nucleus, obstructed by the corona, radiating in the visible light, is cold and dark. It can be made "visible" if illuminated by infrared light.

2. ILLUMINATION TO SENSE SURFACE SHAPE

With an active and controlled illumination of straight cosine-square interference fringes, not only the object outline but also the isometrics of its surface morphology may be re-constructed to generate the surface relief function. This object-illumination method allows the identification of object shapes by their reflectivity upon illumination. First, the object may be confirmed as being within the camera field of view. Second, the object curvature may be calculated by the methods developed in the Moiré interferometry [6]. Thus, the reflected light is incoherent and may be collected by a large telescope, either in space or on the Earth. The object may be recorded as a function of time to obtain the object spin velocity and to reconstruct its image in three-dimensions from a sequence of frames [7].

Active illumination provides the radiative power to a moving object with one, two, or several coherent apertures. When illuminating with more than one aperture, a two or multiple-beam interference pattern is generated.

[illegible]ine-square interference pattern is the simplest to interpret because it results in stri[illegible]s p[illegible]cted on the object surface. For this reason, it is studied further in this paper.

By changing the relative phases of the illuminating apertures, the stripes can be made to travel across the object, "feeling" its shape, once the apertures are locked simultaneously on the moving object. This is somewhat similar to humans using the fingers to feel the shape of an unknown object when sense of vision is not available for the normal "seeing" function.

In order to measure the two principal curvatures of an object at a specific position, two sets of fringes should travel across the object to "feel" its shape in two perpendicular directions. Our simulations, though, are confined to a single dimension.

Several illumination techniques may be used to generate the reflected signal: single aperture, multiple aperture, and two-aperture illumination. They are discussed next.

3. Coherent ilumination approach

The preferred approach to the generation of the signature from an object that has no intrinsic signature is to illuminate it with two mutually coherent laser beams. Because they are coherent, they interfere (on the object surface). Since the illuminated object is located a great distance from the apertures, the beams also diffract.

3.1. Single aperture illumination

Single aperture illumination results in a nearly uniform field illumination of the object, with the only intensity variation due to that of the illuminating source itself. When a laser beam is used as the source of the coherent illumination, its electric field is characterized by magnitude, polarization, and phase. This way we can, in principle, obtain the information about the shape of the object as in any direct observations [8, 9]. However, upon the beam transmission through the atmosphere, the beam reflected from the object suffers distortion in both amplitude and phase.

3.2. Multiple aperture illumination

Earlier studies were performed with several coherent beams illuminating the object[10, 11]. Depending on the relative sizes of different apertures, many intensity peaks are generated over the surface of the body in the case of the theoretical multiple beam interference.

However, the surface curvature information is not obtained easily with either one-aperture or multiple-aperture illumination. Additionally, the option of controlling the illumination by changing the relative phase among beams is lost.

Similarly, the beam misalignment and/or imperfect tracking of the moving object with the illuminating apertures results in the random displacement of the intensity peaks. This jitter results in the spreading out of the intensity, resulting in a decreased modulation of the illuminated beam.

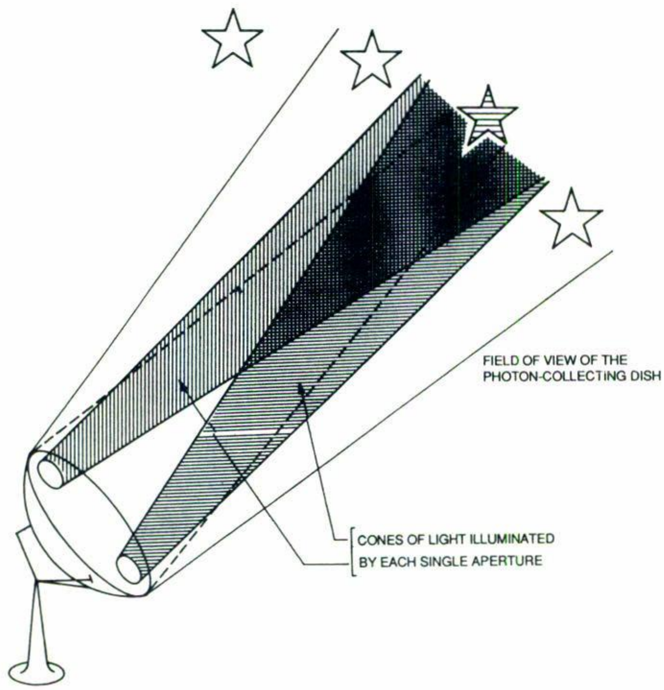

FIGURE 1. Two-aperture illumination of an unknown object.

