Holographic Nondestructive Testing of Materials

1-hologram

a-hologram(hòl´e-gràm´,ho´le-)noun

1. The pattern produced تتولد انماط on a photosensitive medium that has been exposedمعرض by holography andthen photographically developedيحمض اللوح الفوتوغراف.

2. The photosensitive medium so exposed and so developed <u>Also called hologram</u>.

b- hologram (hol'e-gram`) noun

A three-dimensional image record created by holography. The hologram consists of a light interference pattern preservedتحفظ in a medium such as photographic film. When suitably illuminatedيضاء بشكل مناسب, it produces an image that changes its appearance as the viewer changes viewing angle زاوية المشاهدة.

***<u>The first hologram ever made by Dennis Gabor, in 1947, was an in-line, plane</u>, <u>transmission type</u>*. Remember at this time the laser was still yet to be developed, so Gabor had to make due with the quasi-coherent light gained by squeezing light from a mercury vapor lamp through a pinhole and then color filtering it (he used the 0.546 micron mercury green line). In-line means that the reference beam and object beam are coming from the same direction or are the same beam. Gabor had to do this in order to mantain the little coherency he had gainedللحصول على ضوء متشاكه. All in-line holograms are also single beam set-ups. The same beam acts both as reference and object beam. This was made possible by using a transparency جسم شفاف as the object. The light which went through the transparency before reaching the plate was modulateيعدل by the transparency, the light which went through it and was not effected by the transparency was the reference beam. The diffracted light ضوء الحيود and reference light interferedيتداخل on the emulsionمستحلب of the hologram and thus fulfilledيتحقق one basic requirement for the construction of a hologram تكوين الهلوكرام. When the reference beam was later shown back through the hologram at the same angle relationship it had with the plate in the reconstruction stage an image appeared تظهر الصورة. A poor image due to the lack of coherent light, but worse still the reference beam shone directly into the viewers eye, thus**

greatly compromising the viewing of the reconstructed object. Although it was a poor image it was there in all its dimensionality. A new medium had been born, alas, a little prematurely and in 1948, was placed on the shelf until the advent of the laser.

Please note that through his experiments Gabor proved that an interference pattern carries all the information about the original object and that from the interference pattern one can reconstruct the object. For the discovery of these now well accepted concepts, *Dennis Gabor received the 1971 Nobel Prize in Physics*.

Transmission Holograms As I mentioned above in order to playback a hologram the reference beam must be shone back through the hologram at the same angle relationship as it had in construction. This is where the term transmission hologram arises. Transmission merely means that the reference beam must be transmitted through the hologram in order for the image to be reconstructed.

2-Holographic nondestructive testing techniques (HNDT)

are used to locate and evaluateتحديد cracks الشروخ, disbondsالروابط , voidsالفجواة , laminationsالتصفيح ,inhomogeneityعدم التجانس and residual stressesالاجهادات المتبقية in a test sample without destruction غيرأتلافية of the sample.. The holographic interferometry techniquesتقنية التداخل الهلوكرام are applied for nondestructive testing of materials.

***The HNDT techniques* can be used for the testing of laminated structuresالتراكيب المُرَقّقة , turbine bladesالشفرة التوربينية , solid propellant rocket motor casings غلاف الصاروخ ذات الوقودالصلبةِ tyres and air foilsالإنسيابية السطوح. These techniques are also useful in medical and dental researchفي بحث الطبِ وطب الاسنانِ . In HNDT techniques, the test sample is interferometrically comparedمقارنة with the sample after it has been stressed .**

A flawأي عيب can be detected if by stressing the object it creates an أي يَخْلق anomalous deformation تشويهَ شاذ of the surface around the flawشاذ . The holographic interferogram will show up the anomalous deformation by an abrupt changeالتغييرالحاد in the shape of the interference pattern.

The object can be stressed by mechanical stressing أجهادات ميكانكية, pressure or vacuum stressing أجهادات الفراغ والظغط, thermal stressing أجهادات حرارية, vibrational stressing أاجهادات تذبذبية and magnetic stressing أجهادات مغناطسية. The stressing of the object can create gross deformation ً body يُمْكِنُ أنْ يَخْلقَ َ تشويهِ إجمالي على الجسم. This will produce fine interference fringesأهداب ناعمة بسب التداخل in the interferogram if the test area is large. In such a situation على نفس الموقع, the interference fringes around the flawالخلل will be very fine and it would not be detected by unaided eyeالعين المجردة

Field المجالات	Applications التطبيقات
Aerospace الفضاء	Defects in honeycomb plates عيوب في صحون قرص العسل Testing of construction materialsفحوصات لمواد البناء, Testing of welding methods فحوصات في طرائق اللحام Inspection of rocket bodiesفحص أجسام الصاروخ Flow visualization in wind tunnels التصوير في الأنفاق الهوائية Vibration modes of turbine blades أنماط أو أشكال الإهتزازات في الشفراتِ التوربينيةِ
Auto mobiles	Testing of oil pressure sections إختبارفي مقاطع ضغط النفط Testing of welding methods Research in construction of automobile bodies Construction of engines بناء المحرّكاتِ
Machine tools and precision instruments الاجهزة الدقيقةوالمعدات المكانكية	Measurement of deformations of machine parts, jigs and toolsالمعدات Measurement inside cylinders الافحوصات داخل الاسطوانات Measurements of stiffness القياسات الصلدة (heat, static or dynamic) Analysis of construction of instruments بناء الآلاتِ and toolsالمعدات
Electrical and electronic industries	Vibration modes of turbine bladesالشفرات التوربينية , motors ,المحرّكات transformers, loudspeakersالمحولات، السمّاعات الصوتية . Testing of welding and adhesion الإلتصاق Testing of circuit parts الاجزاء الدائرية Analysis of audio equipments التحليل في الأجهزة السمعية Leak test of batteries النضوح في البطاريات
Civil Engineering الهندسة المدنية	
Chemical industry	Measurement of mixed fluids خلط الموائع. Tyre, rubber and NDT of tyres, plastics Testing of molded productsالمُنتَجات المَصْبُوبة . Measurement of adhesion defects وعيوب الالتصاق
Medicine	Measurement on living bodies الأجسام الحيّة . Chest deformation due to inhalation تشويه الصدر بسبب الإستنشاق . Measurement on teeth and bonesقياس مواصفات الأسنان والعظام Testing materials for dental surgery جراحة أسنانِ . Testing of urinary trackالمجاري البولية . Measurement on eyes, ears, etc.مقياسات العيونِ، والآذان
Musical instruments	Measurement of vibration modes مقياس أنماطِ الإهتزازالموسقيةِ .
Cultural الثقافةarticles and paintings الطلاء	NDT and restoration. ا الترميم

2- Hologram Basics

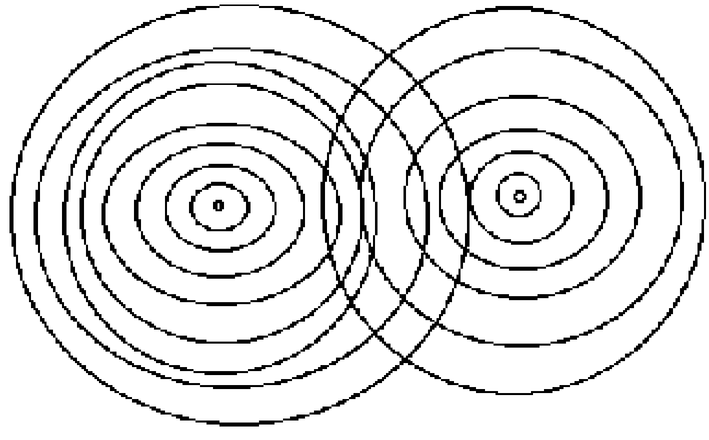
There are a few basic things to learn about holograms.

1) the wave interference patternأنماط تداخل الموجاتَ .
2) the coherencالتشاكه .
3) how holograms store and project information معلومات عن كيفية التصوير المجسم.

