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FROM PHOTOGRAPHY TO *.GRAPHIES: UNCONVENTIONAL IMAGING TECHNIQUES

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Lecture 2.
EVOLUTION OF IMAGING:
TRANSFORM IMAGING

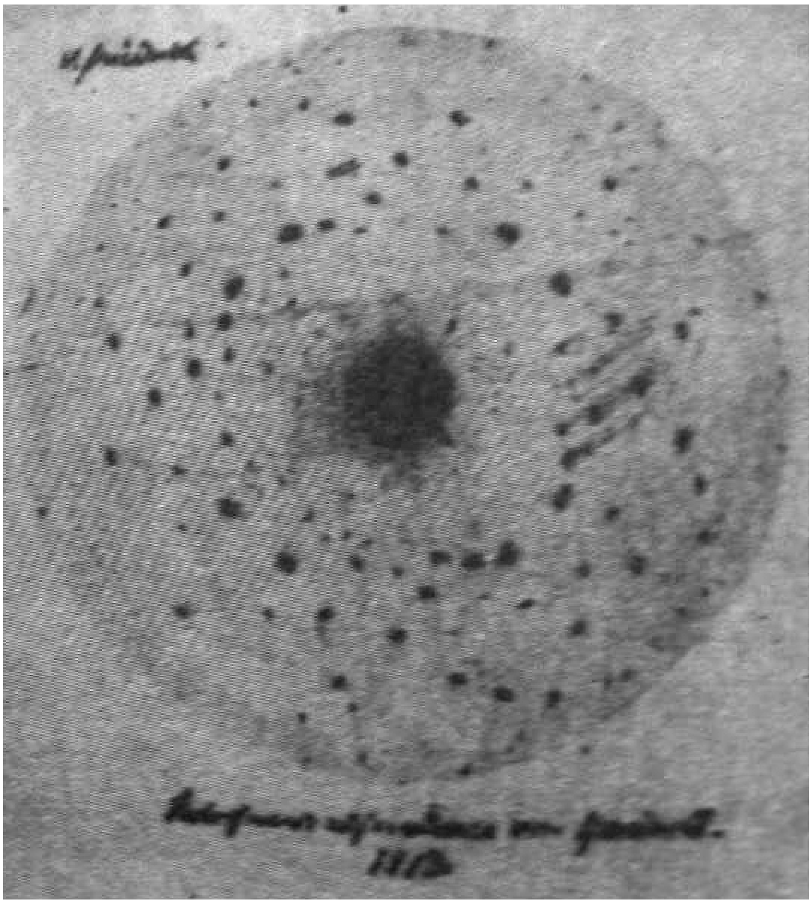
Lecture 2 TRANSFORM IMAGING TECHNIQUES

Imaging technique's evolution:
- direct display
- storage&display combined in one device
- measuring, storage & display

The main advantages of the direct image plane imaging
- It allows generating images that can be immediately perceived by human vision
- It allows direct interpretation of a priori knowledge on images in terms of those of objects

Fundamental drawbacks of direct image plane imaging techniques:
- They require access to individual points (locations) of objects
- They require high sensitivity of the sensor: signal energy

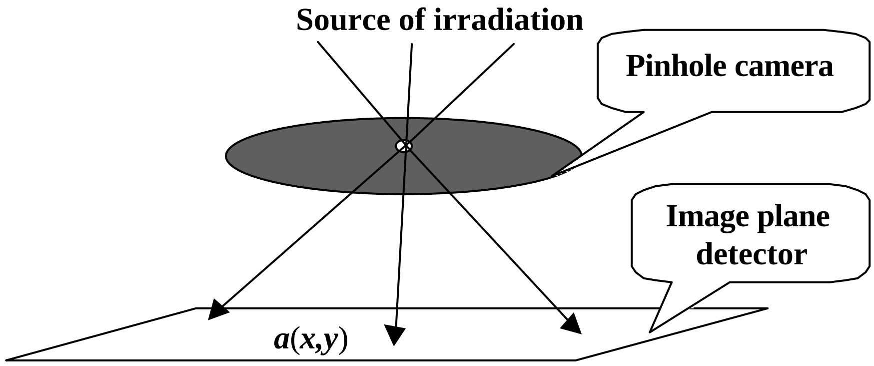
Probably, the very first example of indirect imaging method was that of **X—ray crystallography** (*Max Von Laue, 1912, Nobel Prize 1914-1918*)



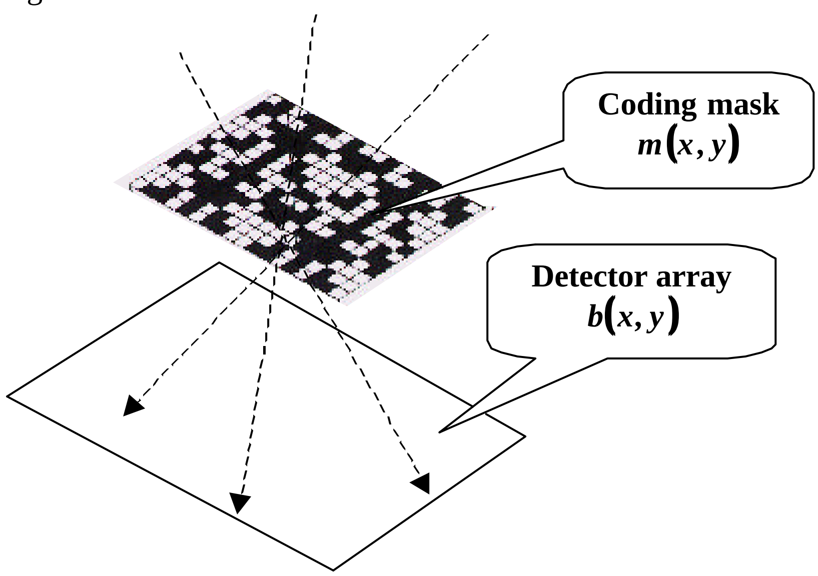
In 1912 Max von Laue and two students (Walter Friedrich and Paul Knipping) demonstrated the wave nature of X-rays and periodic structure of crystals by observing the diffraction of X-rays from crystals of zinc sulfide. Discovery of diffraction of X-rays had a decisive value in the development of physics and biology of XX-th century. One of the most remarkable scientific achievements that is based on X-ray crystallography was discovery by J. Watson and F. Crick of spiral structure of DNA (Nobel Prize, 1953)

Coded" aperture (multiplexing) techniques (1970-th**)**

Pinhole camera (camera obscura) has a substantial advantage over lenses - it has infinite depth of field, and it doesn't suffer from chromatic aberration. Because it doesn't rely on refraction, pinhole camera can be used to form images from X-ray and other high energy sources, which are normally difficult or impossible to focus.



The biggest problem with pinholes is that they let very little light through to the film or other detector. This problem can be overcome to some degree by making the hole larger, which unfortunately leads to a decrease in resolution. The smallest feature which can be resolved by a pinhole is approximately the same size as the pinhole itself. The larger the hole, the more blurred the image becomes. Using multiple, small pinholes might seem to offer a way around this problem, but this gives rise to a confusing montage of overlapping images. Nonetheless, if the pattern of holes is carefully chosen, it is possible to reconstruct the original image with a resolution equal to that of a single hole.



