"Enrico Fermi" Chair
2021/2022

Lectures at Sapienza Università di Roma,
January-May 2022

A History of the Science of Light

From Galileo's telescope to the laser and the quantum information technologies

Serge Haroche,
Ecole Normale Supérieure and
Collège de France, Paris

Motivation of this course

The science of light, culminating with the invention of the laser and all its applications in modern physics, plays an essential role in basic physics and in technology. Reviewing how this science has developed since the early seventeenth century gives the opportunity to reflect on the basic principles of natural sciences, since discoveries about light have accompanied the emergence of the scientific method. The science of light has touched astronomy, mechanics, the earth sciences and navigation, thermodynamics and even chemistry. It is today closely related to quantum technologies. At a fundamental level, the interrogations about light have led to the revolutions of electromagnetism, relativity and quantum physics. Evocation of this history will give us an opportunity to recall the contributions of great scientists of the past and present times.

The course will illustrate the strong link between basic and applied science, showing that advances in one of these fields relies, in a symbiotic way, on progresses in the other. It will also underline the importance of precise measurements made with increasingly sophisticated scientific equipment. And finally it will illustrate the importance of mathematics, since the science of light relies on the discovery of mathematical tools and concepts explaining the results of observations and experiments, bringing disparate phenomena together and predicting new ones. This permanent back and forth process between experiments and theory is an essential aspect of the scientific history of light.

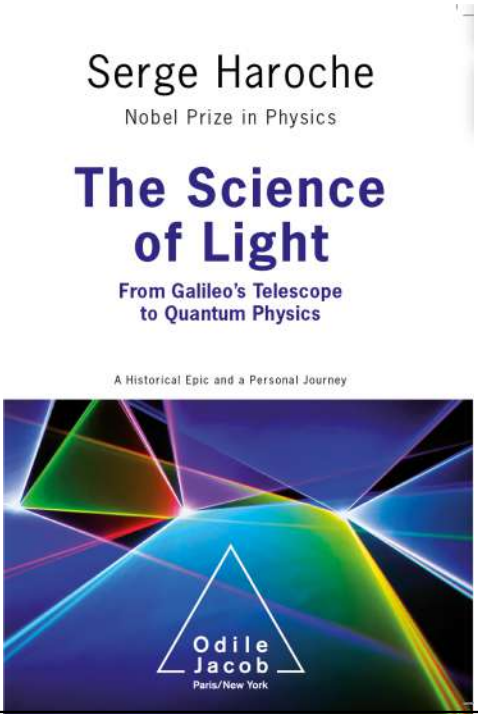
Tentative program

The Course will consist of 15 Lectures, which will be held in **aula Amaldi**, Marconi building, according to the following schedule:

27 January : Light in the seventeenth and eighteenth centuries.
3 February : Light in the nineteenth century: triumph of wave theory and birth of electromagnetism
10 February: Birth of Special and General Relativity.
17 February: Birth of Quantum Physics.
24 February: Introduction to the quantum wave function and its probabilistic interpretation.
3 March : The quantum principles: complementarity, uncertainty relations, Fermions and Bosons
10 March : Dirac equation, origins of quantum field theory; entanglement, measurement and decoherence
17 March : Magnetic resonance and the birth of modern spectroscopy
24 March : Optical pumping and the birth of the laser
31 March : High resolution laser spectroscopy
7 April : Laser cooling and trapping
21 Avril : The measurement of time: from microwave to optical atomic clocks
28 April : Atoms and photons in cavities: Cavity quantum electrodynamics
5 May : Quantum non demolition measurements, Schrödinger cats and decoherence studies
12 May : Introduction to Quantum technologies: metrology, communication, simulation and computing

The course is inspired by a book, published in French under the title « La Lumière révélée, de la lunette de Galilée à l'étrangeté quantique » in 2020 and recently translated in english. The english version will be published in February 2022 (Odile Jacob editor).

This book describes the history of scientific discoveries about light as well as my personal journey in science. It evokes my early research activity, at the time when lasers were in their infancy (in the 1960's). It also describes my research in the last thirty years on the manipulation of simple quantum systems and their application to quantum information science.

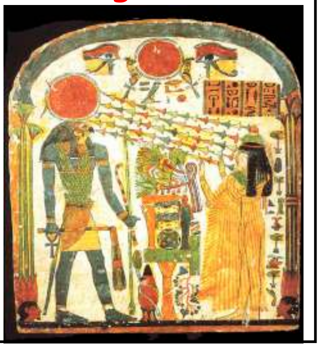


Serge Haroche
Nobel Prize in Physics
The Science of Light
From Galileo's Telescope to Quantum Physics
A Historical Epic and a Personal Journey
Odile Jacob
Paris/New York

First Lecture: Early history of the science of light (from the origins to the 17th & 18th centuries)

It is light which carries most information coming from the world around us and from the Universe.