1. Interference Pattern

The hologram is based upon Nobel Prize winner *Dennis Gabor's theory* concerning Interference patterns. Gabor theorized in 1947 that each crest of the wave pattern contains the whole information of its original source , and that this information could be stored on film and reproduced ويعاد أنتاجها .This is why it is called a hologram كل قمة للانماط للانماط الموجية تحتوي على جميع المعلومات للمصدر الاصلي،وَ أنَّ هذه المعلوماتِ يُمْكِنُ أنْ تُخْزَنَ على الفلمِ وأعادتْ ملاحظتها. وهذا يسمىالهلوكرام او التصوير المجسم للانماط .

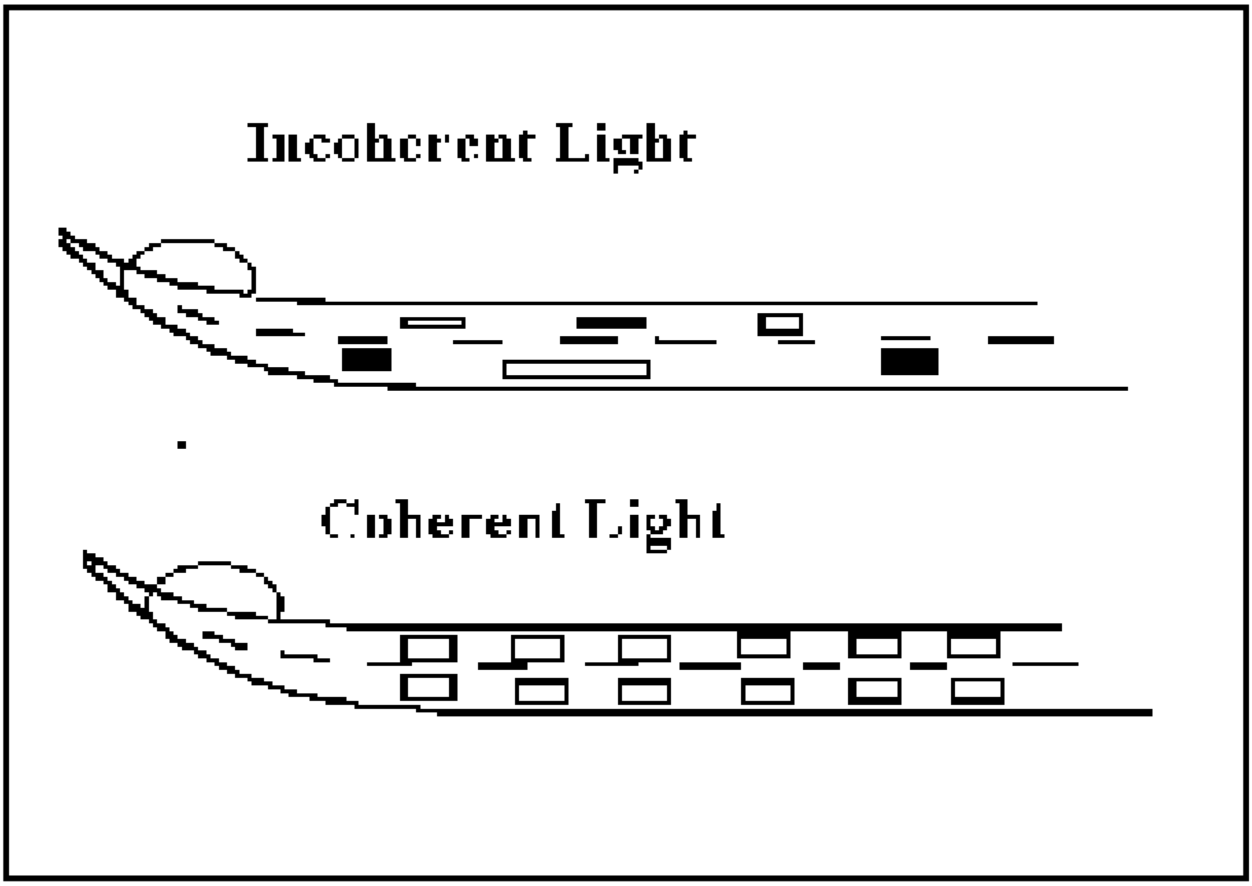
A pebbleحصاة , dropped in a still pond بركةَ هادئة , is the most basic example used to describe the wave interference processعملية تداخِل الموجاتَ . If you drop a pebble into a pond, it creates an infinitely expanding circular wave pattern يَخْلقُ بشكل مطلق أنماطِ موجيةمتوسعةِ . If you drop two pebbles into a pond the waves' crests would eventually meetالقمم تَجتمعُ في النهاية . The intersecting points of the waves' crests are called the points of interference.قمم تَدْعى نقاط التداخل . The interference of two or more waves will carry the whole informationسوف تداخل الموجتان أو موجاتِ أكثر وستحمل المعلوماتَ الكاملة .

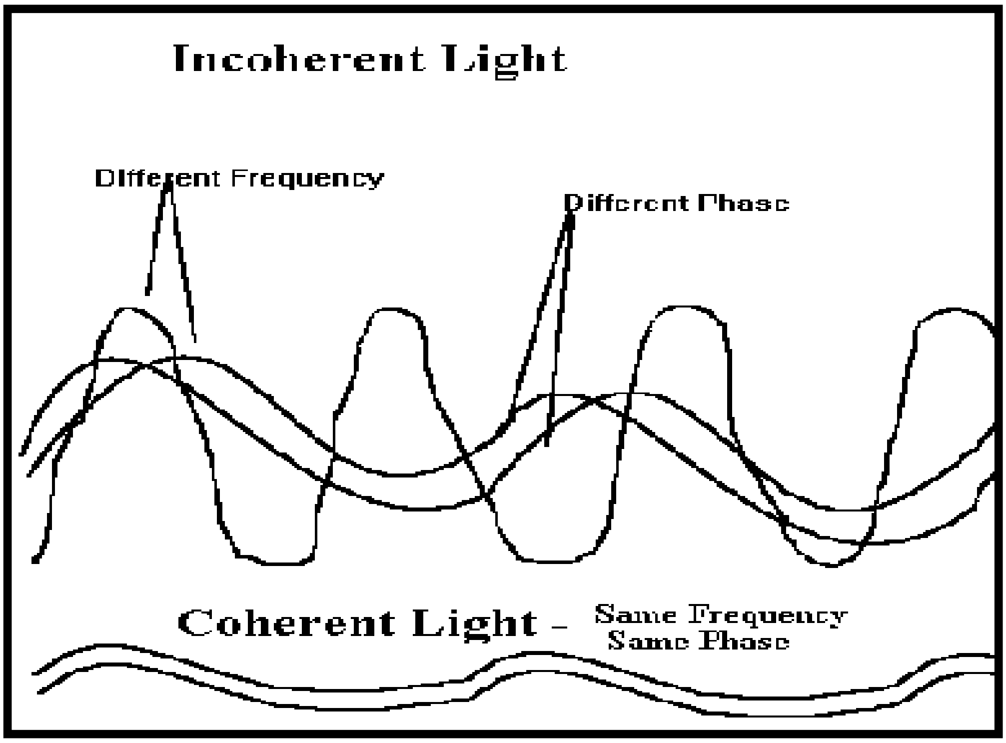


Wave Interference Pattern

2. Coherent Light

Gabor recorded several images holographically, but wasn't successful at producing a clear image because he could only use forms of incoherent, white light.An example of incoherent light would be if you were watching cars coming out of a tunnel, you would likely see many different models and types of cars, traveling at different speeds and at different lengths apart. Now, suppose you started seeing the same model and type of cars, all heading down الانخفاض في the highway at the same speed, and the same distance apart. This would be an example of coherent light. Holograms need coherent light to record or playbackأعادة the image clearly.