3.3. TWO-LASER-BEAM ILLUMINATION

Two-laser-beam illumination results in a very simple illumination pattern-"black and white" stripes that are generated by the intensity peaks, in one direction only. The stripes have a cosine-square characteristic profile along one direction across the target surface. This intensity variation is relatively simple to implement. The laser light from two apertures may be synchronized and apertures may be positioned with respect to each other, generating any required direction of cosine-square pattern. This pattern can be generated by the application of synthetic apertures, or any other currently available technology.

Two-aperture illumination is schematically demonstrated in Fig. 1. Observe that beams originate from two small apertures on a large dish. These beams overlap and interfere on the surface of the unknown object (stars of finite size, in the example shown) on the object surface, producing there intensity fringes. The two illuminating apertures may be actively controlled segments of a large telescope, such as the Keck telescope [12]. The same large telescope or a separate one may be used to detect the illuminated object.

One of the significant features of this approach is that other objects may be within the field of view of the optical system, but they contribute no signal in the selected illuminating wavelength because they are not simultaneously illuminated by the two laser beams. This is particularly useful in the case of a comet nucleus, surrounded by the visible corona that transmits the coherent radiation.

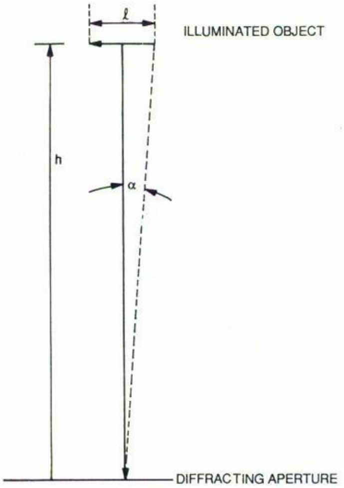

FIGURE 2. Definition of geometrical parameters in the agile object illumination.

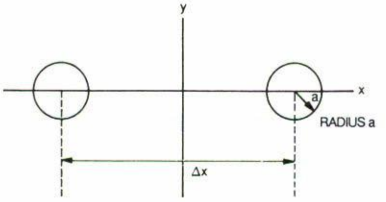

FIGURE 3. Two circular apertures of radius a, separated by distance Δx, produce interference and diffraction.

Objects of interest may be defined with the help of Fig. 2. The object is described by its characteristic dimension, l; its location at a height, h, above the aperture; it subtends an angle, 2α, at the diffracting aperture.

4. INTERFERENCE AND DIFFRACTION EFFECTS

4.1. ANALYTICAL BASIS

Laser light originating at two apertures of radius a, separated by a distance Δx, will produce interference and diffraction effects on a distant object. The analytical development is presented to establish relationships among experimentally controllable quantities to generate agile illumination.

The standard notation used to describe wave properties of light is followed here [13]. Two equal circular apertures with radius a are located along the x-axis of a Cartesian coordinate system. They are separated by distance Δx. This geometry is shown in Fig. 3. Light originating at the apertures diffracts when propagated over large distances. If the aperture radius a is small enough, and distance h is large enough, then the Fraunhof-

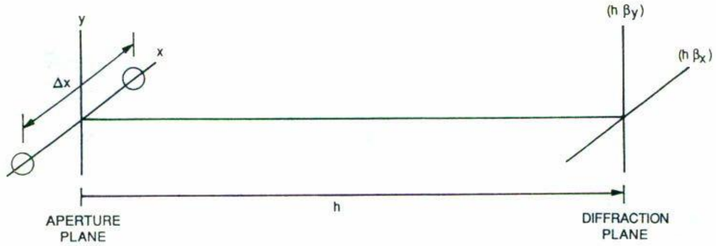

FIGURE 4. Interference and diffraction effects observed at the plane at a distance at h above the plane of the apertures.

fer diffraction approximation is applicable. Light from the two apertures produces an interference pattern on the object when both beams are simultaneously directed on the object. The coordinate system where the diffraction pattern is observed is shown in the Fig. 4. The observation plane is located at distance h above the plane of the apertures. The observation plane is parallel to the plane of the apertures, with the coordinate axes $(h\beta_x)$ and $(h\beta_y)$. This choice allows the angular subtends β_x and by to be used explicitly.

