Lect. 1. Holography and Imaging Methods.

In this lecture, we briefly overview and illustrate the history and evolution of imaging devices from ancient magnifying glasses to holography and computational imaging to show that digital holography along with other methods of computational imaging represents the summit of the evolution.

Three major stages of evolution of the imaging device can be distinguished:
- Direct image plane imaging image formation as a 2-D function by direct mapping each point of an object to corresponding points of the object image.
- Holographic imaging: recording of amplitude and phase of the wave field radiated by the object in form of a hologram and subsequent reproduction of the wave field by reconstruction of holograms
- Computational imaging: collecting numerical data that satisfactorily describe the object of imaging and subsequent image formation from the collected data

Mile stones of evolution of direct image plane imaging
  - Magnifying glass
  - Perspectograph
  - Camera-obscura
  - Optical microscope; telescope
  - Photography
  - X-ray imaging
  - Video camera and electronic television
  - Electron microscope
  - Acoustic microscope
  - Radar, Sonar
  - Linear tomography and laminography
  - Gamma cameras
  - Scanned-proximity probe (SPP) microscopes

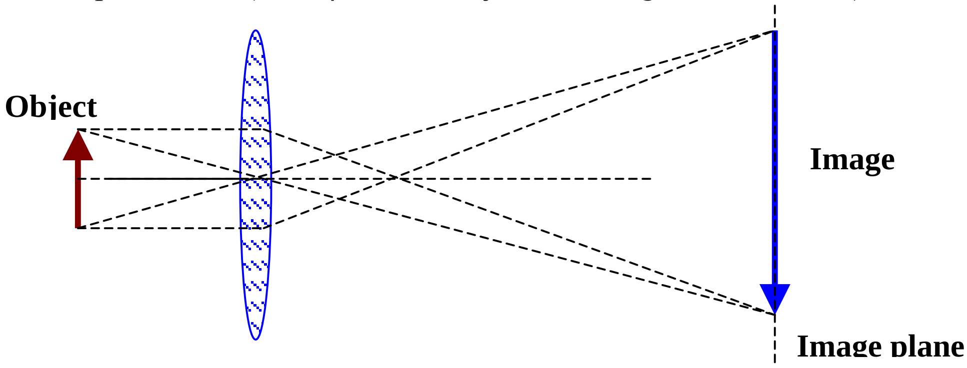
Holographic imaging: recording and reconstruction of wave fields.

- D. Gabor and invention of principles of optical holography
- Leith-Upatnieks's and Denisyuk's holograms
- Synthetic aperture radar
- Holographic interferometry

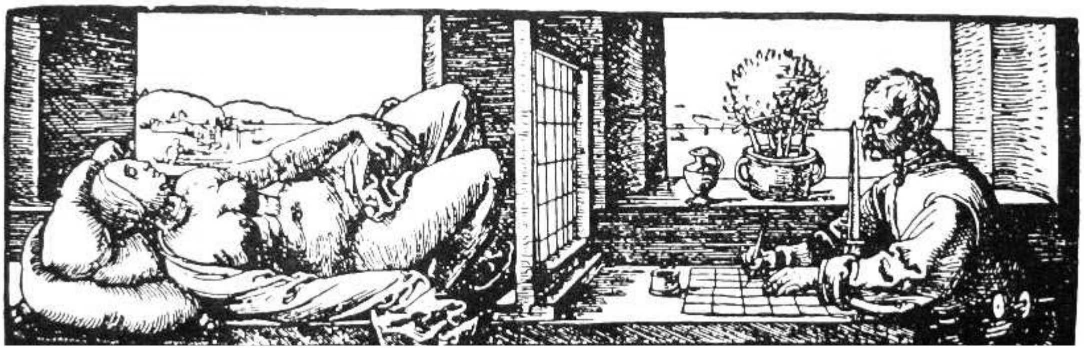
Instances of computational imaging
  - X-ray crystallography
  - Computed tomography
  - Magnetic resonance imaging
  - Coded aperture imaging
  - Optical interferometry and fringe-techniques
  - Digital holography: numerical reconstruction of digitally recorded holograms
  - Digital holography: computer generated holograms

Imaging devices: Direct image plane imaging

Magnifying glass (*Graeco-Roman times*);
Eye-glasses or spectacles – (*End of 13th century Salvino degli Armati, 1299*):



Perspectoraph



A woodcut by Albrecht Dürer showing “Perspectoraph”, an instrument used by painters in 16 century. Dürer was held a while for the inventing this instrument, it goes however back to Leonardo da Vinchi

Camera-obscura (pinhole camera) (*Ibn Al Haytam, X century*):

The image quality was improved with the addition of a convex lens into the aperture in the 16th century and the later addition of a mirror to reflect the image down onto a viewing surface. **Giovanni Battista Della Porta in his 1558** book “Magiae Naturalis” recommended the use of this device as an aid for drawing for artistsThe term "camera obscura" was first used by the German astronomer **Johannes Kepler in the early 17th** century. He used it for astronomical applications and had a portable tent camera for surveying in Upper Austria.

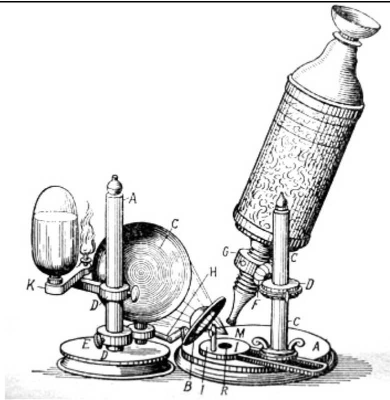
The earliest mention of this type of device was by the **Chinese philosopher Mo-Ti (5th century BC)**. He formally recorded the creation of an inverted image formed by light rays passing through a pinhole into a darkened room. He called this darkened room a "collecting place" or the "locked treasure room."
Aristotle (384-322 BC) understood the optical principle of the camera obscura. He viewed the crescent shape of a partially eclipsed sun projected on the ground through the holes in a sieve, and the gaps between leaves of a plane tree. The Islamic scholar and scientist **Alhazen (Abu Ali al-Hasan Ibn al-Haitham) (c.965 - 1039)** gave a full account of the principle including experiments with five lanterns outside a room with a small hole.
In **1490 Leonardo Da Vinci** gave two clear descriptions of the camera obscura in his notebooks. Many of the first camera obscuras were large rooms like that illustrated by the Dutch scientist Reinerus Gemma-Frisius in 1544 for use in observing a solar eclipse. .

An 1817 encyclopedia page from the Wilgus Collection (Adopted from http://brightbytes.com/cosite/what.html)

Optical Microscope and telescope

Invention of microscope. Inventor of optical microscope is not known. Credit for the first microscope is usually given to Dutch (from other sources, *Middleburg*, Holland) *spectacle-**maker*** **Joannes** and his son **Zacharios Jansen**. While experimenting with several lenses in a tube, they discovered (around the year 1595) that nearby objects appeared greatly enlarged. That was the forerunner of the compound microscope and of the telescope.