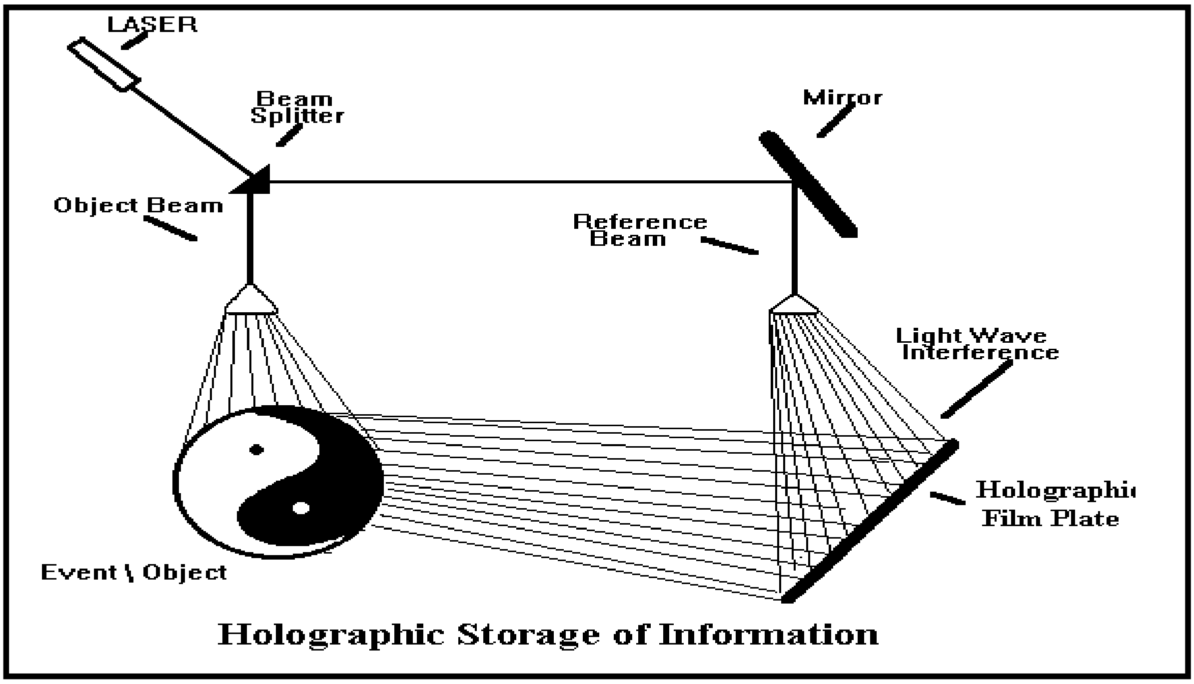


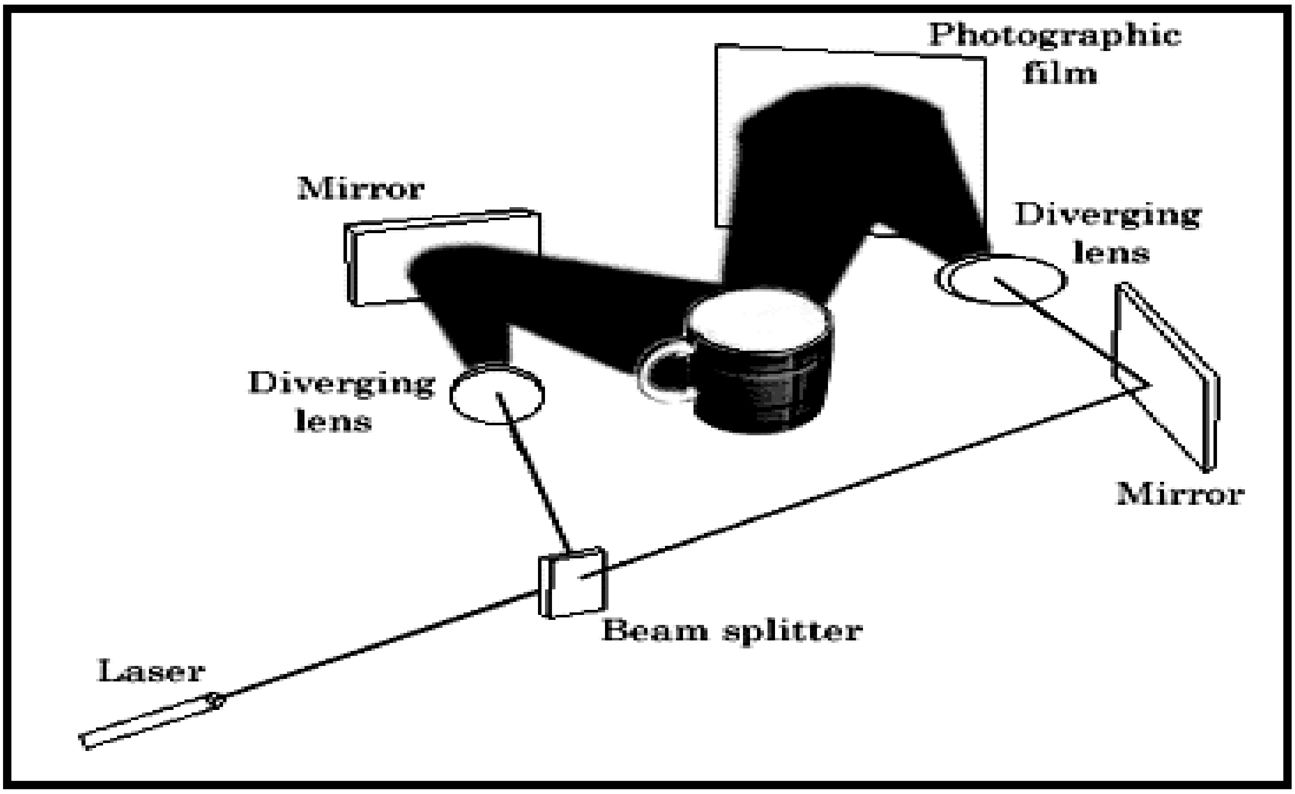


The L.A.S.E.R. (Light Amplified by Stimulated Emission of Radiation) was inventedأخترع to produce coherent light. <u>**Incoherent light travels in different frequencies and in different phases. Coherent light travels in the same**</u> <u>**frequency and in the same phase. (100% coherent light is rare نـادر**</u>**) It is important to use light which is coherent because the information is carried تحمل on the crest of each wave فـي قمـة كل الموجـة. The more points of intersection نقاط الثقاطع المختلفة, the more informationlug معلومـات كثيرة.**

<u>*3. Storing Information*</u>

Unlike a camera آلات التصوير المختلفـة , which has only one point of light reference واحـد واحـدة مِنْ فقط مِنْ نقـاط المرجـع الضـوئي , a hologram has two or more points of light references اكثـر مـن نقطـة نقـاط المرجـع الضـوئي . The intersection points of the two light waves contain the whole information تحتـوي علـى كل المعلومـات of both reference points ا. A LASER is used as the light source so the waves are coherent