Mankind has celebrated light since its origins, through myths and religions.



The first scientific knowledge about light phenomena has been acquired during the Antiquity and the muslim Middle Ages, but it is only since the 17th century that truly scientific theories about light have been developed.

What has this history taught us about Science?

The discoveries about light, which have become really quantitative in the 17th century, have accompanied the birth of the modern scientific method, based upon rational thinking and permanent exchange between observation, experimentation and development of theories expressed in mathematical terms.

There is a symbiosis between basic science («blue sky research») inspired by curiosity and technology. Discoveries of the fundamental properties of light have been made possible by the development of devices measuring space and time such as the Galilean telescope and the Huygens pendulum clock. Conversely, knowledge accumulated about the nature of light have led to the invention of more precise instruments such as prism and grating spectrometers, interferometers which measure light's wavelengths (in the 18th and 19th century) and finally the lasers and all the instruments exploiting visible and invisible light in the 20th century.

With the help of these instruments, scientists have been able to refine their observations and detect new strange and counter-intuitive phenomena, leading to the theories of ***relativity and quantum physics*** which have revolutionized our vision of the world and given birth to most of the modern technologies.

Vision and optics during the Greek and Roman Antiquity

Empedocles
(494-434 BC)

According to Empedocles, vision was due to rays emanating from the eye (similiar to the sense of touch). This point of view was adopted by many greek philosophers in subsequent centuries The « fire » from the eye combined with the fire from flames or the sun makes objects visible:

*« Agamemnon heart was black with rage and **his eyes flashed fire….** » (Illiad)*

Democritus
(460-370 BC)

Democritus, the father of the atomist theory, followed by Epicurus and Lucretius in Rome (author of the *de Natura rerum*), assumed that thin layers of atoms - effigies of the objects to be seen - travel toward the eye. Light from luminaries enlarge the "pores between the atoms of air", permitting this travel which is blocked in obscurity. Vision thus combines two entities: material replicas of objects and light facilitating their transmission through air.

Euclid (circa 300 BC)

Geometrical models of rays emanating from the eye were studied by Euclid who wrote a treaty on vision which is a precursor of the treaties on perspective of the Renaissance. Some of Euclid's ideas were further developped by the astronomer Ptolemy who studied reflection and refraction of rays and the operation of the « camera obscura » ,

Ptolemy
(100-170 AD)

Optics between antiquity and seventeenth century

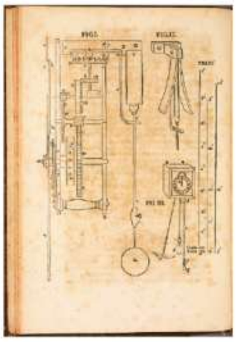
Alhazen (965-1039)

Medieval scholars in the muslim world rediscovered greek science, criticized it and made fundamental discoveries based on observation and experimentation. Alhazen understood that vision is due to light emitted directly by luminaries or scattered by illuminated objects into our eyes. He rejected the idea that light rays emerged from the eye. He made the first description of the eye as an optical instrument and studied the « camera obscura ».

Johannes Kepler
(1571-1630)

At the dawn of the scientific revolution, Kepler improved Alhazen's models and studied the propagation of light rays, with a semi-quantitative description of reflexion and refraction. He gave an accurate description of the eye, recognizing the respective roles of the pupil, the cristalline and the retina. He separated the vision into its physical component (up to the retina) and its perception component (what happens between the retina and the brain). He gave a geometrical analysis of the operation of the refractive telescope used by Galileo. Finally, he understood that the tails of the comets are pushed in a direction opposite to the sun due to the radiation pressure of sun light. Better known for his contribution to the Copernician revolution, Kepler has also been a precursor of the great advances of the science of light which started in the 17th century and have lasted until today.

Two instruments at the origin of modern physics:



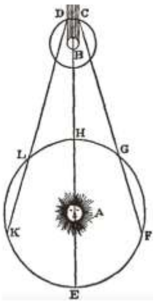
The Galilean telescope and Huygens pendulum clock

First astronomical measurement of light’s velocity

Galileo fails with his naive lantern experiment….