The father of microscopy, ***Anthony*** **Leeuwenhoe*k*** of Holland (1632-1723), started as an apprentice in a dry goods store where magnifying glasses were used to count the threads in cloth. He taught himself new methods for grinding and polishing tiny lenses of great curvature which gave magnifications up to 270, the finest known at that time. These led to the building of his microscopes and the biological discoveries for which he is famous. He was the first to see and describe bacteria, yeast plants, the teeming life in a drop of water, and the circulation of blood corpuscles in capillaries. **Robert Hooke** (1635 – 1703), the English father of microscopy, re-confirmed Anthony van Leeuwenhoek's discoveries of the existence of tiny living organisms in a drop of water. Hooke made a copy of Leeunwenhoek's microscope and then improved upon his design

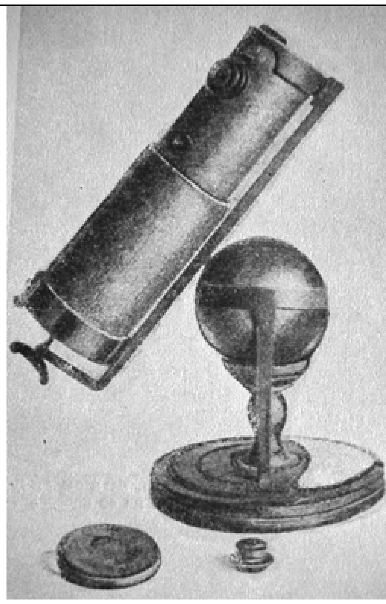


Microscope of Hooke
(*R. Hooke, Micrographia, 1665*)

Telescope (**Zacharias Joannides Janse**n *of Middleburg, 1590*)

In 1609, **Galileo**, father of modern physics and astronomy, heard of these early experiments, worked out the principles of lenses, and made a much better instrument with a focusing device.

Huygens ("Dioptrica, de telescopiis") held the view that only **a superhuman genius could have invented the telescope on the basis of theoretical considerations, but the frequent use of spectacles and lenses of various shapes over a period of 300 years contributed to its chance invention.**



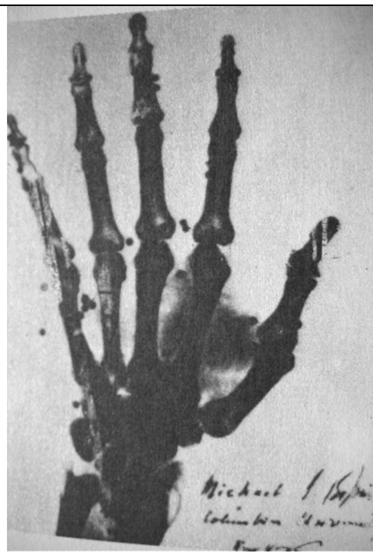
Newton's telescope-refractor

Photographic camera: a revolutionary step
(*H. Nieps, 1826; J. Dagherr, 1836; W. F. Talbot, 1844. First public report was presented by F. Arago, 19.8.1839 at a meeting of L'Institut, Paris*)

Imaging optics + photo sensitive material
Photographic plate/film combines three functions: image recording, image storage and image display

X-ray imaging
(*Wilhelm Conrad Röntgen, Nov. 8,1895; Institute of Physics, University of Würzburg. 1-st Nobel Prize, 1901*):

X-ray point source+ photographic film or photo-luminescent screen

 Wilhelm Conrad Röntgen	 One of the first medical X-ray images (a hand with small shots in it)

Video camera, CRT monitor and electronic television

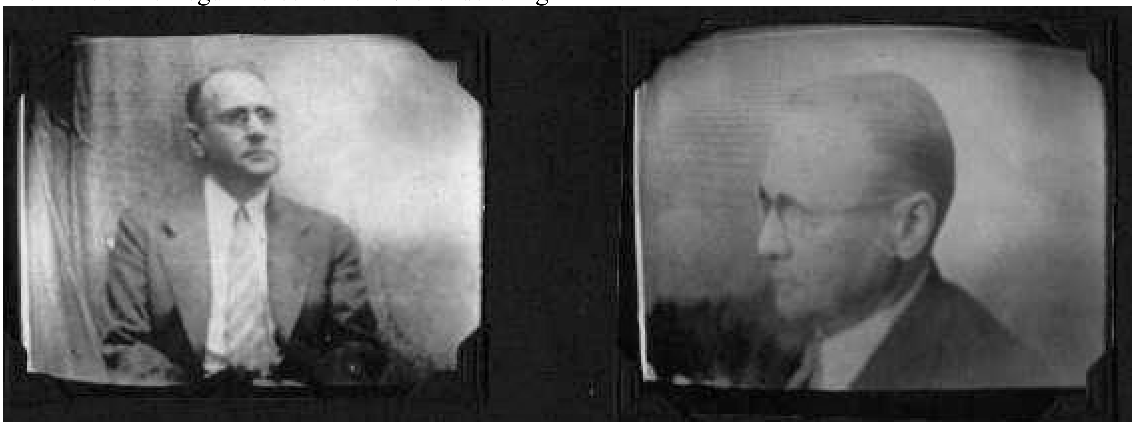
imaging optics + photo-electronic converter + CRT monitor

An important step: image discretization.

~1910, Boris Lvovich Rosing,St. Peterburg: CRT as a display device

~1920-30, Vladimir Kozmich Zvorykin –iconoscope& kinescope, David Sarnov

~1935-39: first regular electronic TV broadcasting

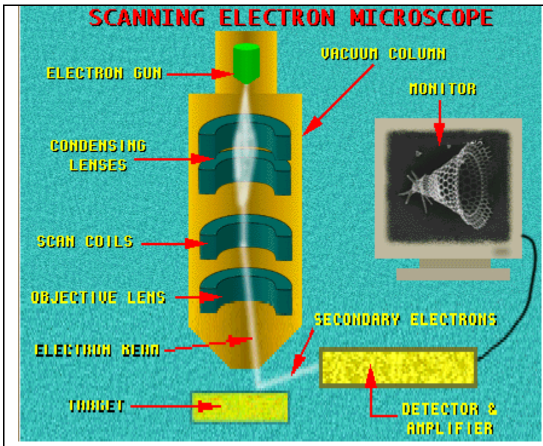


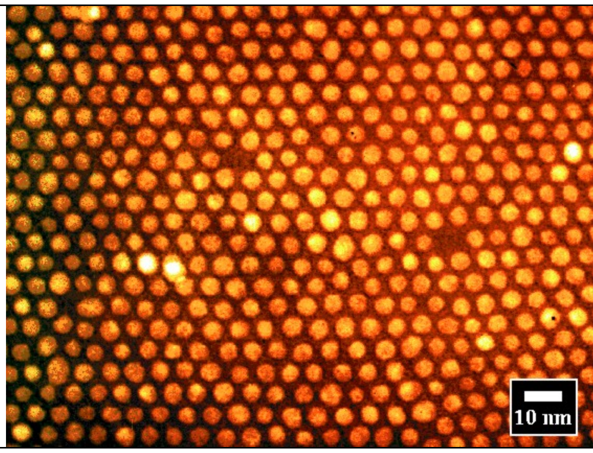
One of the first TV image (V.K. Zvorykin, 1933)