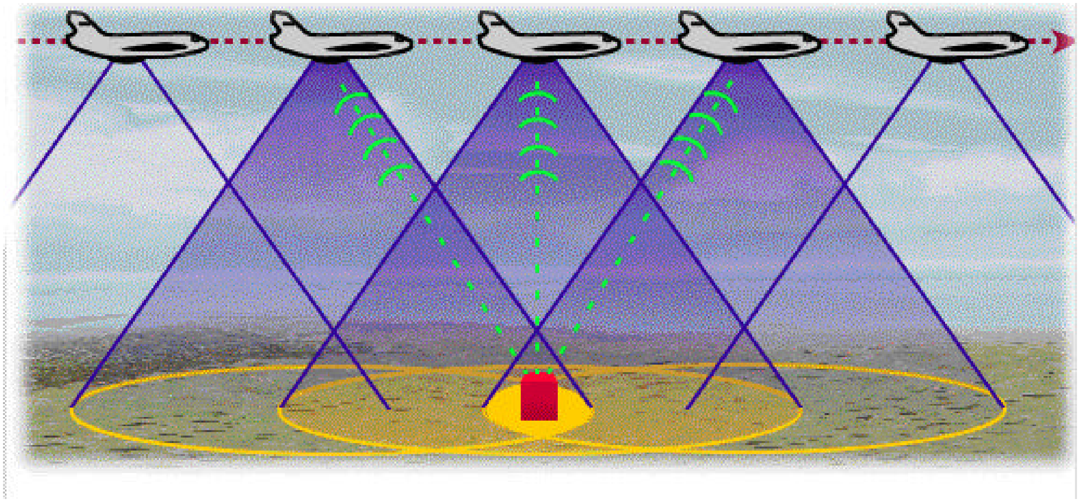
$$b(x,y) = \iint a(\xi,\eta)\, m(x-\xi, y-\eta)\, d\xi\, d\eta$$

Image reconstruction $a(x,y) = \iint b(\tilde{\xi},\tilde{\eta})\, \tilde{m}(x-\tilde{\xi}, y-\tilde{\eta})\, d\tilde{\xi}\, d\tilde{\eta}$ is possible if

$$\iint m(\tilde{\xi}-\xi, \tilde{\eta}-\eta)\, \tilde{m}(x-\tilde{\xi}, y-\tilde{\eta})\, d\tilde{\xi}\, d\tilde{\eta} = \delta(x-\xi, y-\eta)$$

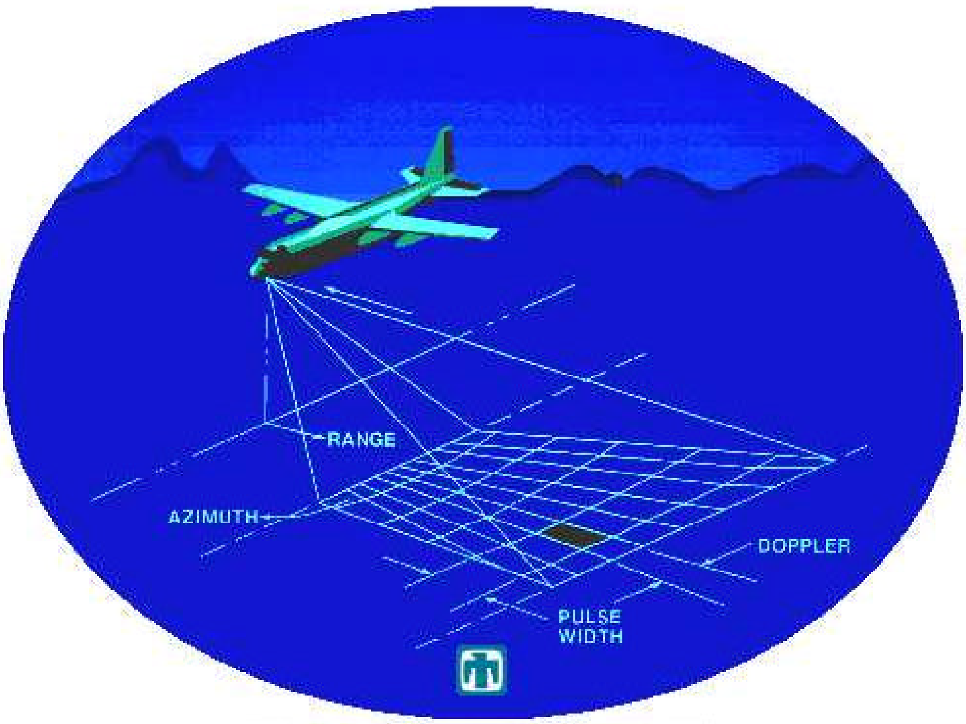
Transform imaging :

Synthetic aperture radar (*C.Wiley, USA, 1951*):

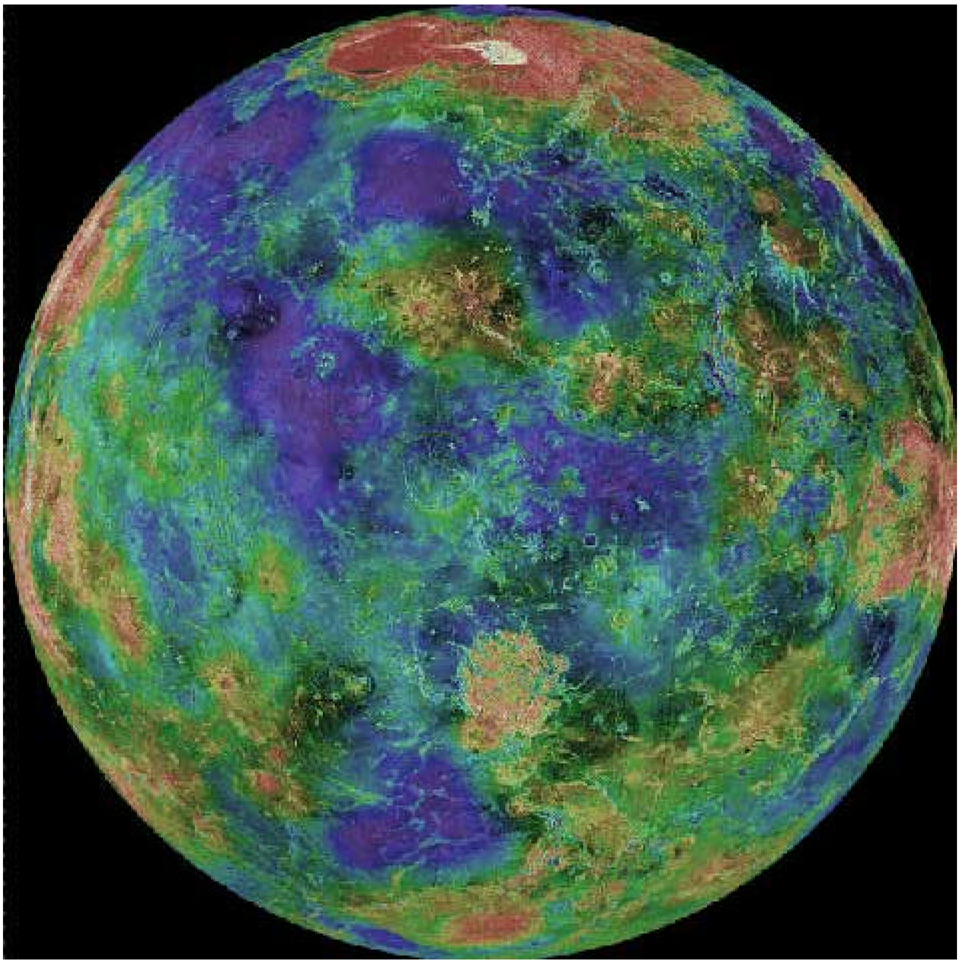


$$E(x) = \int_{-\infty}^{+\infty} a(s)\, exp(i\, p(s))\, h(s, x)\, ds$$

Side looking radar: Direct imaging in "range" co-ordinate and transform imaging in "azimuth" co-ordinate



SAR image of Washington, DC; resolution 1m (SCANDIA)