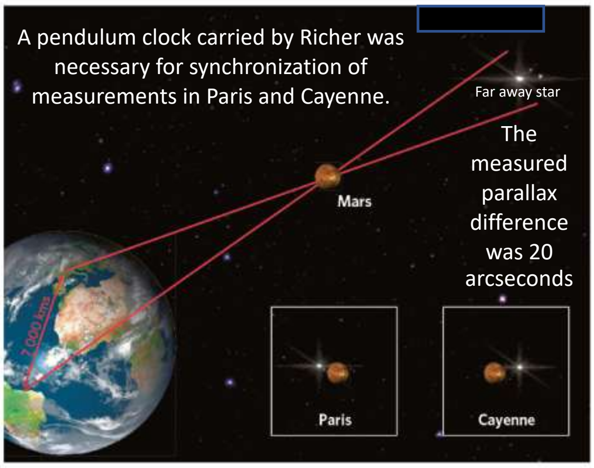
…but improves the refractive telescope which allows him to discover the Jovian satellites…

70 years later, Römer measures in Paris Observatory the period of Io around Jupiter and realizes that it lenthens during six months, then shortens during the next six months. He performs these measurements with a precise Huygens’clock.



He understands that the period shortens or lengthens by the time it takes for light to travel the distance that the Earth has moved on its orbit towards or away from Jupiter during a revolution of Io.

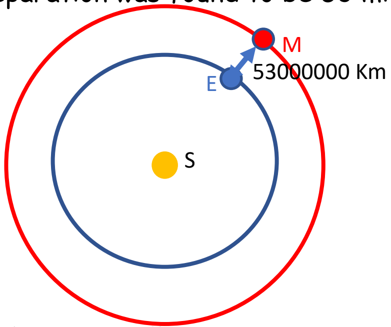
In 6 months, the delay accumulated by Io (about 17 minutes) corresponds to the time it takes for light to travel over the diameter EH of Earth’s orbit around the Sun.



A pendulum clock carried by Richer was necessary for synchronization of measurements in Paris and Cayenne.

The measured parallax difference was 20 arcseconds

In order to estimate the Earth-Sun distance, an astronomer, Jean Richer, was sent to Cayenne in 1672 to measure there the parallax of Mars at opposition and compare it to that observed at the same time in Paris. Knowing the Paris-Cayenne distance, the Mars-Earth distance at the time of closest separation was found to be 53 million kms

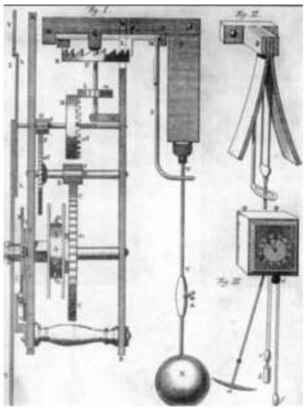


Römer and Huygens conclude from these observations that light's velocity is about 200.000 km/s (this value, better estimated in th 18th century is close to 300000 km/s)

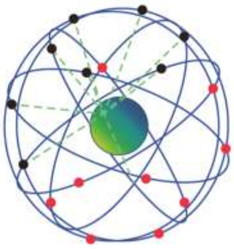
Kepler's laws then allowed astronomers to deduce the Sun-Earth distance (150 million kms)

For these measurements to be possible, clocks with an uncertainty not exceedng about 10 seconds per day were required (1/10000)

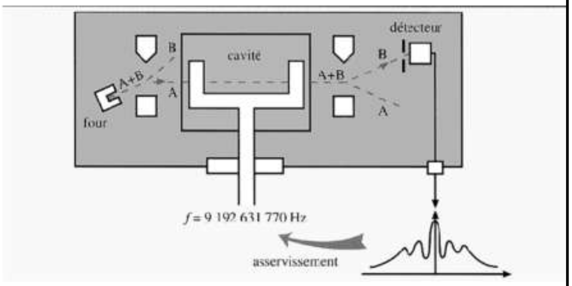
10 orders of magnitude improvements over the precision of time interval measurements between 1650 and 1980…



Huygens mechanical clock
Frequency: 0,5 Hz
Uncertainty: 10^{-4}
(10 seconds/day)

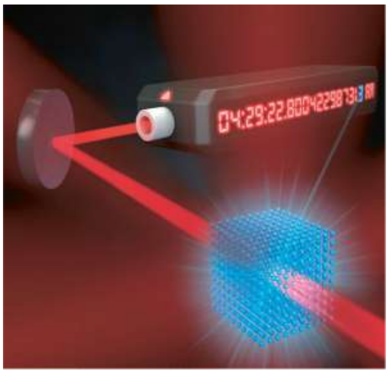


GPS
Navigation



Cesium atomic clock
Frequency: 9197631770 Hz
Uncertainty: 10^{-14}
(One billionth of a second per day)

Another huge jump in precision: Optical atomic clocks (years 2000)



The frequency of a laser is locked to that of an atomic spectral line of a Strontium, 100000 times larger than that of the Cesium clock.