Radar (~1935), Sonar: Beam forming antenna + space scanning mechanism + CRT as a display

Electron microscope (1931, Ernst Ruska, The Nobel Prize in Physics 1986**)**

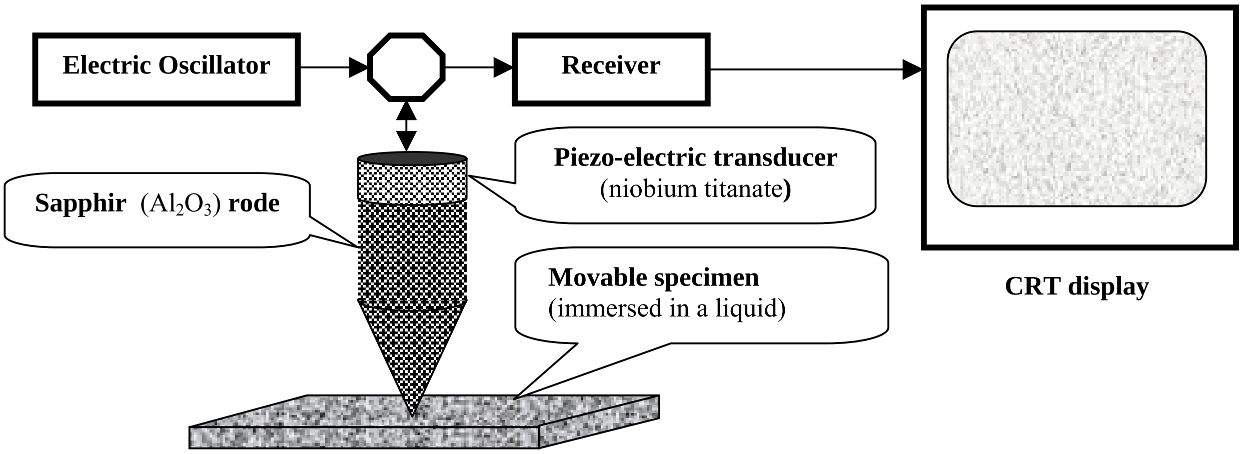
Electron optics + luminescent screen or electron sensitive array + CRT display





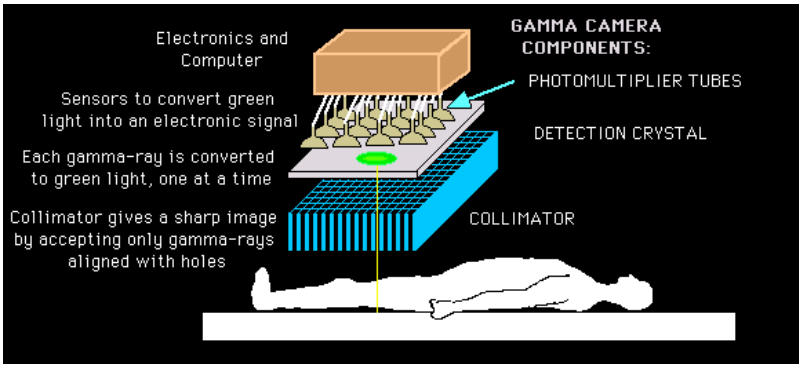
Transmission Electron Microscope: Atoms of gold (Au_clusters) on MoS2.

Acoustic microscope (1950-th, *adopted from R. Bracewell, Two-dimensional Imaging, Prentice Hall, 1995*):

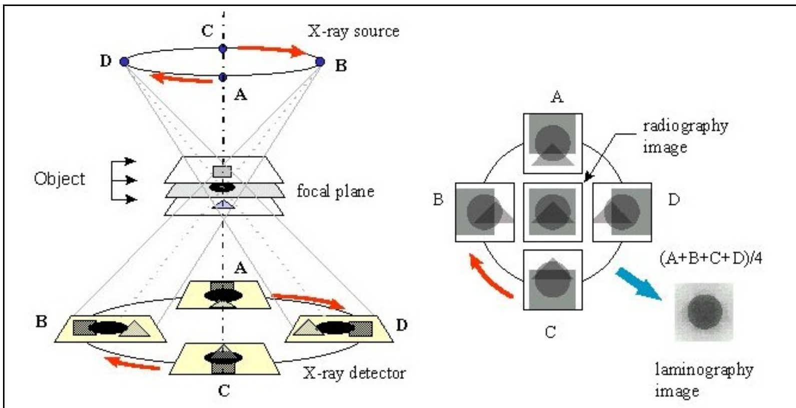


Gamma-camera (Hal Anger, 1957):

Gamma-ray collimator + Gamma-ray-to light converter + photo sensitive array + CRT as a display



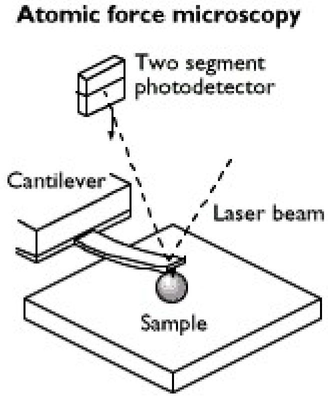
Linear tomography (~1930-th), Laminography

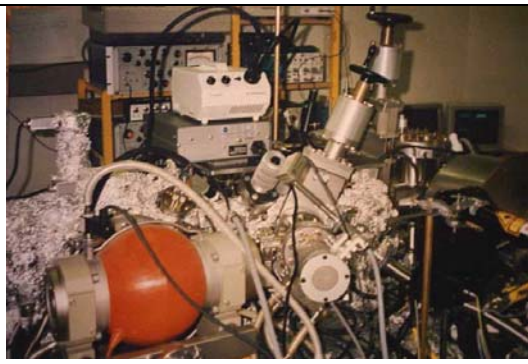


X-ray point source moving in the source plane over a circular trajectory projects object onto X-ray detector plane. The detector moves synchronously to the source in such a way as to secure that a specific object layer is projected on the same place on the detector array for whatever position of the source. The plane of this selected layer is called "focal plane'.