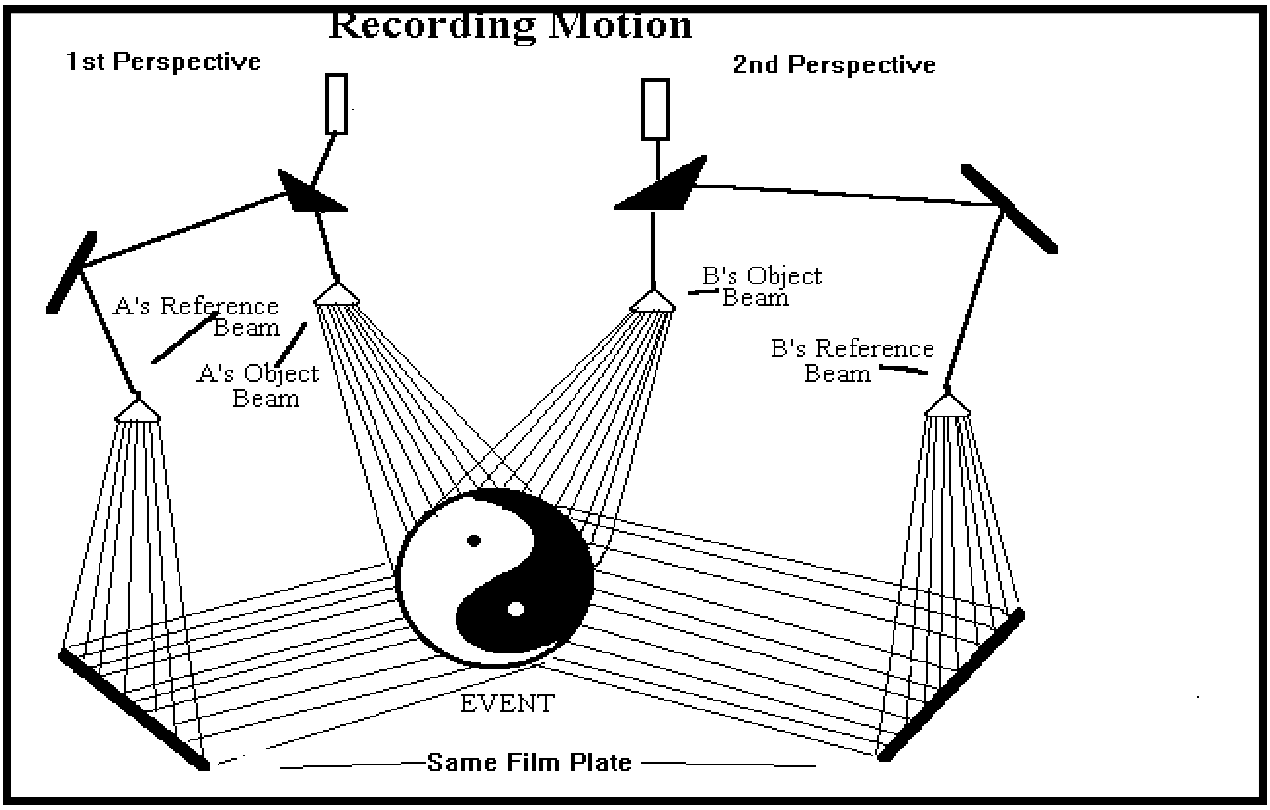




<u>A LASER</u> is projected onto a partially silvered mirror called <u>a beam splitter</u>. This

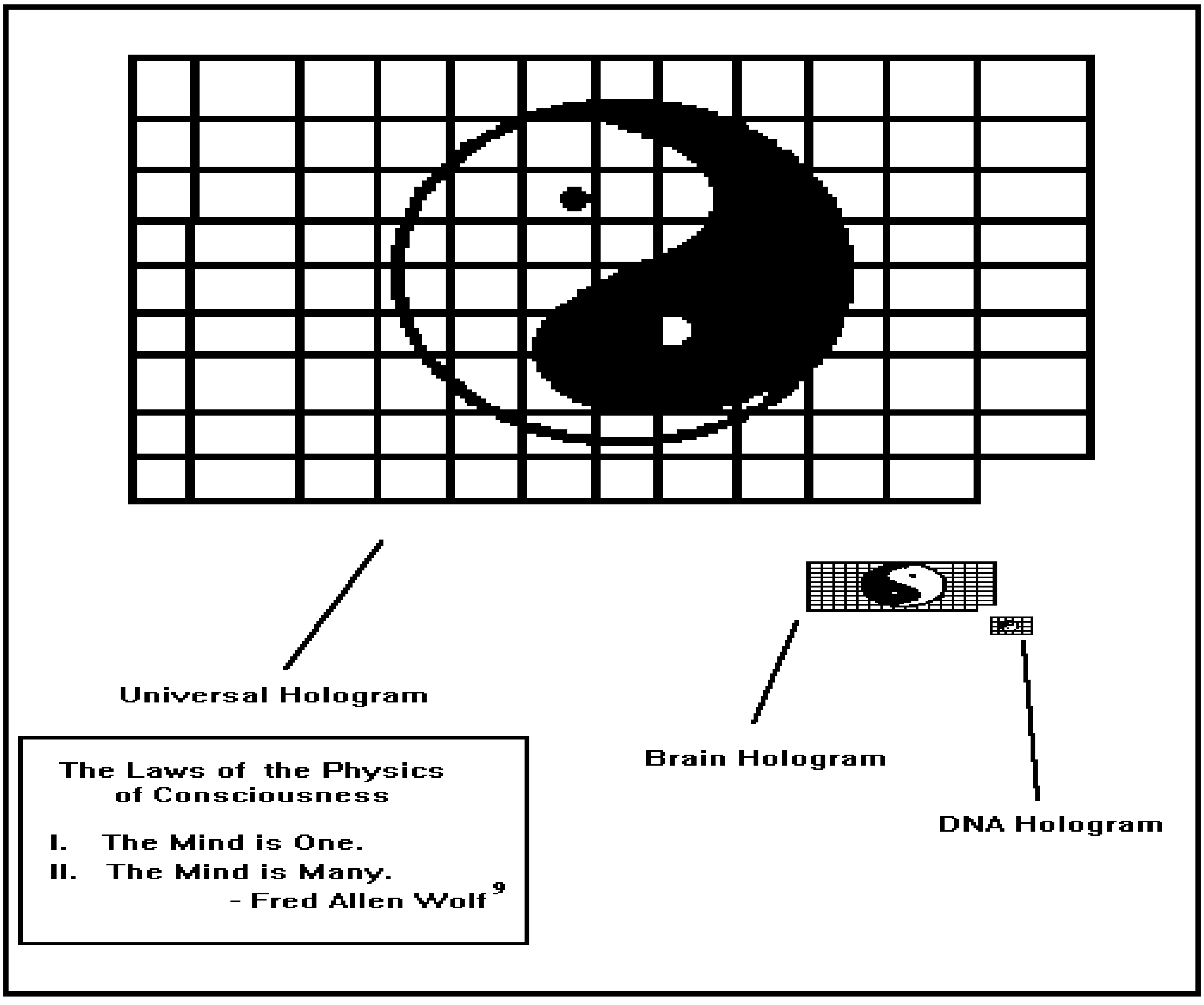
mirror splits the original beam into two beams. One beam travels through <u>a lens</u> that diffuses ينشر the light onto the object being recorded النموذج المراد تصويره. This light, called <u>the object beam</u>, is reflected off the object المنعكس من النموذج onto the <u>film plate</u>. The second beam is bouncedd off ينعكس من a mirror and then through a lens that diffuses the light directly onto the film. This beam is called <u>the reference beam</u>. The same light source needs to be used for both beam so the waves will have perfect intersection pointsنقاط التقاطع المثاليةِ .

To add motionالتغير (time) to your holograph, you would turn قلب the object, or move the mirrors and lenses, and shoot again onto the same film. The original waves recorded on the film, will intersect with the waves from the new perspectiveمنظور اخر .



4. The Whole In Each Part

One of the most interesting qualities of the hologram من الميزات المهمة للهلوكرام is that the whole contains the knowledge o each partالكل يحتوي على المعلومات الكاملة للجزء , and that each part contains the knowledge of the whole كل جزء يحتوي على المعلومات كاملة للكل . If you breakكسر a hologram into many pieces each piece will still contain the whole image, but with a limited perspective قصور في المظور . The image stays the same size but you loose clarityالوضوح and you loose perspectives خسارة فى المنظور. A hologram is like a window If you make the window smaller, the objects don't get smaller but you loose some of your view . إذاجْعلـ ُ النافذة صغيرة، فان الأجسام تبقى على أبعادها الاصليةو لكنك تفقد جزء من الوضوح



3- Characteristics of a Hologram مميزات التصوير المجسم

Leith and Upatnieks in 1962 **demonstrated a technique عمل تقنية which made it possible to separate يفصلthe twin images الصور التوأمية. In this technique a separate coherent reference wave is allowed to fall on the hologram plate شريحة الهلوكرام during the recording process عمليات التسجيل, at an *offset angle* to the beam from the object. The exposed plate تعرض الصحيفة is developed يحمض by normal photographic rocedures so that the amplitude transmittance السعة المارة of the plate after development is proportional to the exposure التعرض.The output consists of the following four terms*:***

(a) attenuated direct beam توهين الشعاع المباشر .

(b) a halo around the direct beam هالة حول الشعاع المباشر.

(c) a virtual image of the object صورة الخيالية الجسم at the same distance from the hologram. This image is deflected off the axis at an angleهذه الصورةِ مُنْحَرفةٌ عن المحور بزاوية .

(d) a real image الصورة الحقيقية at the same distance from the hologram in front of it. This image is deflected off تنحرف عن the axis at an angle the opposite direction.