Uncertainty is 100000 times smaller than that of the GPS clocks, a few femtoseconds (one millionth of a billionth of a second) per day.

A tenth of a second uncertainty over the age of the Uiverse!

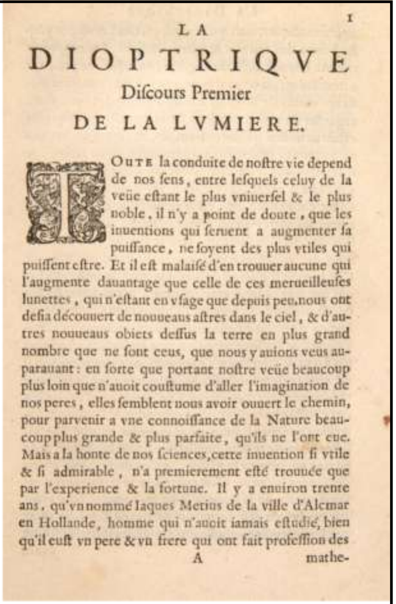
With such a precision, one can check that time ticks at different rates in two points whose altitude difference is of the order of a few mm (General relativity)

The **15 orders of magnitude** won since Galileo and Huygens over the precision of time measurements illustrate how much the science of light has revolutionized our means of action and observation.

René Descartes (1596-1650)

Descartes assumed that light is propagating at infinite speed (it was before Römer experiment).

He described Light as a « tendency of motion » of a medium, the Aether, which is made of infinitely rigid particles filling all space. These particles transmit the light motion instantaneously through elastic collisions.



1

LA

DIOPTRIQVE

Diſcours Premier

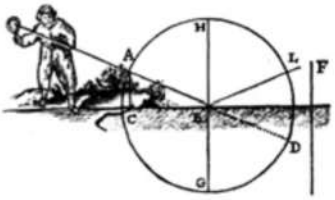
DE LA LVMIERE.

TOUTE la conduite de noſtre vie depend de nos ſens, entre leſquels celuy de la veüe eſtant le plus vniuerſel & le plus noble, il n'y a point de doute, que les inuentions qui ſeruent a augmenter ſa puiſſance, ne ſoyent des plus vtiles qui puiſſent eſtre. Et il eſt malaiſé d'en trouuer aucune qui l'augmente dauantage que celle de ces merueilleuſes lunettes, qui n'eſtant en vſage que depuis peu, nous ont deſia découuert de nouueaus aſtres dans le ciel, & d'autres nouueaus obiets deſſus la terre en plus grand nombre que ne ſont ceus, que nous y auions veus auparauant: en ſorte que portant noſtre veüe beaucoup plus loin que n'auoit couſtume d'aller l'imagination de nos peres, elles ſemblent nous auoir ouuert le chemin, pour parvenir a vne connoiſſance de la Nature beaucoup plus grande & plus parfaite, qu'ils ne l'ont eue. Mais a la honte de nos ſciences, cette inuention ſi vtile & ſi admirable, n'a premierement eſté trouuée que par l'experience & la fortune. Il y a enuiron trente ans, qu'vn nommé Iaques Metius de la ville d'Alcmar en Hollande, homme qui n'auoit iamais eſtudié, bien qu'il euſt vn pere & vn frere qui ont fait profeſſion des

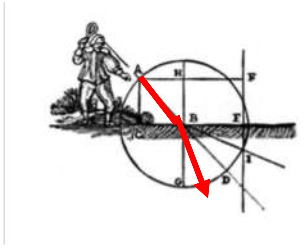
A mathe-

To describe light's reflexion and refraction, Descartes makes the analogy with the motion of a ball bouncing on a flat surface or changing direction when it penetrates water. This analogy allows him easily to find the law of reflexion on a mirror (the angle of incidence is equal to the angle of refraction):

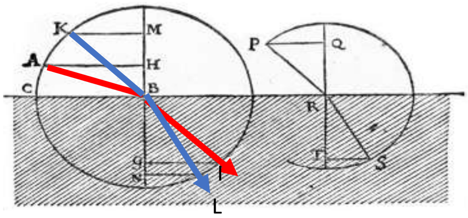
Using this mechanical analogy, he assumes that the « virtual ball » keeps after bouncing the same momentum along the surface, while the momentum component normal to the surface is reversed, the speed of the ball remaining unchanged.