Projections of other object layers located above or beneath of the "focal plane" will, for different position of the source, be displaced. Therefore if one sums up all projections obtained for different positions of the source, projections of the focal plane layers will be accumulated coherently producing a sharp image of this layer while other layers projected with different displacement in different projections will produce a blurred background image. The more projections are available the lower will be the contribution of this background into high frequency components of the output image. (http://lca.kaist.ac.kr/Research/2000/X_lamino.html)

Scanned-proximity probe (SPP) microscopes (Tunnel microscope, *1980-th;* **The Nobel Prize in Physics 1986,** Atomic force microscope)

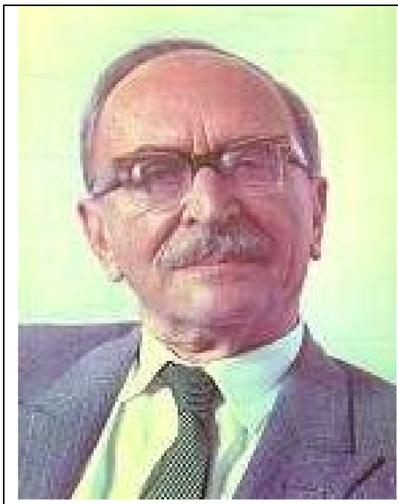



Atomic force microscope, University of Konstanz, May 1991

Holographic imaging

Holography (1948, D. Gabor, The Nobel Prize, 1971)

Invention of holography by D. Gabor (1948) was motivated by the desire to improve resolution power of electron microscopes that was limited by the fundamental limitations of the electron optics. The term “holography” originates from Greece word “holos” (ηωλωσ). By this, inventor of holography intended to emphasize that in 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 was demonstrated in 1961 by radio-engineers E. Leith and J. Upatnieks in Michigan University and by Physicist Yu. Denisyuk in State Optical Institute, St. Petersburg, Russia.



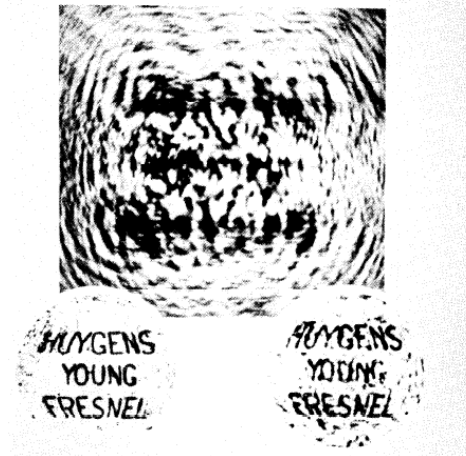
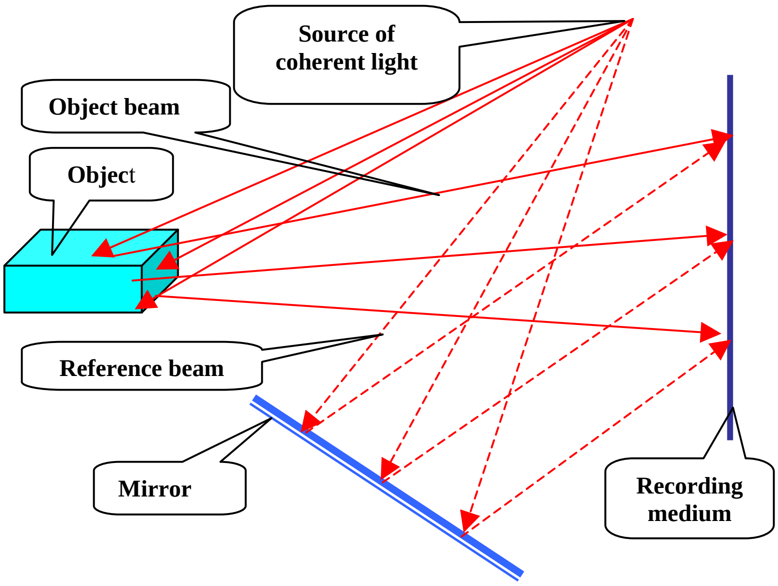
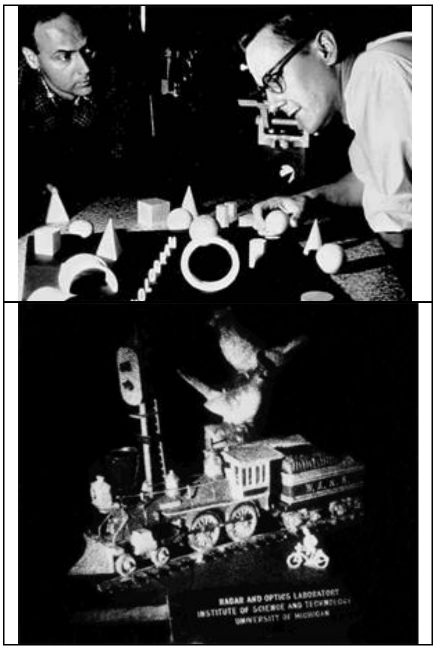


Fig 4.
First Holographic Reconstruction, 1948

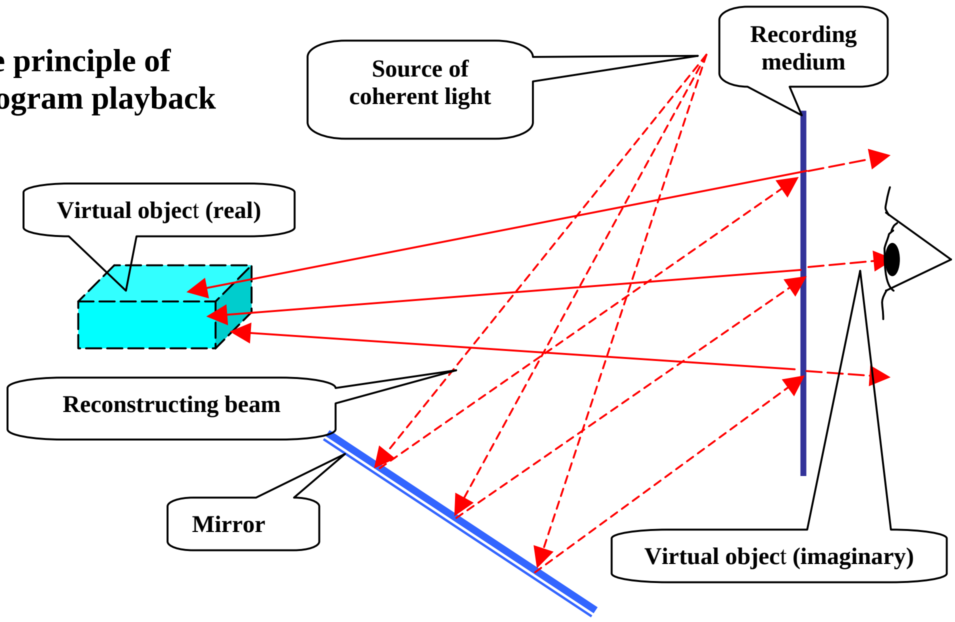
In holography, interference pattern between optical waves reflected by or transmitted through object and a special “reference” wave is recorded**.**