If the radius a is small enough, distance h is large enough, and the wavelength is short enough, then the Fraunhoffer diffraction approximation is applicable to describe distribution of the diffracted light. Two plane waves with uniform amplitude and phase difference δ are incident on the apertures. Using the analysis similar to that in Born and Wolf in Ref. 13, Sect. 8.5, the intensity distribution can be written as

$$I(\beta_x, \beta_y) = 4\pi E \left(\frac{a}{\lambda}\right)^2 \left[\frac{2J_1\left(2\pi a h\sqrt{\beta_x^2+\beta_y^2}/\lambda\right)}{2\pi a h\sqrt{\beta_x^2+\beta_y^2}/\lambda}\right]^2 \cos^2\left(\frac{\pi \Delta x h \beta_x}{\lambda} + \frac{\delta}{2}\right) \qquad (1)$$

where β_x is the angle measured parallel to the line through centers of apertures, β_y is the angle measured perpendicular to β_x, E is a constant, depending on total energy in the beam, a is the radius of the aperture, λ is the wavelength of the laser, h is the height of the observation plane above the aperture plane, Δx is the separation of the aperture centers, δ is the difference in phase for the electric fields originating at the two apertures, and $J_1(x)$ is the Bessel function of the first kind.

The intensity distribution of Eq. (1) depends on two factors: (a) the square bracket with the Bessel function is due to the diffraction at a single aperture, and (b) the interference term is represented by the cosine-square factor. The diffraction pattern due to a single circular aperture is sometimes called an Airy pattern. For most cases of interest, the interference term modulates the term that contains the Bessel function.

4.2. TYPES OF ILLUMINATION

Three-dimensional interference and diffraction patterns were obtained for a specific observational and detecting geometry, feasible with the current telescope technology. In all cases that follow, the aperture radius has been chosen to be 0.05 m. This is the radius

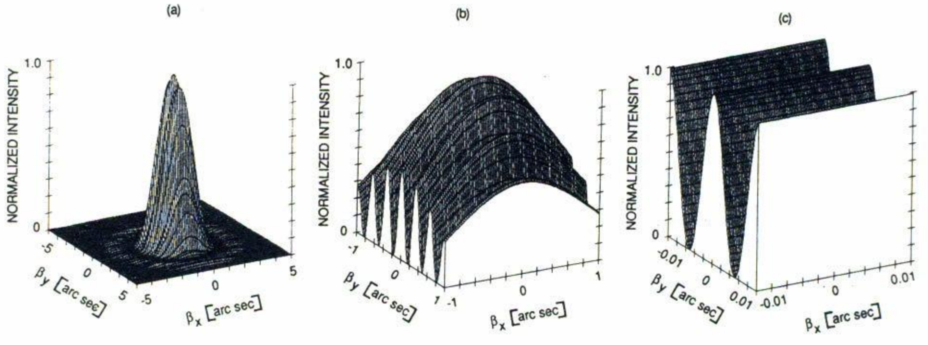

FIGURE 5. The intensity distribution due to combined interference and diffraction effects shows how the apparent dominance of the diffraction effects gives way to interference effects (as the horizontal scale is expected). The first two figures are under sampled; there are many more zeros than shown two circular apertures, radius 0.05 m, separation 1 m, wavelength 1 μm, phase difference 0.

of the largest aperture that will maintain coherent illumination despite the presence of atmospheric turbulence [14]. Figure 5 shows the illumination pattern on an unknown object as a function of angle due to two-aperture laser illumination. The number of zeros in the cosine-square interference term is so large, that the plot (a) is under-sampled because of a course plotting routine. It is necessary to expand the horizontal scale significantly to see each zero. This figure also illustrates how the Bessel function intensity pattern changes into a cosine-square pattern as the horizontal scale is expanded.