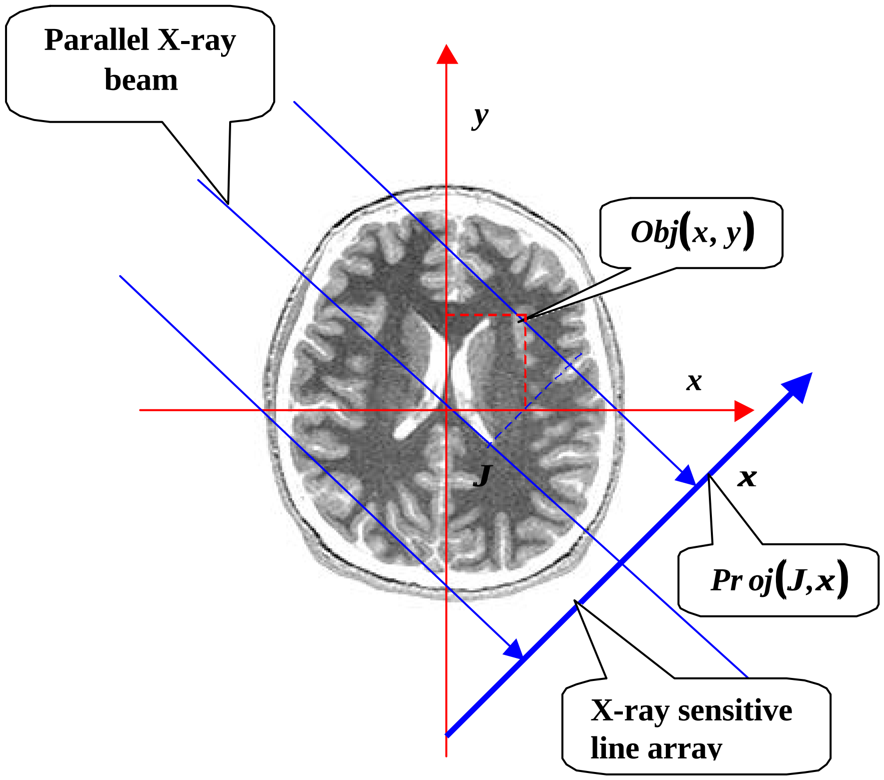


Radar map of Venus

If the thick clouds covering Venus were removed, how would the surface appear? Using an imaging radar technique, the Magellan spacecraft was able to lift the veil from the Face of Venus and produce this spectacular high resolution image of the planet's surface. Red, in this false-color map, represents mountains, while blue represents valleys. This 3-kilometer resolution map is a composite of Magellan images compiled between 1990 and 1994. Gaps were filled in by the Earth-based Arecibo Radio Telescope. The large yellow/red area in the north is Ishtar Terra featuring Maxwell Montes, the largest mountain on Venus. The large highland regions are analogous to continents on Earth. Scientists are particularly interested in exploring the geology of Venus because of its similarity to Earth.

Principles of reconstructive tomography

The x-ray-based computerized tomography (CT) was introduced by Hounsfield in 1973 (Nobel pize, ~1980)

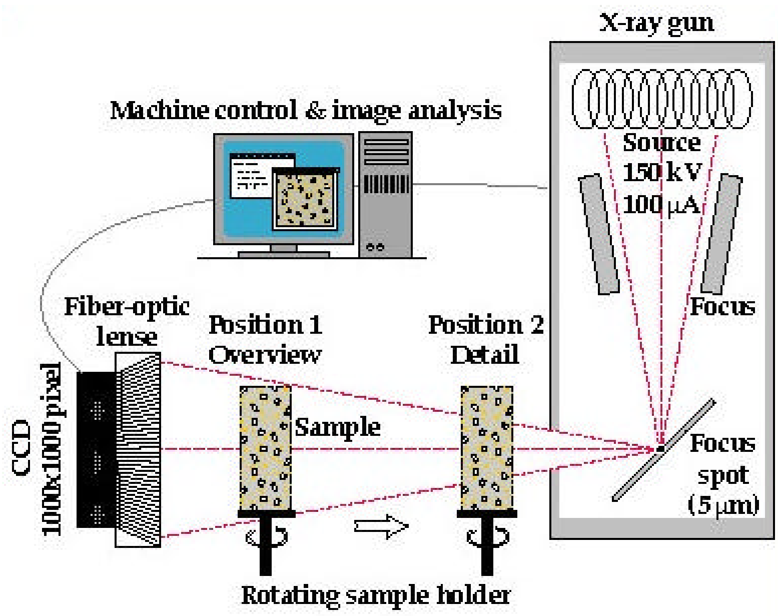


Schematic diagram of parallel beam projection tomography

In computer tomography, a set of object's projections taken a different observation angles is measured and used for subsequent reconstruction of the object:

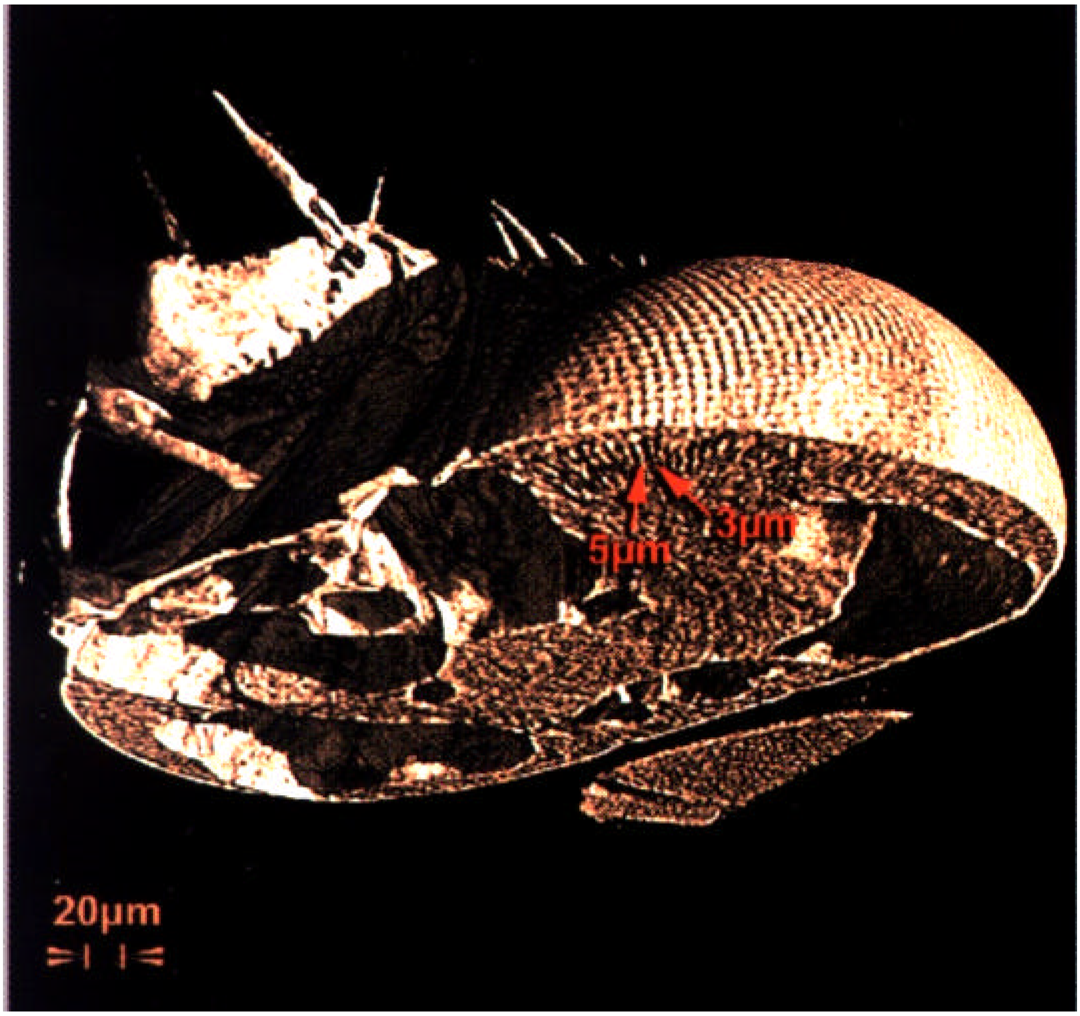
$$Proj(\theta,\xi) = \int\int Obj(x,y)\, h(\xi - x\cos\theta - y\sin\theta)\, dxdy$$

where $h(\xi - x\cos\theta - y\sin\theta)$ is source and sensor's aperture function.