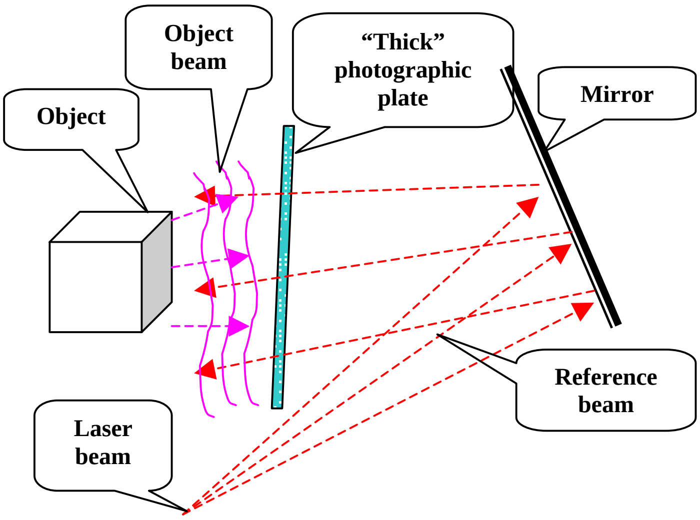


E. Leith and Yu. Upatnieks method of recording holograms (1962)

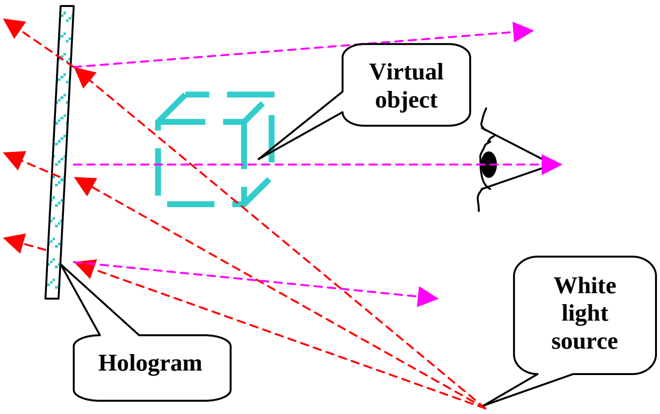
The principle of hologram playback



Yu. Denisyuk's method for recording display holograms (1962)