The illumination parameters can be related to the object dimensions by examining arguments of the Bessel function and the cosine-square function. The argument of the Bessel function is

$$\frac{2\pi a(h\beta_x)}{\lambda}. \tag{2}$$

The distance measured on the target, along the $(h\beta_x)$ axis, is $(h\beta_x)_T$. The argument of the cosine-square factor is

$$\frac{\pi\Delta x(h\beta_x)}{\lambda}. \tag{3}$$

A characteristic object dimension, $(h\beta_x)T$, is generally not available for modification; other illumination parameters, including a, λ, and Δ_x, can be chosen in such a way as to produce an optimum signal. Different relationships among illumination parameters may be constructed depending on the required type of illumination: uniform object illumination (Case 1), maximum illumination of a single object (Case 2), and single fringe illumination (Case 3).

4.2.1. Case 1. Uniform object illumination

The linear dimension on the target, $(h\beta_x)_T$, subtends only a portion of the peak area of the Airy function. One fifth of the distance between the peak and the first zero of the

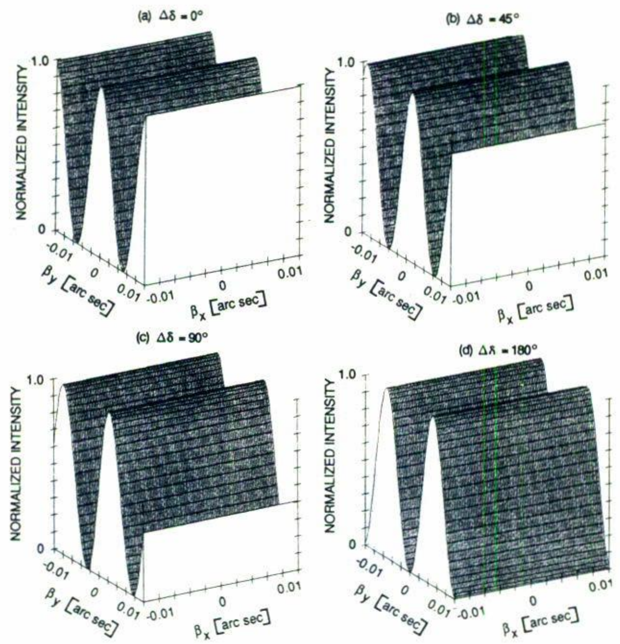

FIGURE 6. Uniform object illumination. The fringes travel across the object by changing the phase of one aperture with respect to the other. Two circular apertures, radius 0.06 m, separation 20 m, wavelength 1 μm, phase difference varies.

Bessel function will result in a nearly uniform illumination:

$$(h\beta_x)T = 0.12\,\frac{\lambda}{a}\,. \tag{4}$$

The width of the stripe, $(h\beta_x)s$, may be defined as the separation between two zeros of the cosine-square factor:

$$(h\beta_x)_S = \frac{\lambda}{2\Delta x}\,. \tag{5}$$

The target object needs to be illuminated with about five stripes across its long dimension:

$$(h\beta_x)_T = 5(h\beta_x)_S\,. \tag{6}$$

When Eq. (4) and Eq. (5) are substituted into Eq. (6), we get a surprising relationship among the quantities of interest:

$$\frac{a}{\Delta x} = 0.048. \tag{7}$$

For the requirement of a uniform illumination the separation of the apertures is approximately 20 times the aperture radius. In the case of a 0.05 m radius for the aperture, the separation is 1 m. It is interesting to observe that the wavelength does not enter into this relationship. Figure 6 shows uniform object illumination.