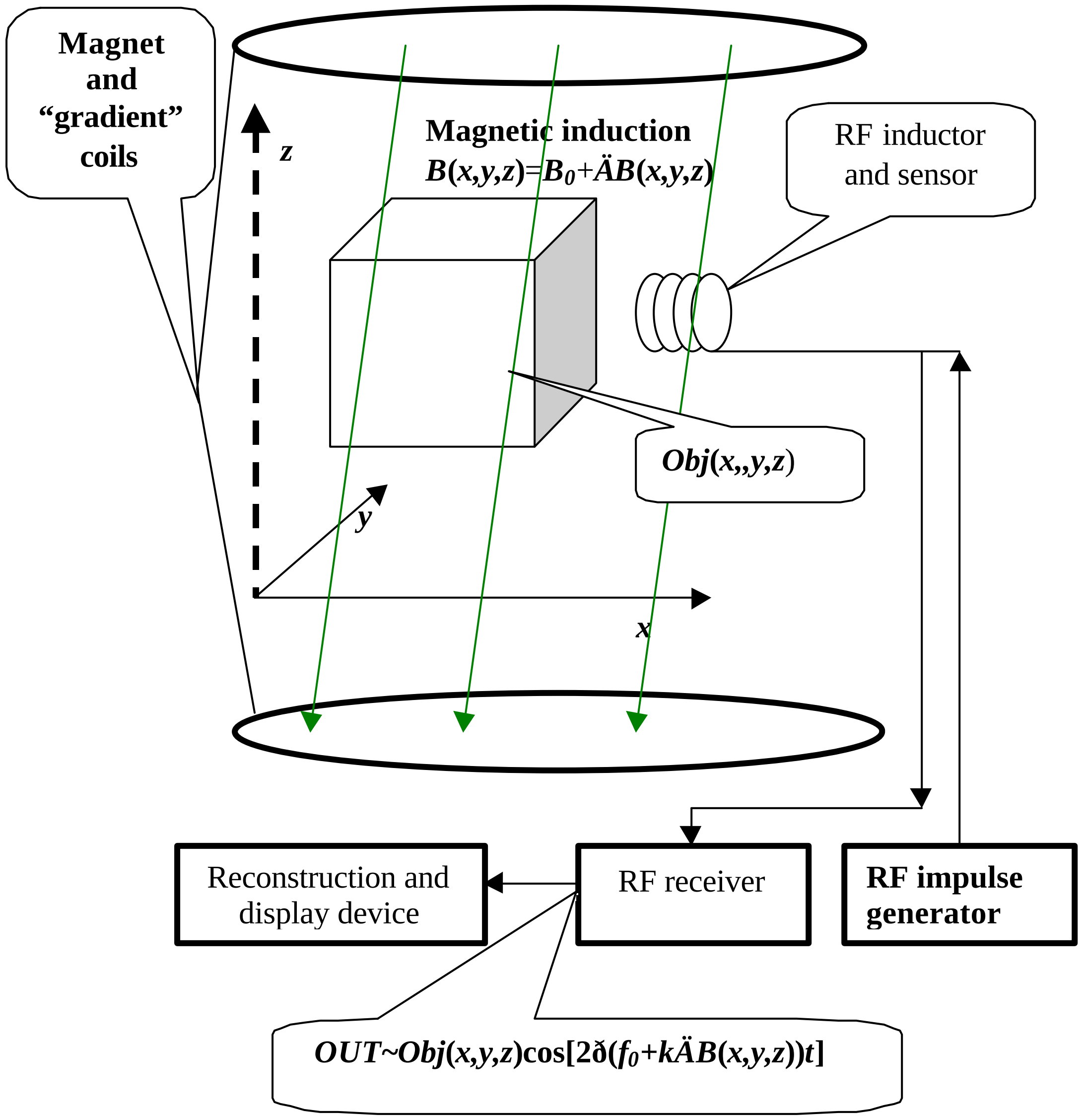
Schematic diagram of micro-tomography

SkyScan micro-CT scanner Model L1072



Surface rendering of a fly head reconstructed using a SkyScan micto-CT scanner Model L1072 (*Advanced imaging, July 2001, p. 22*)

NMR (MRI) tomography



- Schematic diagram of NMR imaging

Magnetic resonance imaging (MRI) is an imaging technique used primarily in medical settings to produce high quality images of the inside of the human body. MRI is based on the principles of nuclear magnetic resonance (NMR), a spectroscopic technique used by scientists to obtain microscopic chemical and physical information about molecules. The technique was called magnetic resonance imaging rather than nuclear magnetic resonance imaging (NMRI) because of the negative connotations associated with the word nuclear in the late 1970's. MRI started out as a tomographic imaging technique, that is it produced an image of the NMR signal in a thin slice through the human body. MRI has advanced beyond a tomographic imaging technique to a volume imaging technique.

MRI Timeline

http://www.cis.rit.edu/htbooks/mri/inside.htm

1946	MR phenomenon - Bloch & Purcell
1952	Nobel Prize - Bloch & Purcell
1950	NMR developed as analytical tool
1960	
1970	
1972	Computerized Tomography
1973	Backprojection MRI - Lauterbur
1975	Fourier Imaging - Ernst
1980	MRI demonstrated - Edelstein
1986	Gradient Echo Imaging
	NMR Microscope
1988	Angiography - Dumoulin
1989	Echo-Planar Imaging
1991	Nobel Prize - Ernst
1994	Hyperpolarized ^{129}Xe Imaging

The brief history of MRI

Felix Bloch and Edward Purcell, both of whom were awarded the Nobel Prize in 1952, discovered the magnetic resonance phenomenon independently in 1946. In the period between 1950 and 1970, NMR was developed and used for chemical and physical molecular analysis.

In 1971 Raymond Damadian showed that the nuclear magnetic relaxation times of tissues and tumors differed, thus motivating scientists to consider magnetic resonance for the detection of disease.

In 1973 the x-ray-based computerized tomography (CT) was introduced by Hounsfield. This date is important to the MRI timeline because it showed hospitals were willing to spend large amounts of money for medical imaging hardware. Magnetic resonance imaging was first demonstrated on small test tube samples that same year by Paul Lauterbur. He used a back projection technique similar to that used in CT.

In 1975 Richard Ernst proposed magnetic resonance imaging using phase and frequency encoding, and the Fourier Transform. This technique is the basis of current MRI techniques. A few years later, in 1977, Raymond Damadian demonstrated MRI of the whole body. In this same year, Peter Mansfield developed the echo-planar imaging (EPI) technique. This technique will be developed in later years to produce images at video rates (30 ms / image).

By 1986, the imaging time was reduced to about five seconds, without sacrificing too much image quality. The same year people were developing the NMR microscope, which allowed approximately 10 μm resolution on approximately one cm samples. In 1987 echo-planar imaging was used to perform real-time movie imaging of a single cardiac cycle. In this same year Charles Dumoulin was perfecting magnetic resonance angiography (MRA), which allowed imaging of flowing blood without the use of contrast agents.