Thus an off-axis hologram generates virtual and real images angularly separated from each other and from the direct beam

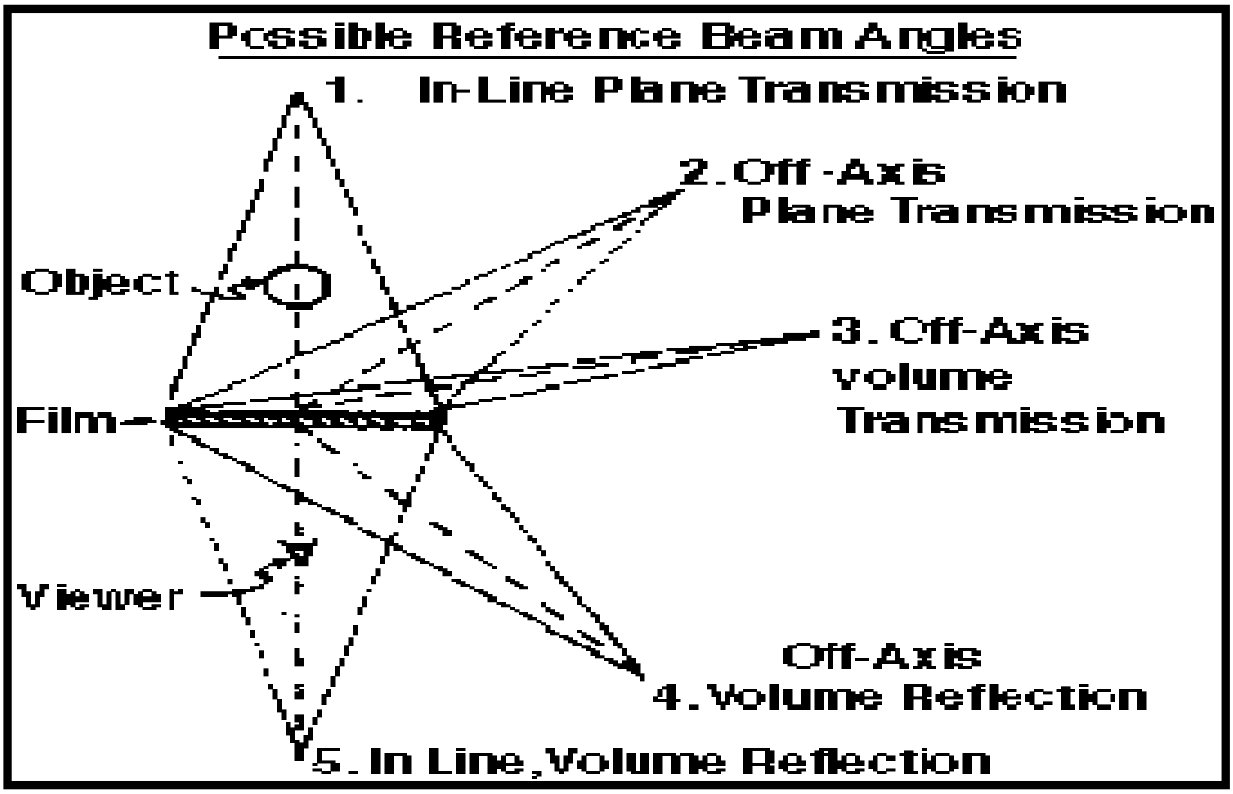
هكذاالهلوكرام يُولّدُ صورَ خيالية وحقيقية تنفصل الواحدة عن بعضها البعض وعن الشعاع المباشر.

The term off-axis means that the reference beam and object beam are not coming from the same direction. Naturally in order to perform ينجزthis featعمل we must have two different beams, thus the term twin beam. Because the laser gives a homogenous beam of coherent light we can extract a beam from the original beam as I mentioned earlier. This is done with the aid of a beam splitter, which could be nothing more than a piece of optical glass. A part of the original beam goes through the glass and a part is reflected at the same angle as its incident. This allows one to bring in the reference beam from an infinite number of angles in relation to the object directed beam, thus avoidingيتجنب the inconvenienceالازعاج in play back of having to look directly in the reference beam as with the in-line, transmission hologram.

4-Plane and Volume Holograms

This is a good time to point out the differences between a plane hologram and a volume hologram. As the angle difference between the object beam (or the wavefronts bouncing off the object) and the reference beam changes, so does the spacing of the patterns in the emulsion. As long as the angle difference remains less than 90 degrees the hologram is called a plane hologram. Plane meaning that the holographic information is primarily contained in the two-dimensional plane of the emulsion. Although the emulsion does have a thickness, usually around seven microns or 7/millionths of a meter, the spacing between fringes is large enough, when the angle is under 90 degrees, for us to imagine that the depth of the emulsion isn't really being utilized in the recording of the hologram. At 90 degrees, which is really a convenient but arbitrary point, the angle is great enough and fringe spacing has become small enough for us to say that the recording process is taking place throughout the volume of thickness of the emulsion. A point to remember is that although there are different thicknesses of emulsion put on celluloid or glass plates seven microns is an average. One can use the same emulsion say seven microns thick, and make both plane and volume holograms depending on the angle difference between reference and object beam.

Thus if you imagine your film in a fixed plane and your object in a stationary position, as you rotate the incidence angle of the reference beam, you can determine whether you are making a plane or volume holograms. If your angle is under 90 degrees it's plane, from 90 degrees - 180 degrees it's volume. Naturally, past 180 degrees you merely begin coming back the other way, through the volume to the plane and when finally you reach 360 degrees you are back at the in-line, a transmission hologram, .



A very important point for differentiation occurs as the reference beam swings around its arc of possible positions. In a plane transmission hologram the reference beam is hittingيصطدم the film from the same side as the object beam. In a volume reflection hologram the reference beam has made an arc clear around so that it hits the film from the opposite side as the modulated object beam. When 180 degrees difference is reached you are the constructing an in-line, volume, reflection hologram.

<u>A transmission type hologram</u> means that the reference beam must be transmitted through the hologram, in order to decodeيولد the interference patterns and render the reconstructed imageواعادة تكوين ا. The light which is used for playback must be coherent or semi-coherent or the image will not be sharp.

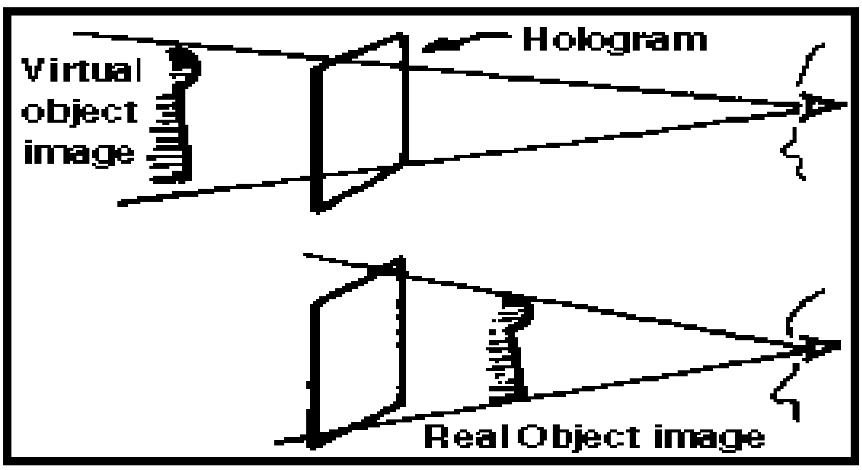
A hologram will playback just as well with laser light of a different color or wavelength than the light with which it was made. However, the object will appear to be of a different size and/or distance from the plate. For example, a hologram of an object made with neon

or red light will playback that object smaller or seemingly further away if a blue color laser is used. This is because the grating will bend the blue or shorter light less severely than the red with which it was made and with which it is meant to be decoded.