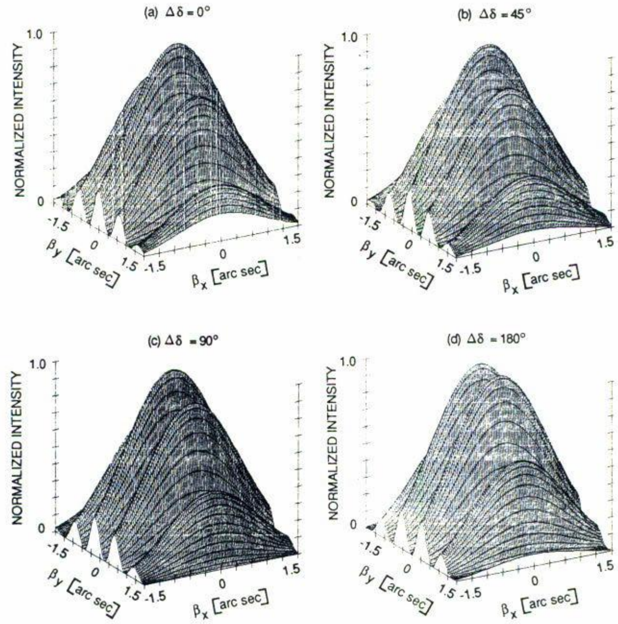

FIGURE 7. Maximum illumination of a single object. The fringes travel across the object by changing the phase of one aperture with respect to the other. Two circular apertures, radius 0.05. m, separation 0.03, wavelength 1 μm, phase difference varies.

The temporal dependence of the signal collected from the illuminated object requires that a time-dependent illuminating intensity pattern be generated. This is most easily achieved by scanning the interference fringes across the object. Fringes can be made to scan across the object by changing the relative phase of laser light originating at two illumination-producing apertures. This is also shown in the Fig. 6.

Uniform object illumination has two shortcomings for object identification. First, if there are others objects in the vicinity, they will also be illuminated; and so the unique identification of the object is not possible. Second, laser power is diluted over a large area; therefore, power density on the target is decreased. A more effective utilization of the laser power is obtained in the case of the maximum illumination of a single object.

4.2.2. Case 2. Maximum illumination of a single object

The linear dimension on the object subtends up to the first zero of the Bessel function:

$$(h\beta_x)_T = 0.061\frac{\lambda}{a}. \tag{8}$$

If the object is again assumed to be illuminated with about five stripes, then the following relationship is obtained:

$$\frac{a}{\lambda} = 0.24. \tag{9}$$

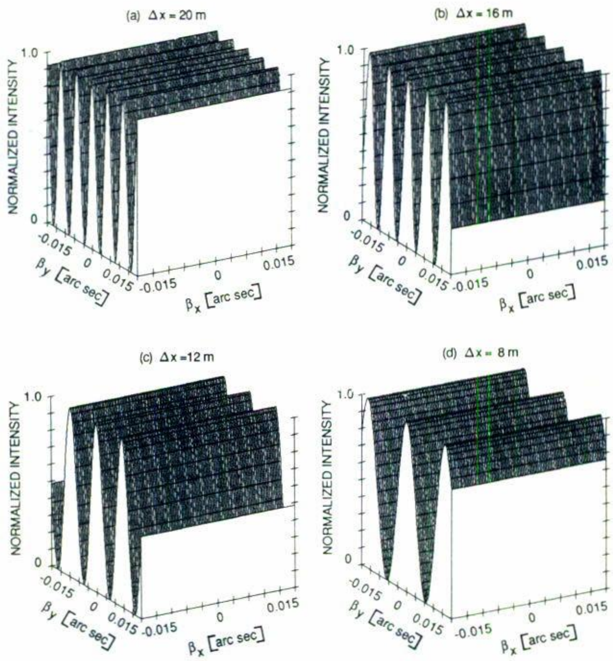

FIGURE 8. The number of fringes across an object of a fixed angular size can be va anging the separation of the centers of the apertures. Two circular apertures, radius 0.05 m, separation varies, wavelength 1 μm, phase difference 0.

The wavelength again drops out of the relationship. For the requirement of the maximum illumination of a single object, the separation of the apertures is approximately equal to four times the aperture radius. In the case of a 0.05 m aperture radius, the aperture separation is 20 cm. Figure 7 shows maximum illumination of a single object. The fringes are seen to travel across the object by changing the phase of one aperture with respect to the other.

4.2.3. Case 3. Single fringe illumination

Signal-to-noise analysis of the returned signal shows that one fringe across the object results in the optimal signature to confirm the object presence, but not object shape. The agile illumination technique can be applied to the generation of a different number of stripes per characteristic object dimension, just by changing one or more of the illumination parameters.