In 1991, Richard Ernst was rewarded for his achievements in pulsed Fourier Transform NMR and MRI with the Nobel Prize in Chemistry. In 1993 functional MRI (fMRI) was developed. This technique allows the mapping of the function of the various regions of the human brain. Six years earlier many clinicians thought echo-planar imaging's primary applications was to be in real-time cardiac imaging. The development of fMRI opened up a new application for EPI in mapping the regions of the brain responsible for thought and motor control.

NMR scanner

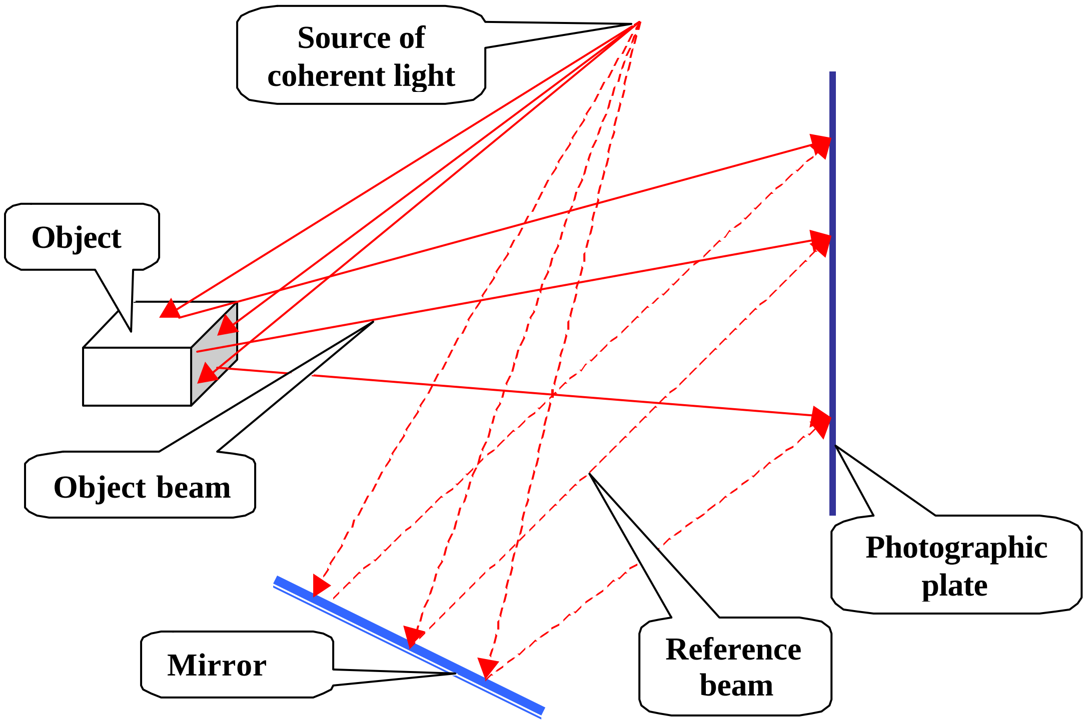
Nuclear magnetic resonance (NMR)
An effect observed when an atomic nucleus is exposed to radio waves in the presence of a magnetic field. A strong magnetic field causes the magnetic moment of the nucleus to precess around the direction of the field, only certain orientations being allowed by quantum theory. A transition from one orientation to another involves the absorption or emission of a photon, the frequency of which is equal to the precessional frequency. With magnetic field strengths customarily used the radiation is in the radio-frequency band. If radio-frequency radiation is supplied to the sample from one coil and is detected by another coil, while the magnetic field strength is slowly changed, radiation is absorbed at certain field values, which correspond to the frequency difference between orientations. An NMR spectrum consists of a graph of field strength against detector response. This provides information about the structure of molecules and the positions of electrons within them, as the orbital electrons shield the nucleus and cause them to resonate at different field strengths. (*The Macmillan Encyclopedia 2001, © Market House Books Ltd 2000*)

Holography

Invention of holography by D. Gabor or was motivated by the desire to improve resolution power of electron microscope that was limited by the fundamental limitations of the electron optics. The term “holography” originates from Greece word “holos” (
holography full information regarding light wave, both amplitude and phase, is recorded by means of interference of two beams, object and reference one. Due to the fact that at that time sources of coherent electron radiation were not available, Gabor carried out model optical experiments to demonstrate the feasibility of the method. However, powerful sources of coherent light were also not available at the time, and holography remained an “optical paradox” until the invention of lasers. The very first implementation of holography were demonstrated in 1961 by radio-engineers E. Leith a nd J. Upatnieks and by optician Yu. Denisyuk.

- *D. Gabor, A New Microscopic Principle, Nature, v. 161, 777-778, 1948, Nobel Prize*
- *E.N. Leith, J. Upatnieks, New techniques in Wavefront Reconstruction, JOSA, v. 51, 1469-1473, 1961*
- *Yu. N. Denisyuk, Photographic reconstruction of the Optical Properties of an Object in its Own Scattered Radiation Field, Dokl. Akad. Nauk SSSR, v. 1444, 1275-1279, 1962).*

Basic principle of holography: is illustrated in the figure.



Recording hologram:

$$H(x,y) = \left|A_{obj}\, exp\left(i2\pi\Phi_{obj}\right) + A_{rej}\, exp\left(i2\pi\Phi_{ref}\right)\right|^2 =$$
$$A_{obj}^2 + A_{ref}^2 + A_{obj}A_{ref}\, exp\left[i2\pi\left(\Phi_{obj} - \Phi_{ref}\right)\right] + A_{obj}A_{ref}\, exp\left[i2\pi\left(\Phi_{ref} - \Phi_{obj}\right)\right]$$

Reconstructing hologram:

$$I = H \cdot A_{ref}\, exp\left(i2\pi\Phi_{ref}\right) =$$

$$\left(A_{obj}^2 + A_{ref}^2\right) A_{ref}\, exp\left(i2\pi\Phi_{ref}\right) +$$