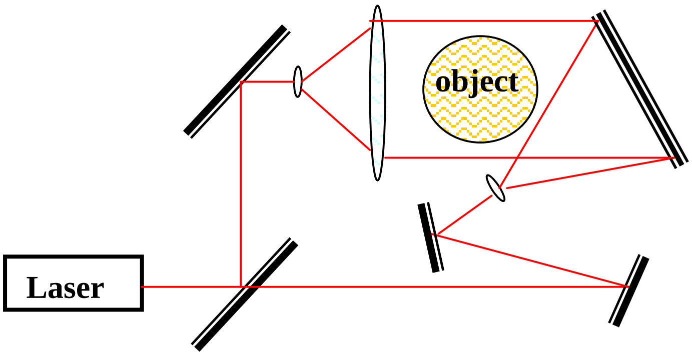


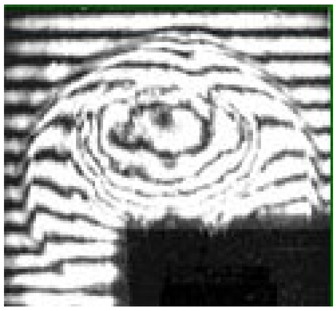
Schematic diagram of hologram recording

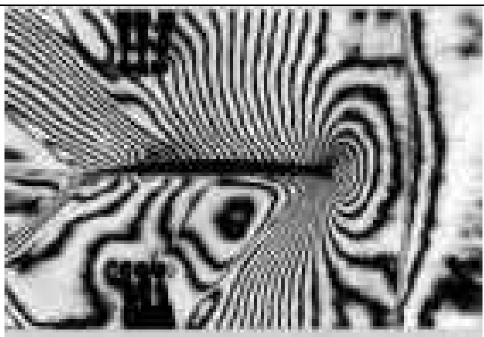


Schematic diagram of hologram play back

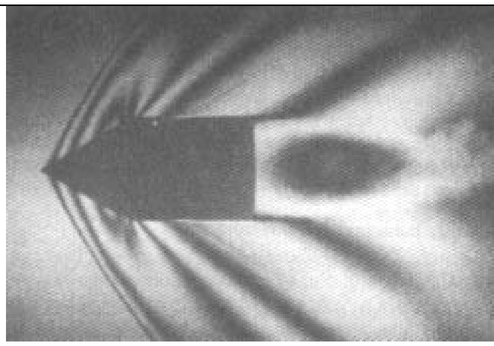
Holographic interferometry



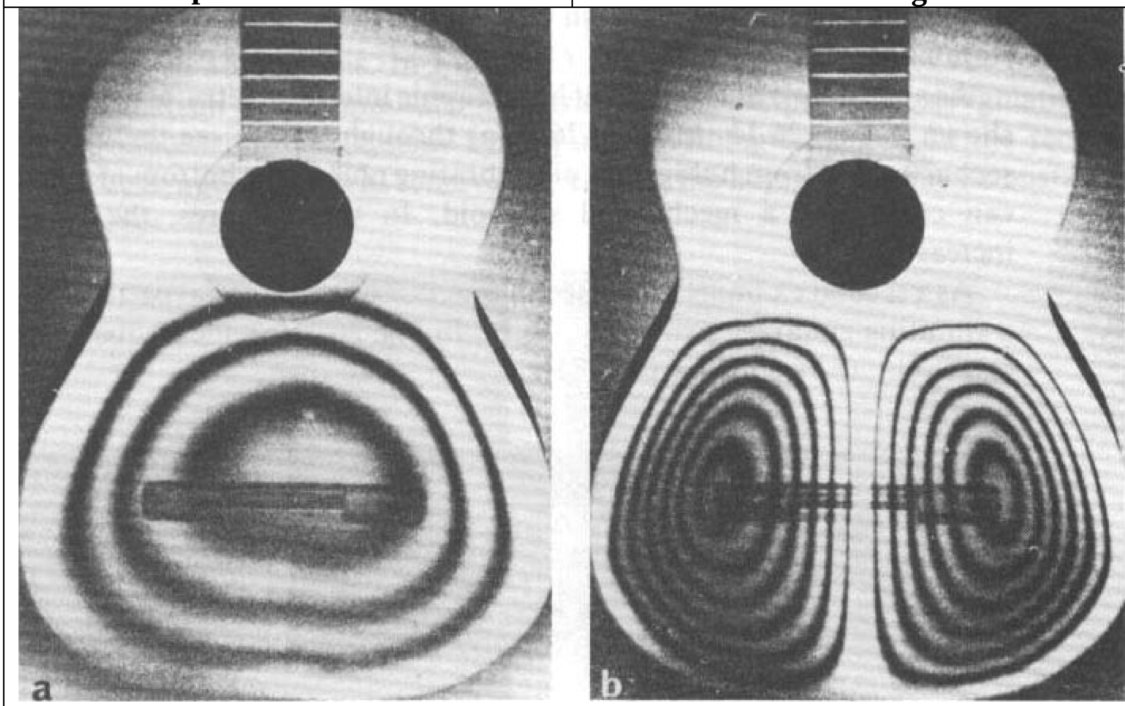




Supersonic air flow

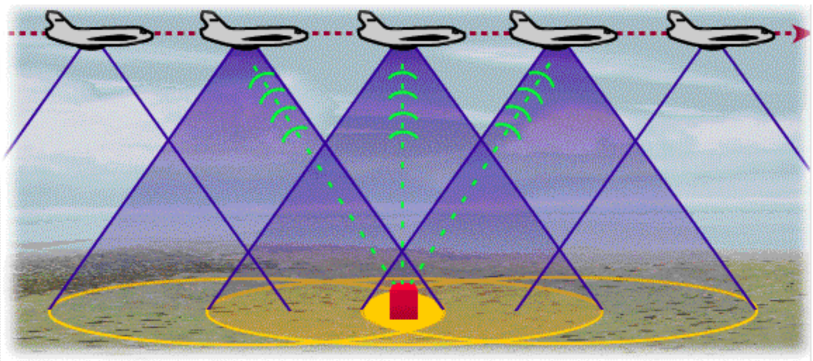


Bullet in flight



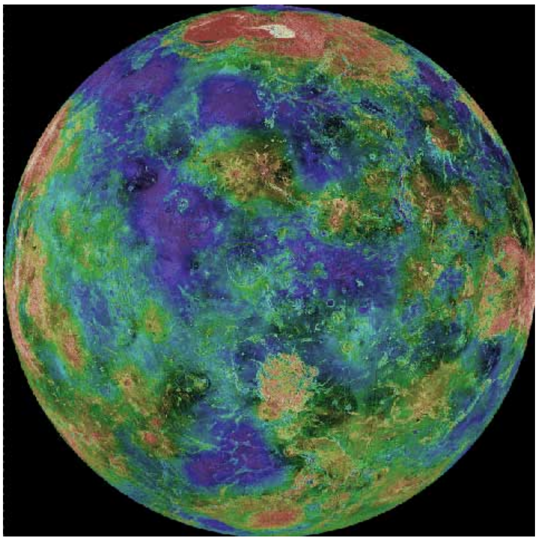
Guitar

Synthetic aperture radar (*1951*)



In synthetic aperture radar imaging, **amplitude and phase of radio waves reflected by the object** is recorded in course of plain flight around the object. These flight data are then used for reconstruction of wave reflectivity distribution over the object surface. The reconstruction is carried out either optically, or, presently, in digital computers.

SAR image of Washington, DC

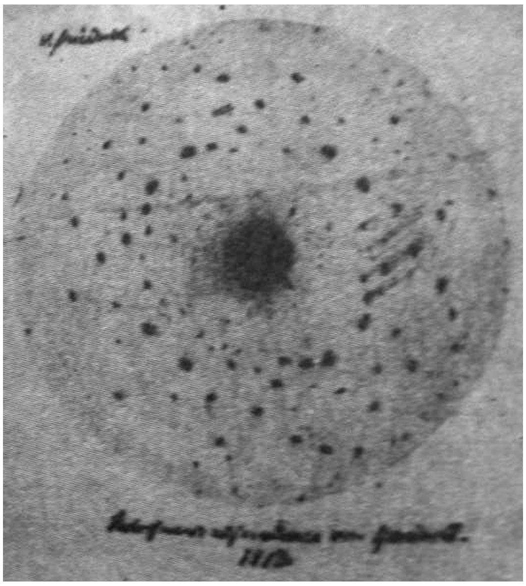


3-km resolution map of Venus. Red represents mountains, while blue represents valleys.. The large yellow/red area in the north is Ishtar Terra featuring Maxwell Montes, the largest mountain on Venus. The large highland regions are analogous to continents on Earth. (Venus2_mag_magellan_space_craft_28_11_99)

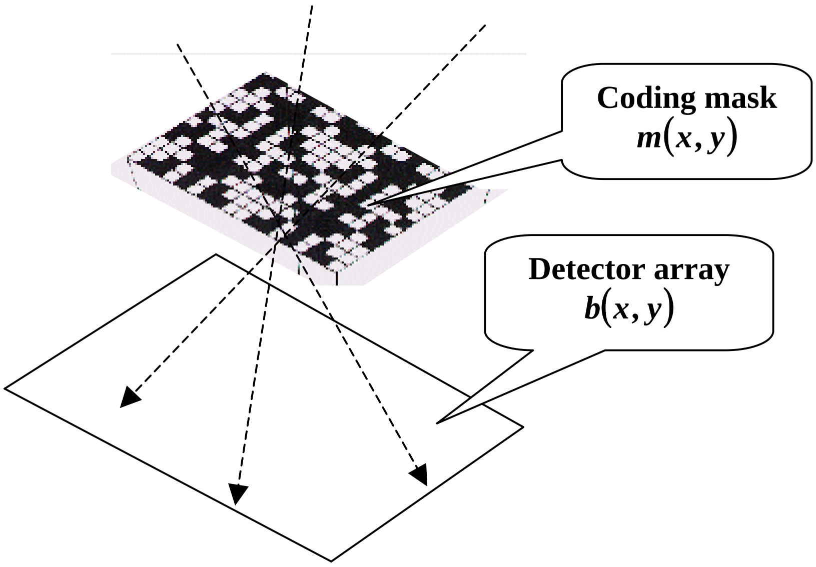
Computational imaging

X—ray crystallography (*Max Von Laue, 1912, Nobel Prize 1914-1918*)
The very first example of computational imaging