<u>Reflection Hologram</u> **Unlike a plane hologram, sometimes called a thin hologram, which requires a coherent or highly filtered playback source, a reflection, or thick, hologram can be viewed very satisfactorily in white light or light which contains many different wavelengths. The one requisiteمن الضروري is that the light be from a point source and be a somewhat straight line, such as a slide projector light or penlight, or the sun on a clear day. The reflection hologram can do this because in a way it acts as its <u>own filter</u>.**

In a reflection type hologram the playback light or reconstruction beam comes from the same side of the hologram as the viewer. Some parts of the incident light are reflected, some are not, depending on the interference pattern. If the hologram was made correctly the result should be a visible three dimensional image. <u>As I mentioned before in the transmission type the reconstruction beam must pass through the hologram and come towards the viewer from the opposite side of the hologram while in the reflection type the playback source comes from the same side of the hologram as the viewer.</u>

<u>The image produced</u> by the hologram can either appear to be in front of the holographic plate or film, or behind the film. In the former case it is called a real image (projection) and the latter a virtual image. If you imagine your position as viewer to be constant then you can easily determine whether an image is real or vitual. If the image appears between you and the hologram it is a real image, if the hologram is between you and the apparent object then it is called a virtual image

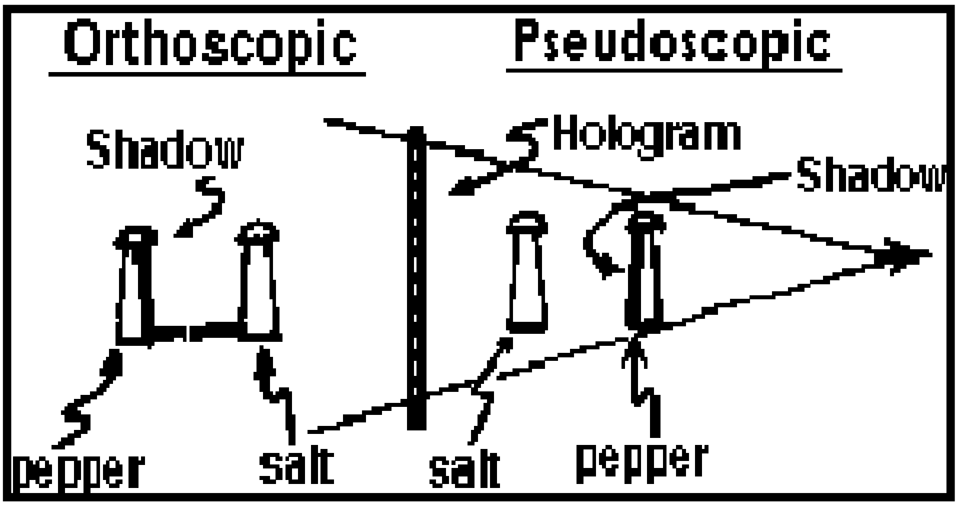


In general it is easier to view a virtual image because you can see through the hologram as if it were a window. I would like to mention here that as with other windows if you change the size of the windows the object or objects you are viewing do not change their size. For example, let's say you are lucky enough to have a window in your house that looks out on a beautiful tree. If for some terrible reason you have to make your window smaller, your tree luckily does not shrink, you merely have a more confined view or less possible angles of view of the tree.
To view a virtual image you must look through the hologram to perceive the object floating in the space behind it. In order to see a real image you look at the hologram and see the object in free space in front of the hologram. It is a little more difficult to view a real image because you have to find the image or focus your eyes in front of the hologram and in this case the hologram is less capable to act as a guide for your eyes. You may move a screen or sheet of paper back and forth in front of the hologram in order to find where the object is focused and then, keeping your eye on that place in space, remove the sheet and look straight into the hologram.

The real image is very exciting but there are a number of drawbacks. The object holographed should be quite a bit samller than the size of the film you are using, if not, you will not be able to see the complete real image of the object all at once. It will necessitate craning your neck and stretching in all which ways to see parts of the whole object or objects. Also, unless you take special precautions in the construction of the hologram, the real image will be pseudoscopic. This means simply that everything that was closer to the film when the hologram was made will now be further away and vice versa. This includes both individual objects in a shot or the different planes of space of an individual object. The pseudoscopic image is made by reversing the direction of the reference beam, or by turning the completed hologram around until seeing the image in front of the plate.

For example, if in making your hologram you placed a salt shaker closer to the film than a pepper shaker (let's imagine the salt shaker is even casting a shadow from the object

beam onto the pepper shaker), then in a pseudoscopic playback as a real image the pepper shaker will appear to be closer to you than the salt shaker which is no longer there.



Naturally, if you playback the virtual image of the same hologram the shakers would resume their original positions (in the latter sections we will discuss further the real image hologram, show possible ways of making holograms specifically for real image playback and also touch lightly on why there is a real image.)

6-Hologram Aberrations *إنحرافات الهلوكرام*

Holograms suffer يعاني from aberrations caused by a change in the wavelength from construction تكوين to reconstruction اعادة تكوين and also by a mismatch in the reference and reconstruction اعادة تكوين beams . Both the chromatic لوني and nonchromatic aberrations الزيغ الالوني are quite important even when only small deviation انحراف from the recording geometry هيئة الشعاع المسجلة are present in the reconstruction geometry هيئة اعادة البناء . The condition that will eliminate all the aberrations simultaneously متزامن is to duplicate أستنساخ exactly one construction beam in the reconstruction process.

7-Holographic Film & Plates(holograms)

There are numerous types of holograms, for example, they have just made a reflection hologram or transmission hologram or in line hologram. Holograms can differ in the way in which they are produced and they can incorporate and store the information for

playback. Under normal conditions we will be using a silver halide type film so we will talk about that specific case. The holographic information is coded in the emulsion according to the localized microscopic differences in the absorption of light or by the amount of silver halide converted to silver atoms during exposure and development. This is referrred to as an absorption hologram. The absorption pattern on the film corresponds with the amount of light incident on the plate during exposure. If that same hologram is put through a bleaching process it will then be termed a phase hologram. The absorption index by changing the different residues of silver to corresponding thickness of transparent substance. The hologram is then played back by the refraction of the reference beam dictated by changes of refraction in the emulsion. In a phase hologram the reference beam is phase modulated in order to reconstruct the wavefronts of the original objects. In absorption holograms the reference beam is diffracted by the small patterns of exposed emulsion in the form of silver residue.

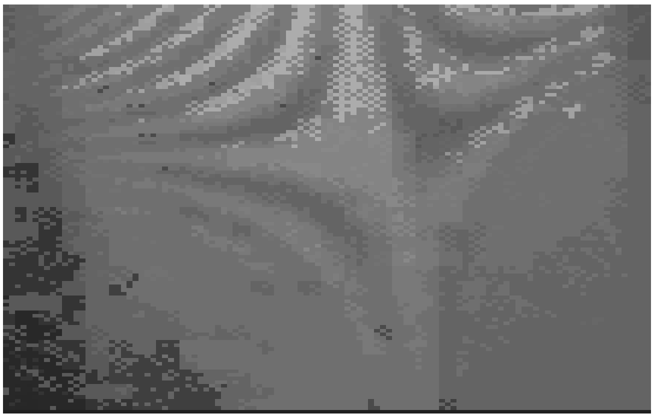
Many holographers bleach all of their holograms because phase holograms absorb less valuable reconstructing laser light than the absorption type and thus create a brighter image. However, some holographers do not bleach regularly, especially if they have made a perfect exposure in their original hologram. This is due to the fact that there is a slight loss of resolution along with the gain in brightness. Also, a poor bleaching technique increases the amount of noise and can greatly reduce the resolution. The source of the controversy, if any, is merely personal taste.

It is important to remember that the term absorption or phase hologram has nothing to do with way the hologram was exposed but, in the case of silver halide emulsion, refers only to a bleaching process which follows exposure and development, (although you may alter your development process if you know in advance you are going to bleach).

The following different types of holograms have special terms because they are actually constructed using different beam arrangements.. Remeber all the different types I'm about to describe can ultimately be either absorption or phase type holograms'.

Applications of Holography

INTERFEROMETRIC HOLOGRAMS as ART



Interferometry **is a method of creatingابتكـار holographic التصـوير المجسـم'contour' patterns (wave disturbances 'in time أظطراب الموجـات مـع الـزمن'), typically as a superimposition of two moments ('before' and 'after' disturbance)نموذجيـاً تركيـب مِـنْ لحظتـين and is found uniquely in holographic artويُوْجَدُ إستثنائياً في فن التصوير المجسّم , and more commonly in 'non destructive testing' in technical quality control (for example, testing wing structure integrity, tire integrity, etc.).**

Interferometry records and displays the wave nature of light subject to diffraction and interferenc في تقنية النتروفيرومتي يتم يُسجّلُ وعْرضُ الموجات الضوئية الاصليةِ للنموذج اعتمادا على مبدأ التداخل والحيود.هو a رسالة تذكير جميلة التe . It is a beautiful reminderرسالة تذكير جميلة that we live in a world of energy interfering, diffracting and recombining to shifting patterns and contours of lighبأنّنا نعيش في عالم تداخّل الطاقةِ و الحيود ةِ ثم جمع المقاطع المتحرّكةِ .