The angle subtended by the unknown object at the illuminating apertures will be different depending on the object size and its height. The number of fringes across the object can be decreased by reducing the aperture separation, as shown in Fig. 8. This is easily implemented using the system shown in Fig. 1, where a larger diameter dish may consist of a large number of small, actively controlled apertures. The number of fringes across an object can also be decreased by increasing the laser wavelength as is shown in Fig. 9. This approach requires several operational lasers for its practical implementation, and it may not be very efficient.

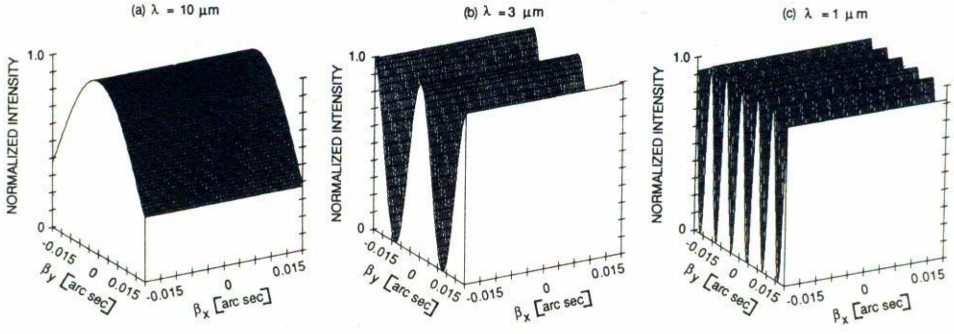

FIGURE 9. The number of fringes across an object of a fixed angular size can be varied by changing the wavelength of the laser beam. Two circular apertures, radius 0.05 m, separation 20 m, phase difference 0.

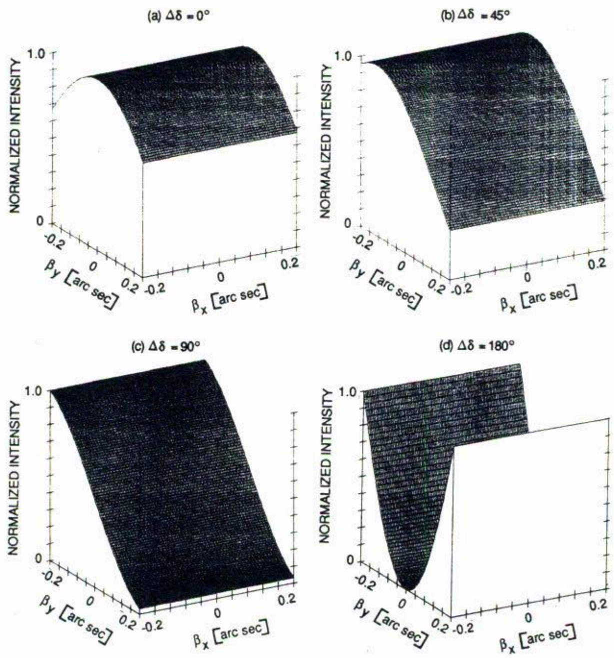

FIGURE 10. Single fringe illumination. The fringe travels across the object by changing the phase of one aperture with respect to the other. Two circular apertures, radius 0.05 m, separation 1 m, wavelength 10 μm, phase difference varies.

Single fringe illumination can be seen in Fig. 10. The interference fringes travel across the object by changing the phase of the aperture with respect to the other. Figure 11 also shows a single fringe illumination. However, it is seen that de-tuning the laser beam by making it run at a slightly different wavelength results only in a small displacement of the cosine-square intensity distribution.

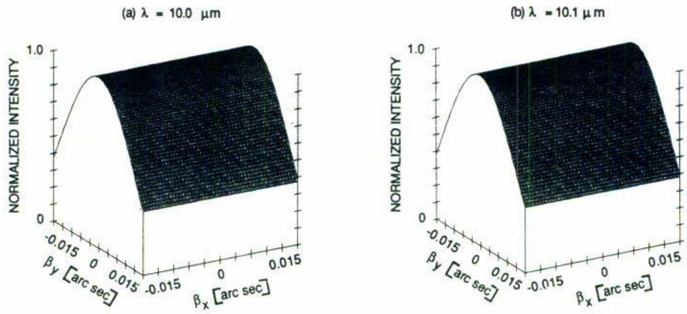

FIGURE 11. A small change in cosine-square intensity distribution is produced by changing the laser wavelength at 10 mm by a small amount. Two circular apertures, radius 0.05 m, separation 20 m, phase difference 0.