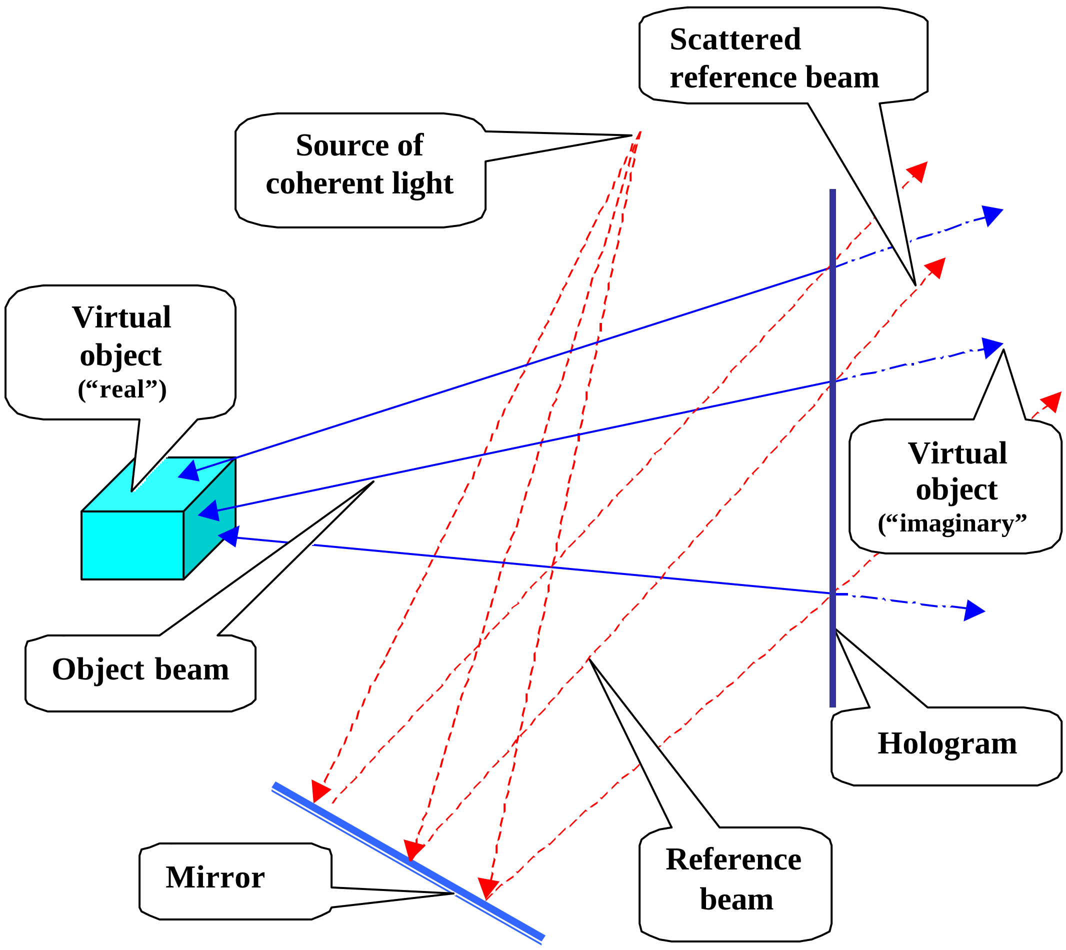
$$A_{ref}^2 \left\{A_{obj}\, exp\left[i2\pi\Phi_{obj}\right]\right\} +$$

$$A_{ref}^2\, exp\left(i2\pi\left(2\Phi_{ref}\right)\right)\left\{A_{obj}\, exp\left[i2\pi\left(-\Phi_{obj}\right)\right]\right\}$$

Scattered reference beam

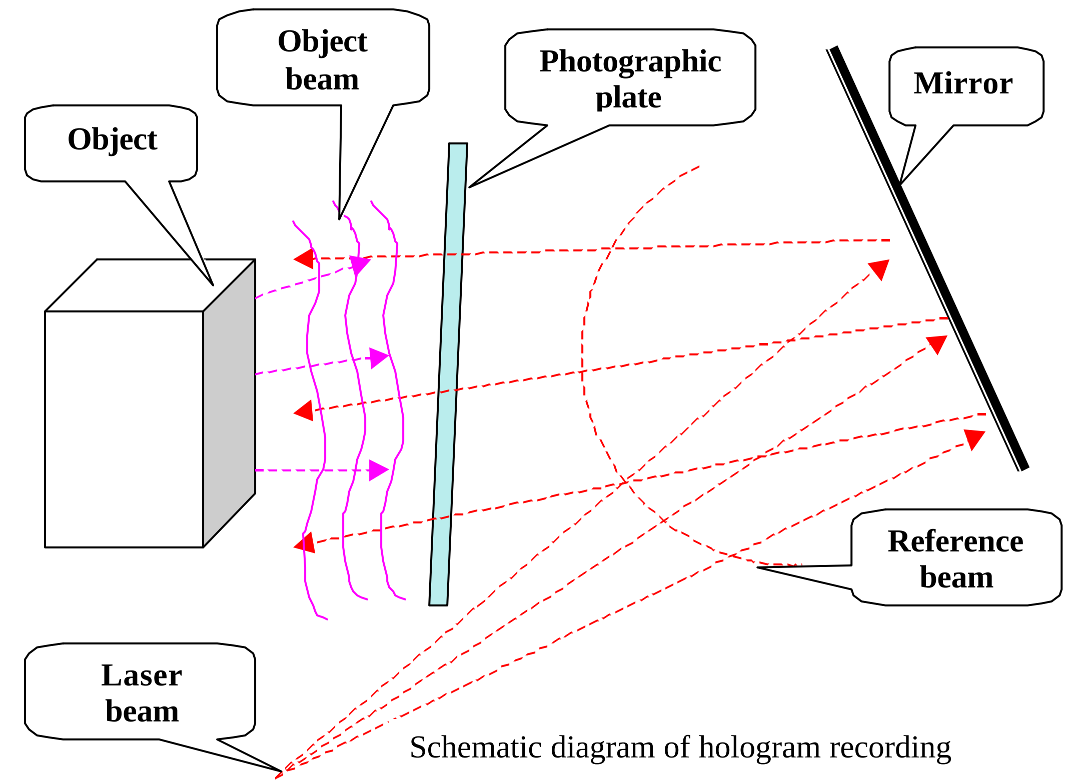
Virtual object (“real”)

Virtual object (“imaginary”)