In holographic art **interferometry is a process of creating ribbon-like contour mappings and textures in objects or seemingly translucent media (water, air, glass, etc.) by the direct introduction (by the artist) of deformations or by making recordings at certain points of a changing state. Simply stated, the aesthetics of interferometric holograms as art are compositions of light interference that are more akin to the creation of 'musical chords of light' (which displays wave characteristics) than the study of fluid dynamics or 'stress measurements'. It isn't about old Pythagorean (new age) 'music of the spheres' but about the 'music of light' all around us.**

In Scientific measurements/tests, interferometry is used to reveal resonance patterns, properties of elasticity, stress, deformations in materials or media, and it is used in technical-industrial evaluations of structures, integrity of materials, hidden flaws in manufacturing, etc. And it got Michaelson and Moreley a Nobel prize for 'measuring the speed of light' and while inventing their interferometer, advancing our knowledge of the electro-magnetic wave nature of light.

Testing of Materials

- ***Successful class project.*** **The holographic image at the top left contains time average fringes for torsional vibration of a bar. The central bright fringe represents the nodal line. Higher order fringes are of progressively lower contrast in accordance with theory. The bar is clamped at the upper left and is driven at the lower right.**

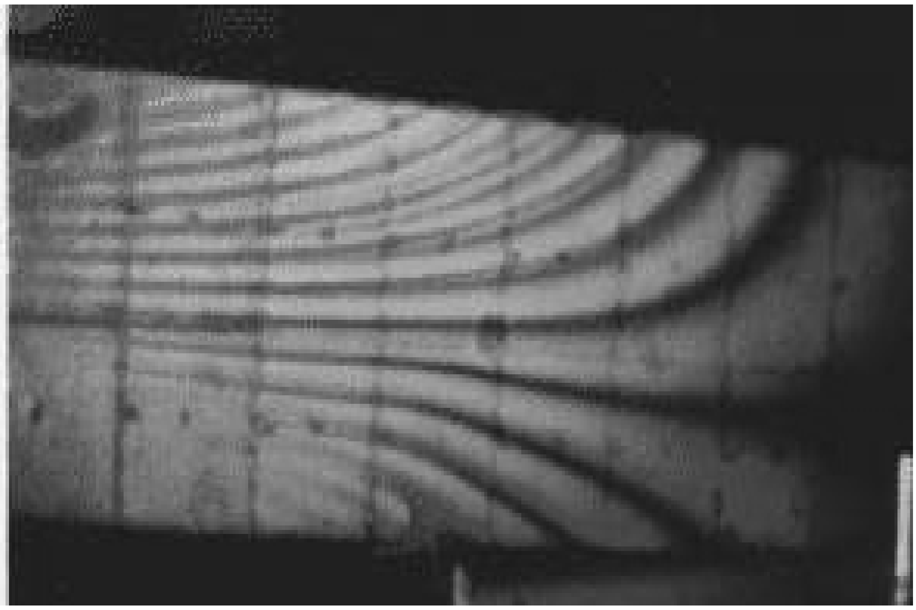
  Successful class project. The holographic image in the upper frame segment contains fringes for bending of a bar of dense polyethylene foam. The hologram is a reflection type illuminated with white light from a spotlight. The bar is clamped at the right and is loaded in the vertical direction (by a brass weight) at the left. In

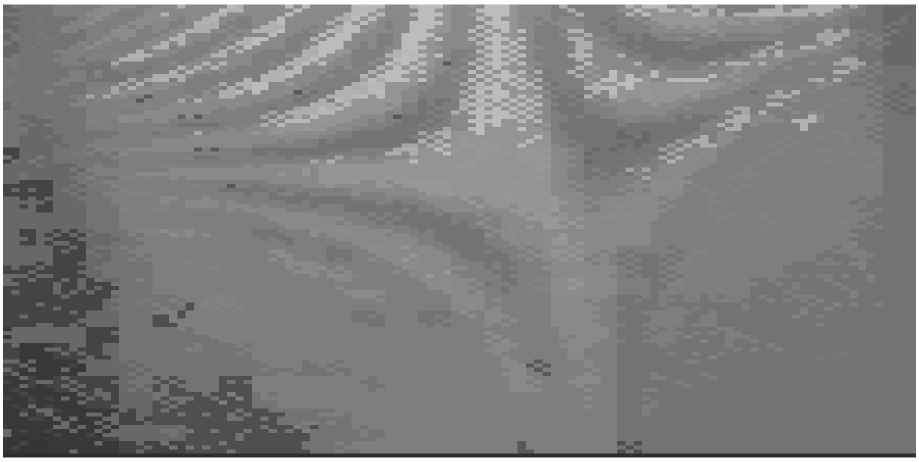
contrast to the bending fringes shown below, these fringes are vertical or nearly so. The reason is that the observation direction is different. A change in the camera angle reveals a change in the fringe pattern.

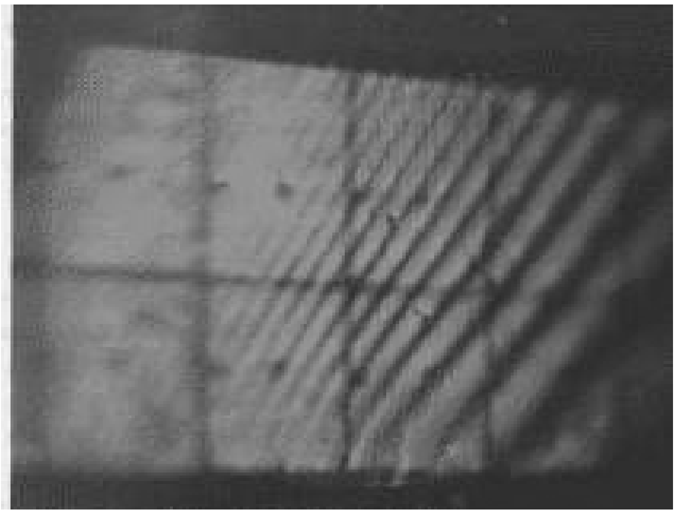
- **Successful class project. The holographic image in the upper frame segment contains fringes for bending of a plastic bar. The hologram is a reflection type illuminated with white light from a spotlight. The bar is clamped at the right and is loaded in the vertical direction (by a dead weight) at the left. Observe fringes on the clamp support (below). Therefore the support moved. Even though it is made of metal, there are interfaces which move. Observe also the discontinuity of fringe order at the horizontal boundary between the support and the bar. This signifies some slip has occurred during the bending. Observe the movement of the fringes. The camera angle was varied in the vertical direction, for each frame of the animation. Stop the animation if you want, by clicking on the image. The change in fringe order is due to motion orthogonal to the line of sight, in the direction of movement of the camera.**