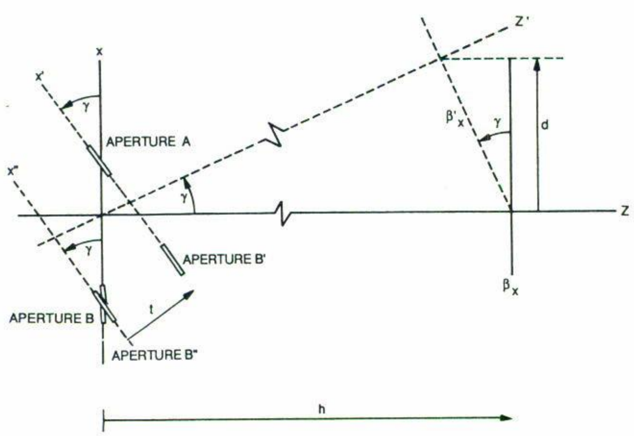

FIGURE 12. Tilt of two apertures: A and B' are two tilted coplanar apertures; A and B" are two tilted non coplanar apertures.

4.3. SHAPE RECOGNITION

The phase change introduced uniformly on one of the coplanar apertures will shift the cosine-square pattern (the zero location will be changed). The introduction of a phase shift on one aperture will not change the amount of illumination on the target because of the large number of the stripes. The amount of illumination will only be affected if the target is illuminated by one stripe or less.

The phase delay necessary for fringe scanning across the object can be introduced into the beam originating at one aperture with respect to the other by changing the path length leading to the aperture. In an actively controlled aperture, the phase shift can also be introduced by rotating the apertures around their own axes. The tilt of two coplanar apertures (apertures lying in the same plane) results in the displacement of the position of the diffraction peak. This tilt results in the change in the pointing of the illuminating beam.

4.3.1. Case 1. Tilt of two coplanar apertures by the same angle

Two coplanar apertures are tilted by the same angle γ, as shown for apertures A and B' in Fig. 12. The rotation of the x-axis on which the apertures are located results in the rotation of the z-axis along which the peak of the Bessel function is found. The peak is displaced by the distance

$$d = h \sin\gamma \approx h\gamma\,. \tag{10}$$

The tilt of two coplanar apertures results in the displacement of the position of the peak of the Bessel function.

4.3.2. Case 2. Tilt of two apertures by the same angle

Two apertures are tilted by the same amount, but their centers remain on the original x-axis. They are apertures A and B" in Fig. 12. Apertures B' and B" are separated by distance t.

The displacement of aperture B' to B" so that it is lying on x"-axis results in a phase shift:

$$\delta_t = \frac{t}{\lambda} - \left[\frac{t}{\lambda}\right]. \tag{11}$$

$[t/\lambda]$ represents the maximum integer smaller than t/λ.

The tilt of the two apertures by the same angle results in a change in the pointing of the illuminating beam, accompanied by a phase shift. Thus, it represents a combination of a phase shift on coplanar apertures and the tilt of two coplanar apertures by the same angle.

5. CONCLUSION

The two coherent beam illumination technique has been demonstrated analytically. A large number of graphical show that the informative illumination approach may be used to characterize the shapes of objects that in a direct-imaging approach may appear unclear or even invisible. This analytical development has been use to develop optimal parameters for agile illumination, such that efficient use of laser power is obtained. It was shown that the optimal aperture separation equals three to four aperture radii. This result is independent of the laser wavelength.

A very sensitive technique for changing the amount of light reflected from an object is obtained when the fringes are made to travel across the object by varying the relative phase of the illuminating beams. Intensity stripes can be drawn over an object of fixed but unknown dimensions by varying parameters, such as aperture diameter, aperture separation, and wavelength.

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