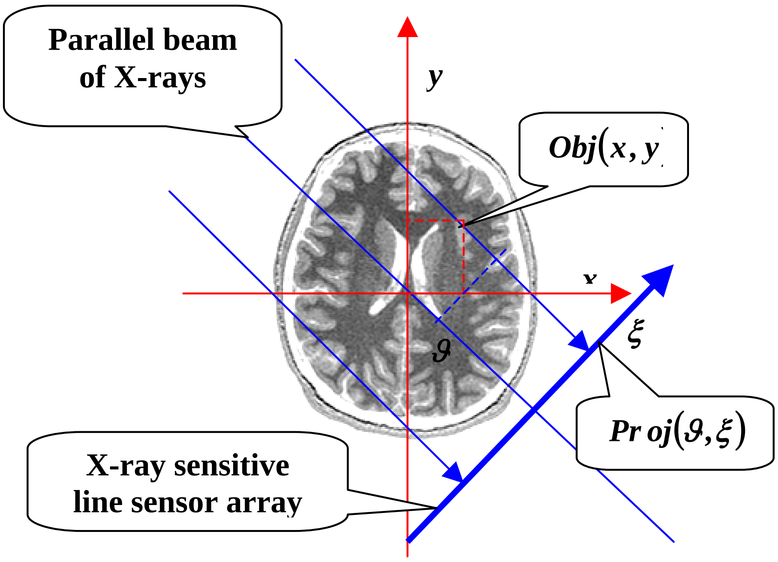
In 1912 Max von Laue and his two students (Walter Friedrich and Paul Knipping) demonstrated the wave nature of X-rays and periodic structure of crystals by observing the diffraction of X-rays from crystals of zinc sulfide. This discovery ended up in crystallography as a new imaging technique. In crystallography, geometrical parameters and intensity distribution of the pattern of diffraction spots is used for calculation of spatial distribution and density of atoms in crystals.



"Coded" aperture (multiplexing) techniques (1970-th**)**
In coded aperture imaging, image projections obtained through a set of special binary masks are recorded and used for image reconstruction carried out in computers

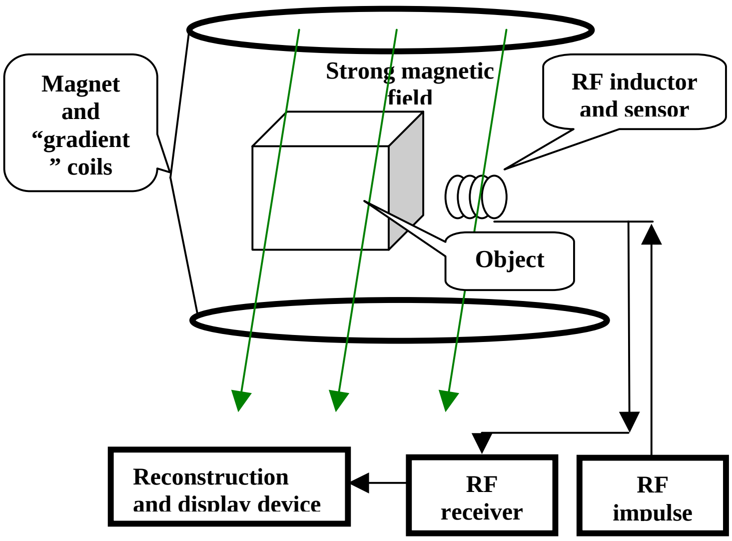


Computed tomography (Cormack**,** Hounsfield, 1973, The Nobel Prize, 1979**)**
The first full scale example of computational imaging



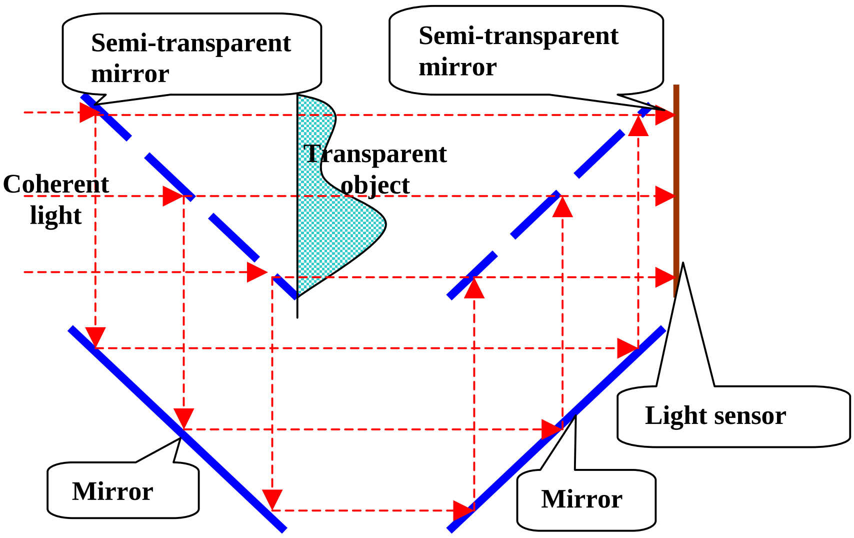
Schematic diagram of parallel beam projection tomography

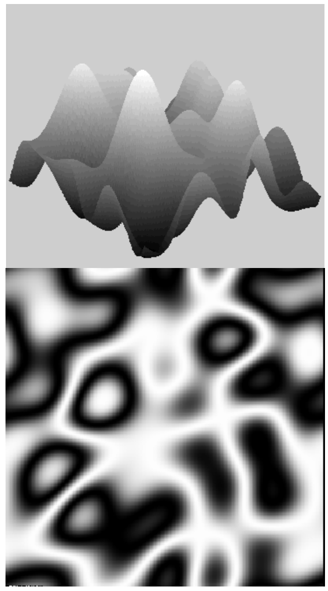
Magnetic resonance tomography (MRI , Felix Bloch and Edward Purcell, The Nobel Prize, 1952, for the discovery of the magnetic resonance phenomenon in 1946; Richard Ernst, The Nobel Prize in chemistry, 1991 for his achievements in pulsed Fourier Transform NMR and MRI; Paul C. Lautenbur and Sir Peter Mansfield, UK, the Nobel Prize in physiology and medicine, 2003) .



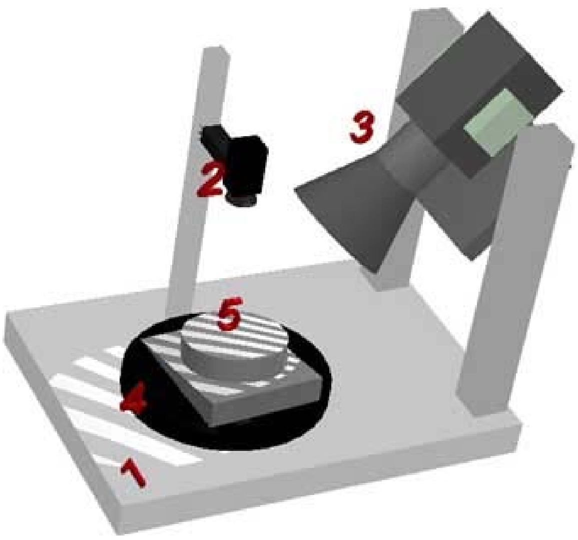
MRI is based on the principles of nuclear magnetic resonance (NMR). An effect is observed when an atomic nucleus is exposed to radio waves in the presence of a magnetic field. A strong magnetic field causes the magnetic moment of the nucleus to precess around the direction of the field, only certain 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. (adopted from *The Macmillan Encyclopedia 2001*, © *Market House Books Ltd 2000*)

Optical interferometry.