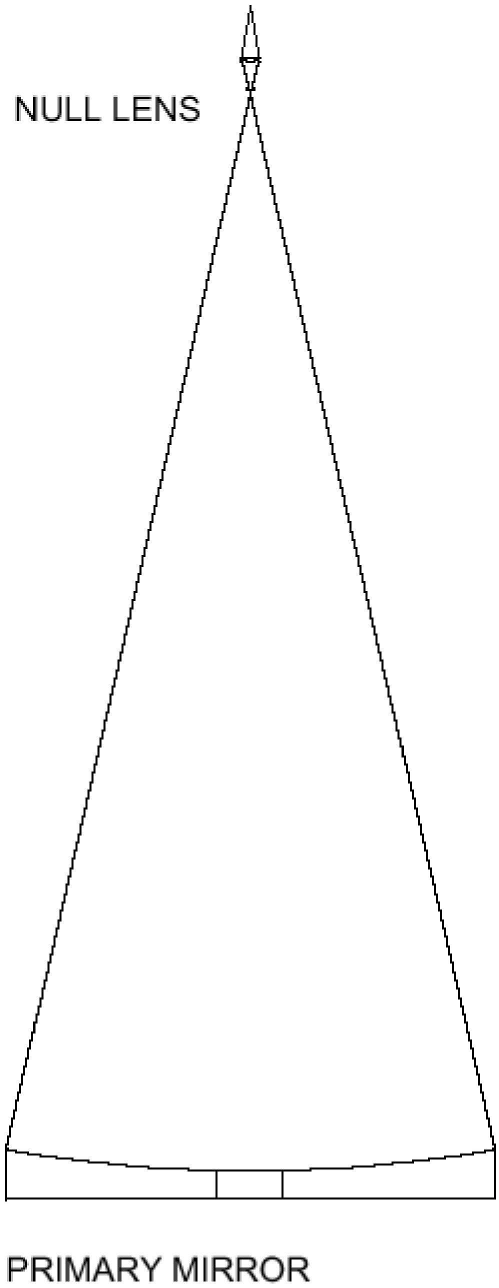
- **Successful class project. The holographic image in the upper frame segment contains laser transmission holographic fringes for indentation of a block of rubber by a small weight.**

- **The fringes in the still images below represent deformation of a bent bar. Both images were derived from the same transmission image-plane hologram. The hologram was made with red laser light and was illuminated with white light. The image on the left is of the hologram illuminated with conjugate white light. The image in the middle is of the hologram illuminated with oblique white light. The neutral axis of bending is revealed by the absence of color dispersion along the horizontal center line.**

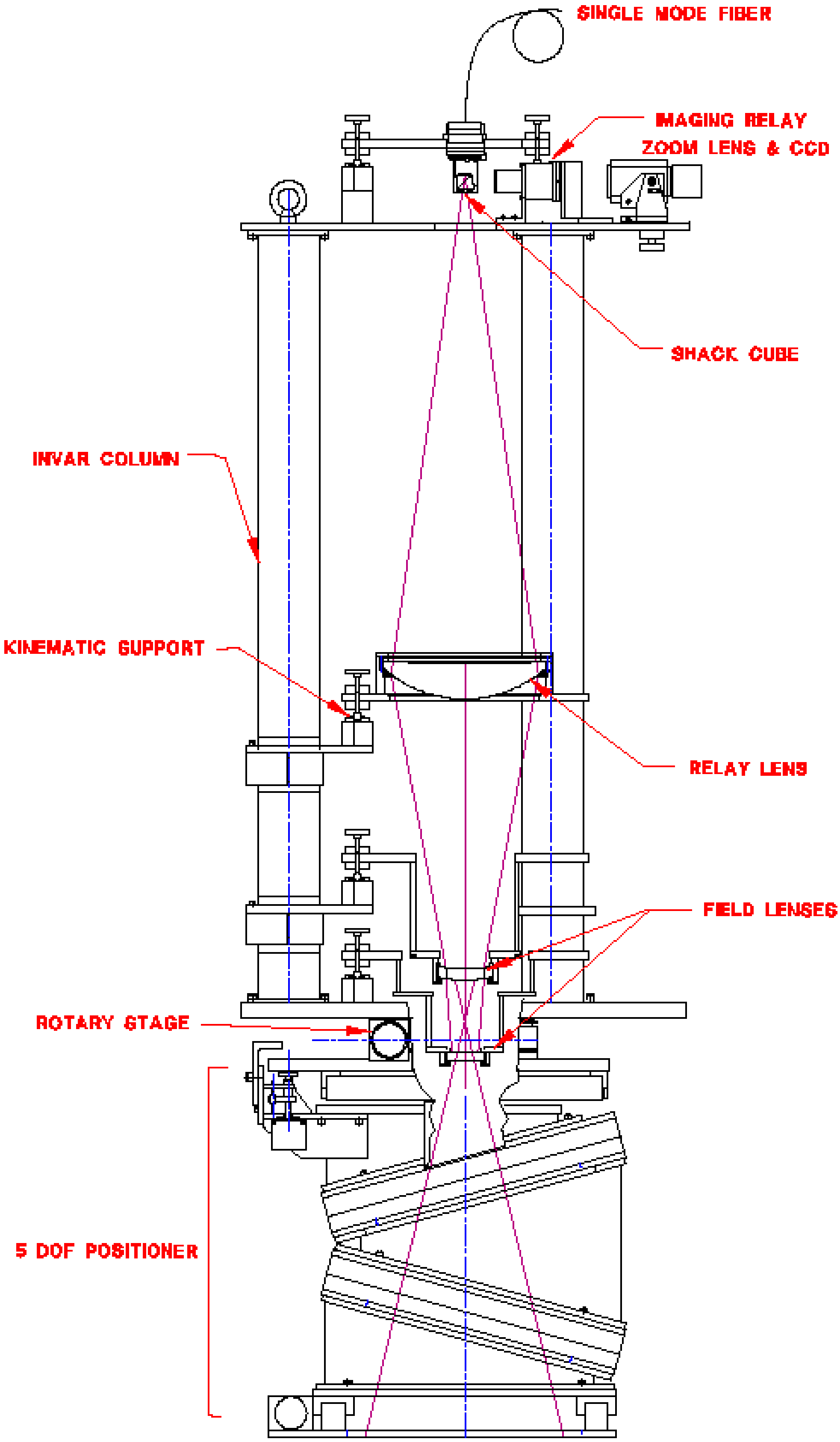








Null test for aspheric concave surfaces.

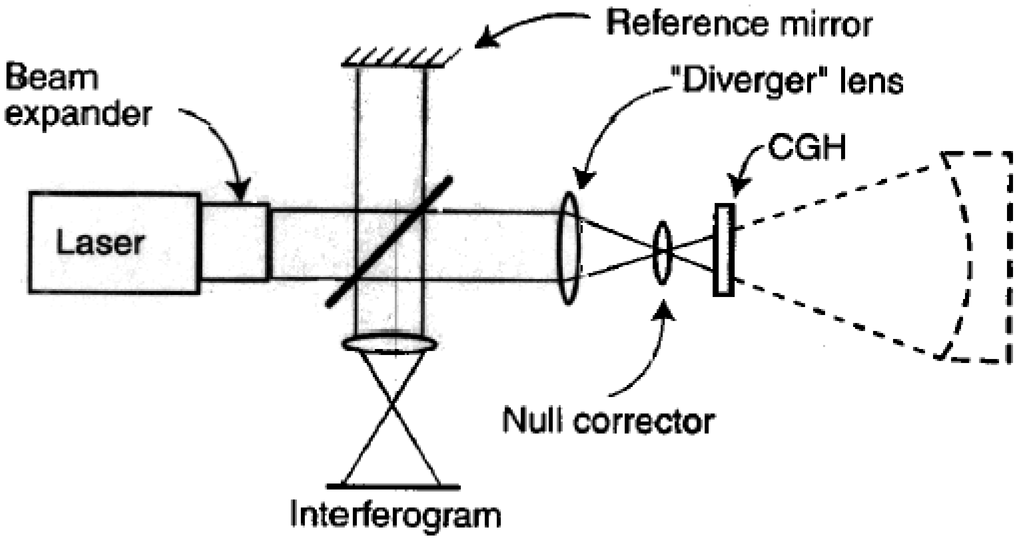


Opto-mechanical layout of the visible null lens for the Magellen 6.5-m F/1.25 primary mirrors. This assembly is about 2.4 m high.

- The null lens test is standard
    - It relies on the null corrector prescription and installation being exactly right

- This is where the problem with the Hubble telescope primary mirror arose
  - The field lens in the null corrector was improperly positioned
  - As a result, the mirror was figured perfectly but to the wrong prescription

- The null lens can be tested by generating a hologram with a computer
  - The hologram is used to create a wavefront that simulates a perfect primary mirror
  - If there is no error in the null corrector, the interferogram from the computer-generated hologram (CGH) will look perfect
    - This is like comparing the physical optics of the null corrector to a mathematical prescription



Verification of a null corrector with a LUPI and a CGH. The CGH creates a wavefront that simulates a perfect primary mirror. If there is no error in the null corrector, the interferogram from the CGH will appear perfect.