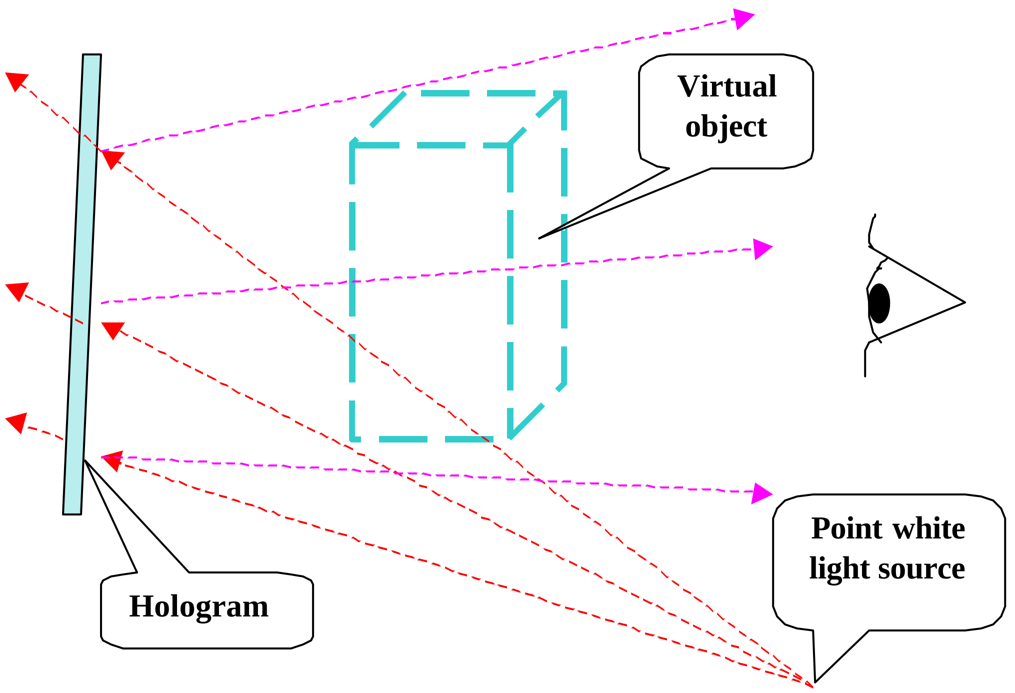


Schematic diagram of hologram reconstruction

Reflection (Denisyuk type) hologram



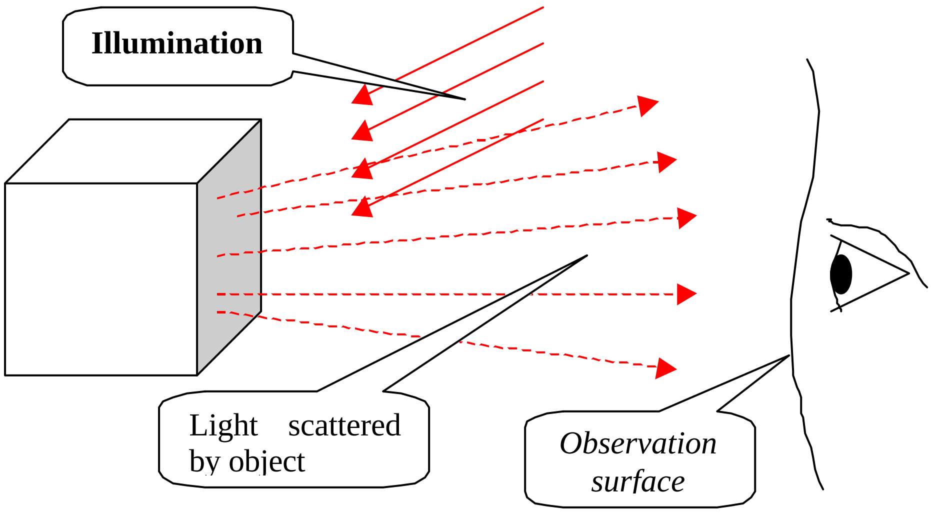
Schematic diagram of hologram recording



Hologram playback

Digital holography: synthesis and analysis of holograms by digital processing

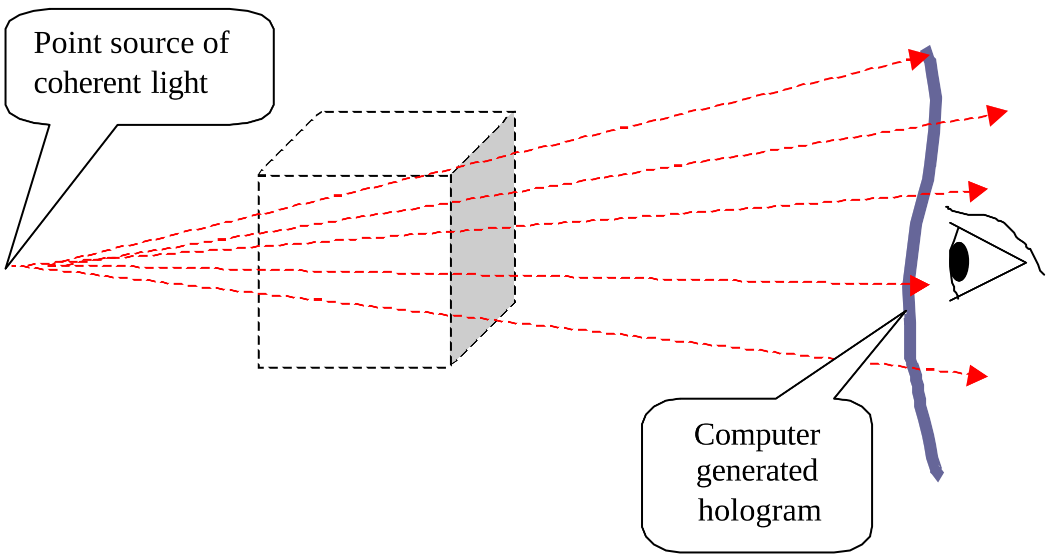
Synthesis:



Scheme of object visual observation

Mathematical model or signal – computation of the hologram –recording synthesized hologram

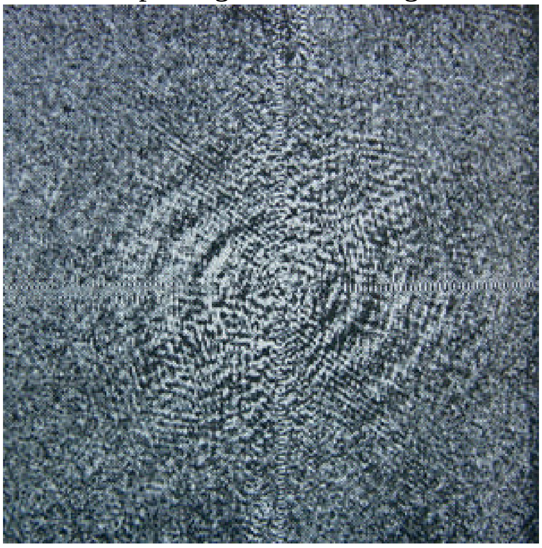
$$G(\xi,\eta)=\iiint Obj(x,y,z)T(x,,y,z;\xi,\eta)dxdydz$$

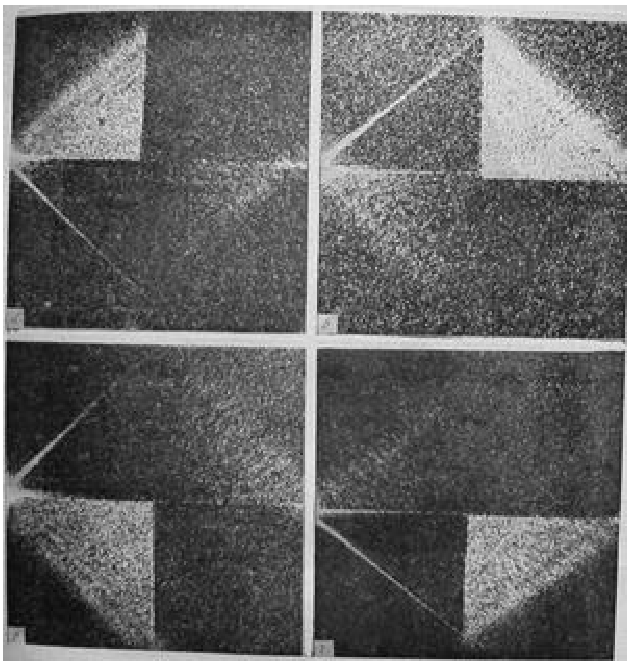


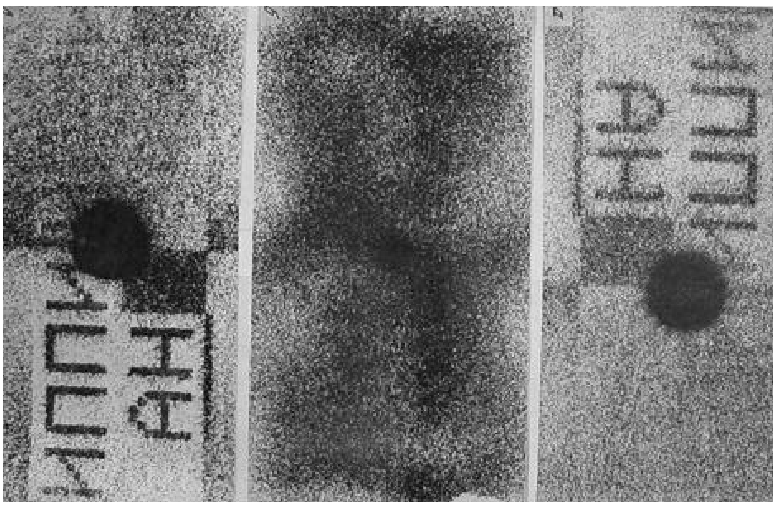
Scheme for visual observation of computer generated holoogram

Recording computer generated hologram is a specific digital-to-analog conversion process