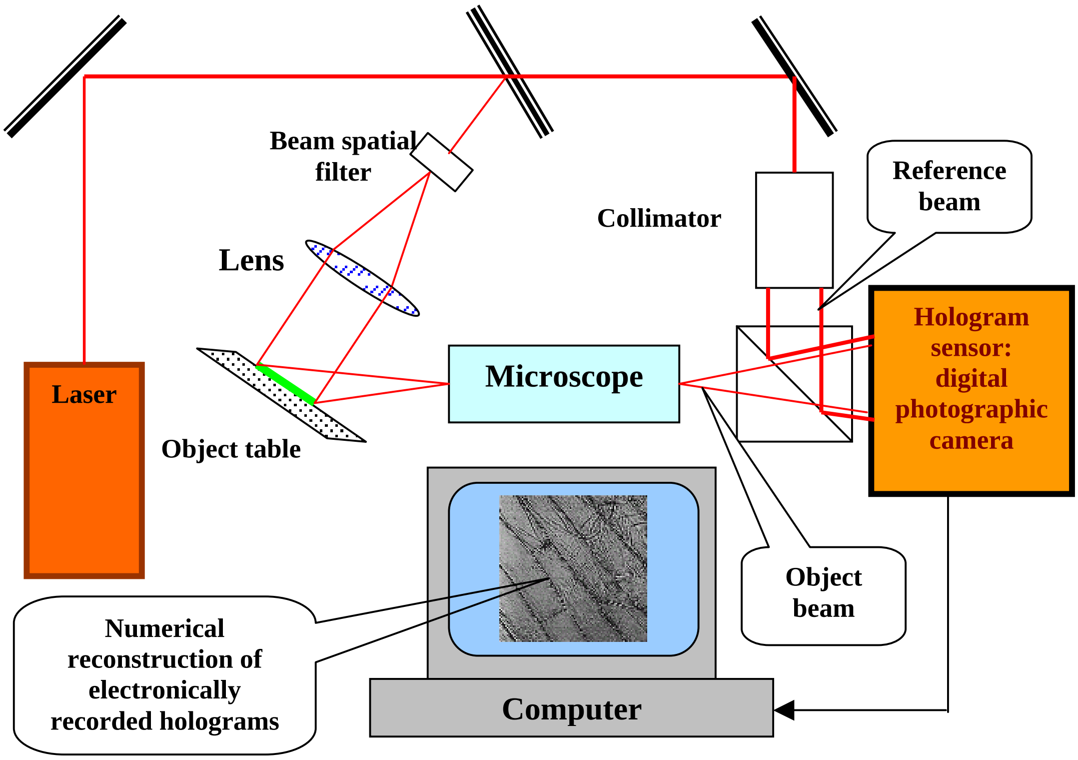
Shape measurement by mean of structured illumination. Moire (Fringe) techniques



Schematic diagram of shape measurement by mean of structured light illumination (1 – fringe image; 2 – image sensor; 3 – illumination source; 4- support; 5 - object)

Digital holography:
In the end of 1960-th beginning 1970-th it was suggested (A. Lohmann, J. Goodman, T. Huang) to use digital computers for reconstruction and synthesis of holograms. Digital holography reflects, in the most purified way, the informational pith of holography, which motivated inventors in holography, D. Gabor and Yu.N. Denisyuk

Numerical reconstruction of digitally recorded holograms



Latest development: digital holographic microscopy (end of 1990-th)

Computer generated display holograms:

Appendix
Nobel prizes for new principles of imaging and imaging devices

1. **Wilhelm Conrad Röntgen,** Germany, Munich University , Munich, Germany b.1845, d.1923. The Nobel Prize in Physics **1901 "In recognition of the extraordinary services he has rendered by the discovery of the remarkable rays subsequently named after him"**
2. **Gabriel Lippmann,** France, Sorbonne University, Paris, France b.1845 (in Hollerich, Luxembourg), d.1921: The Nobel Prize in Physics **1908 "For his method of reproducing colours photographically based on the phenomenon of interference"**
3. **Max von Laue,** Germany, Frankfurt-on-the Main University , Frankfurt-on-the Main, Germany b.1879, d.1960:The Nobel Prize in Physics **1914 "For his discovery of the diffraction of X-rays by crystals"**
4. **Patrick Maynard Stuart Blackett,** United Kingdom, Victoria University, Manchester, United Kingdom b.1897, d.1974. The Nobel Prize in Physics **1948 "For his development of the Wilson cloud chamber method, and his discoveries therewith in the fields of nuclear physics and cosmic radiation"**
5. **Cecil Frank Powell,** United Kingdom, Bristol University, Bristol, United Kingdom b.1903 d.1969. The Nobel Prize in Physics **1950 "For his development of the photographic method of studying nuclear processes and his discoveries regarding mesons made with this method"**
6. **Frits (Frederik) Zernike,** the Netherlands, Groningen University , Groningen, the Netherlands, b.1888, d.1966. The Nobel Prize in Physics **1953 "For his demonstration of the phase contrast method, especially for his invention of the phase contrast microscope"**
7. **Donald Arthur Glaser,** USA, University of California , Berkeley, CA, USA b.1926. The Nobel Prize in Physics **1960 "For the invention of the bubble chamber"**
8. **Dennis Gabor,** United Kingdom, Imperial College of Science and Technology London, United Kingdom b.1900 (in Budapest, Hungary), d.1979, The Nobel Prize in Physics **1971 "For his invention and development of the holographic method"**
9. **Allan M. Cormack,** USA, Tufts University Medford, MA, USA, b.1924 (in Johannesburg, South Africa) d.1998, **Godfrey N. Hounsfield** United Kingdom Central Research Laboratories, EMI, London, United Kingdom b.1919. The Nobel Prize in Physiology or Medicine, **1979 "For the development of computer assisted tomography"**
10. **Ernst Ruska**, Germany Fritz-Haber-Institut der Max-Planck- Gesellschaft, Berlin, b.1906, d.1988. The Nobel Prize in Physics **1986 "For his fundamental work in electron optics, and for the design of the first electron microscope"**
11. **Gerd Binnig**, Germany, b.1947, , IBM Zurich Research Laboratory, Switzerland
12. **Heinrich Rohrer**, Switzerland, b.1933, IBM Zurich Research Laboratory, Switzerland. The Nobel Prize in Physics 1986 "For their design of the scanning tunneling microscope"
13. **Paul C. Lautenbur, Peter Mansfield**, UK. The Nobel Prize 2003 in Physiology and Medicine "For their discoveries concerning magnetic resonance imaging".