Computer generated hologram

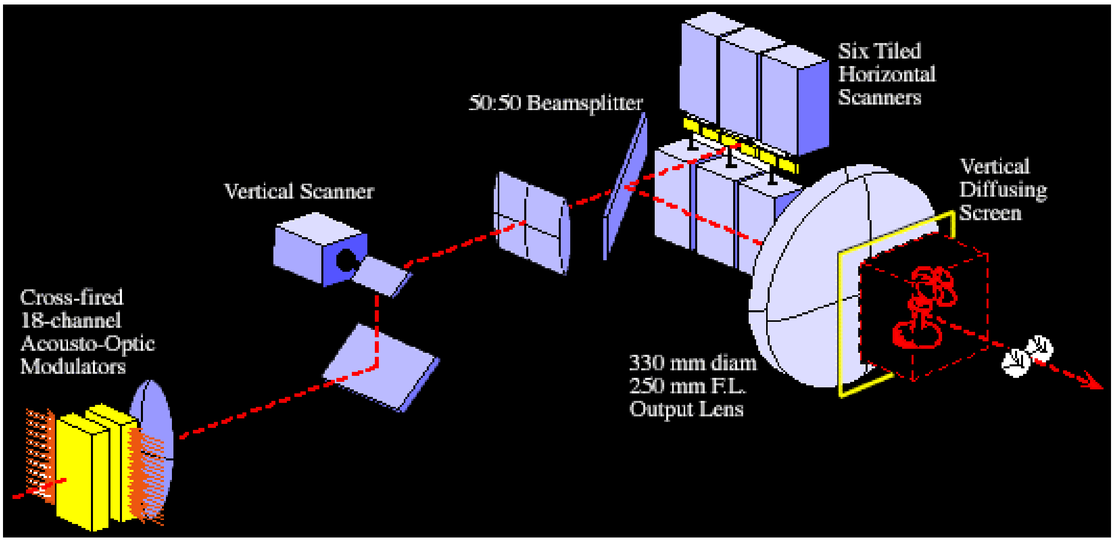






Examples of reconstruction of computer generated holograms

Computer generated holographic movie

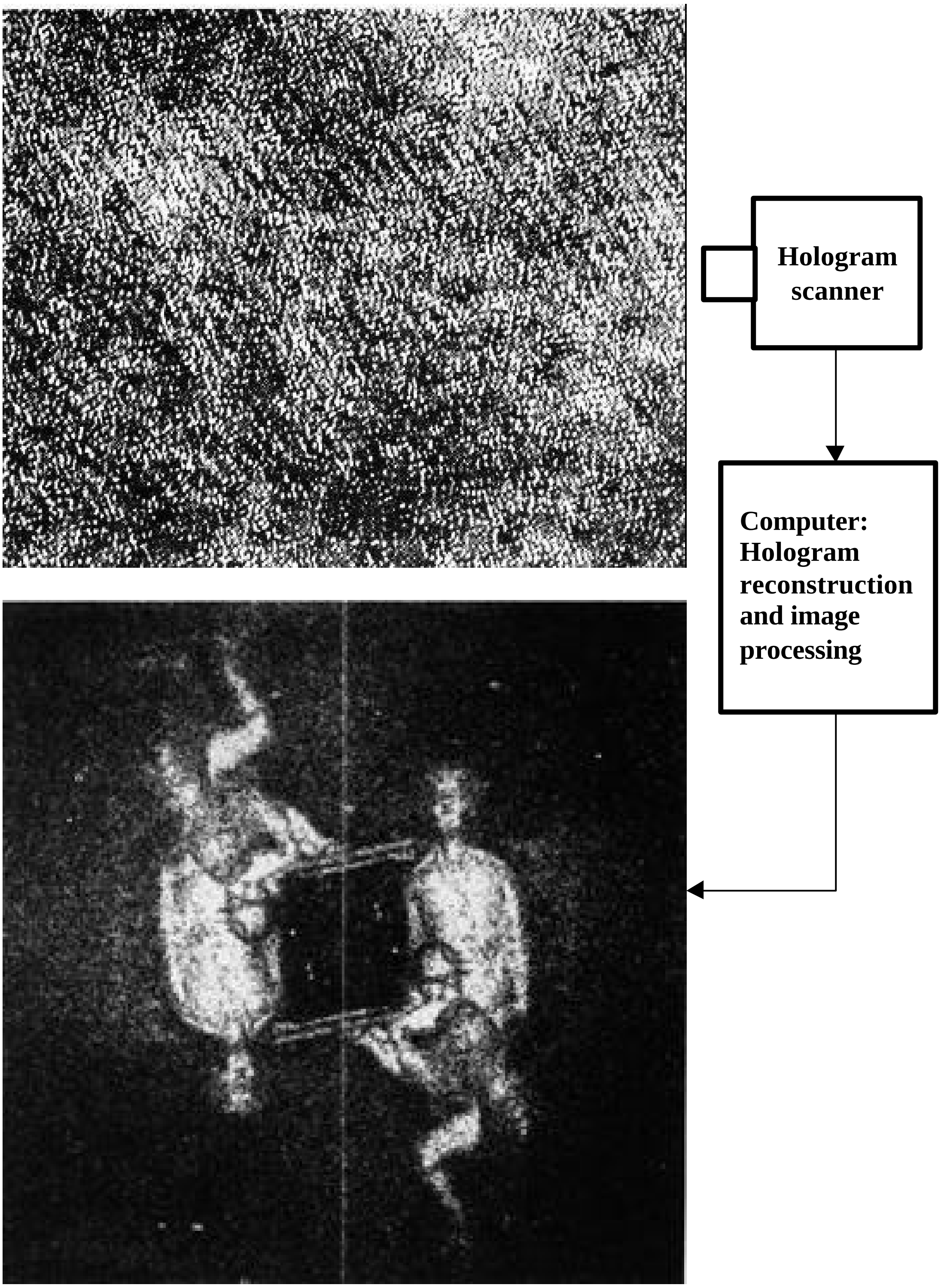


MarkII holographic display (MIT, Media Lab)

Digital reconstruction of holograms:

Inversion of the imaging inttegral

$$Obj(x,y,z) = \int\int G(\xi,\eta) T^{-1}(x,,y,z;) d\xi d\eta$$



Optical hologram and its digital reconstruction (*L. Yaroslavsky, N. Merzlyakov, Methods of Digital Holography, Consult. Bureau, New York, 1980*)

Digital optics: digital processing of optical and similar signals:

New qualities that are brought to optical systems by digital computers and processors:

The first is flexibility and adaptability. The most substantial advantage of digital computers as compared with analog electronic and optical information processing devices is that no hardware modifications are necessary to reprogram digital computers to solving different tasks. With the same hardware, one can build an arbitrary problem solver by simply selecting or designing an appropriate code for the computer. This feature makes digital computers also an ideal vehicle for processing optical signals adaptively since, with the help of computers, they can adapt rapidly and easily to varying signals, tasks and end user requirements.

The second is that digital computers integrated into optical information processing systems enable them to perform not only element-wise and integral signal transformations such as spatial and temporal Fourier analysis, signal convolution and correlation that are characteristic for analog optics but any operations needed. This removes the major limitation of optical information processing and makes optical information processing integrated with digital signal processing almost almighty.

The third is that acquiring and processing quantitative data contained in optical signals, and connecting optical systems to other informational systems and networks is most natural when data are handled in digital form. In the same way as in economics money are general equivalent, digital signals are general equivalent in information handling. A digital signal within the computer that represents an optical one is, so to say, purified information carried by the optical signal and deprived of its physical integument. Thanks to its universal nature, the digital signal is an ideal means for integrating different informational systems.

Basic problems:

- Digital representation of signals
- Digital representation of signal transforms
- Development of adaptive algorithms to achieve potential quality limits
- Efficient computational algorithms

Test questions:

1 Describe and explain similarity and dissimilarity between X-ray crystallography and holography
2 Describe and explain similarity and dissimilarity between linear tomography, laminography and computer tomography.
3 Describe main stages in digital synthesis of holograms
4 Describe main stages of digital reconstruction of holograms

Bonus task:
Formulate a mathematical model of the relationship between 3-D object and its reconstructed slice in linear tomography