The Snell-Descartes empirical sine law



Descartes stated this law, first disovered by Snell in 1620, trying to give it a qualitative explanation based on the supposed increased tendency of light to penetrate in the medium



He applied the "virtual" ball analogy to the refraction of a light beam penetrating from air into a transparent medium. He assumed that the ball keeps its momentum along the surface constant (as for reflexion), but that the momentum component along the normal to the diopter is changed. Observation shows that light is refracted at an angle with respect to the normal smaller than the incidence angle. The virtual ball must thus be «sucked in » the medium, acquring a larger component of its momentum along the normal to the diopter. Descartes assumed that light has a greater tendency to penetrate in the medium than in air because the Aether particles are in contact with a rigid medium less « soft » and less « damping » than air. The virtual ball momentum along the normal to the diopter is increased while the momentum along the surface is unchanged. Experimental evidence leads to the conclusion that the velocity of the virtual ball is *augmented* by a constant ratio, equal to that of the sines of the angles of incidence and refraction:

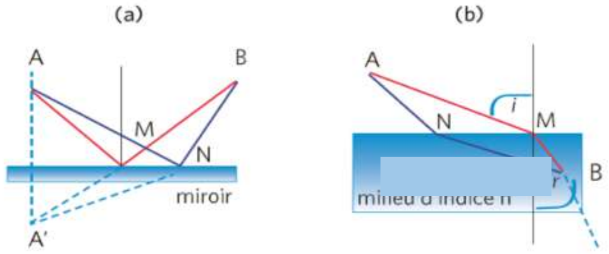
$$\frac{\sin i}{\sin r}=\frac{AH}{GI}=\frac{KM}{NL}=n(\text{refractive index})$$

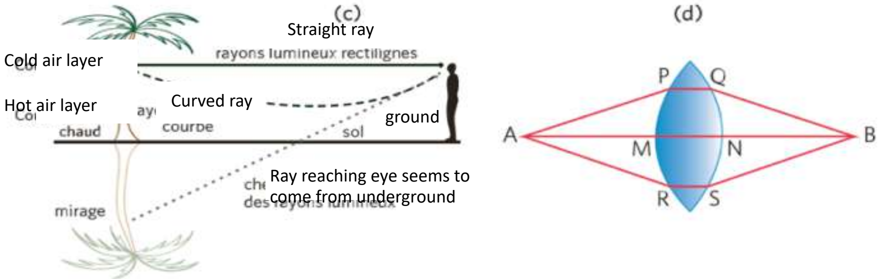
No demonstration of this empirical law

Fermat's principle: to go from point to point, light choses path corresponding to shortest (or extremum) time

« Nature always acts by the simplest means »

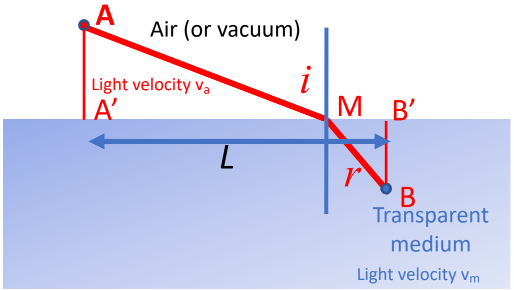
Pierre de Fermat
(1607 ?-1665)





Fermat's principle implies that light has a finite velocity, smaller in matter than in air. This is the first theoretical model of Light which does not make any unnecessary assumption (does not rely on an Aether model)

Retrieving sine's law from Fermat's principle (using calculus)



Choose as variable $x = A'M/L$

$$AM = \sqrt{AA'^2 + x^2 L^2}$$

$$MB = \sqrt{BB'^2 + (1-x)^2 L^2}$$

Light propagation time from A to B:

$$t = \frac{AM}{v_a} + \frac{MB}{v_m}$$

Express extremum of $t(x)$:

$$dt = x dx \frac{L^2}{AM\, v_a} - (1-x) dx \frac{L^2}{MB\, v_m} = 0$$

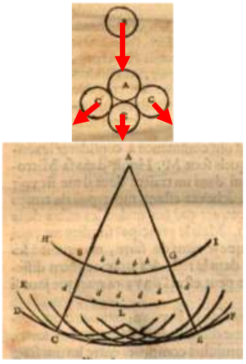
Hence: $$\frac{v_a}{v_m} = \frac{xMB}{(1-x)AM} = \frac{xL}{AM} \times \frac{MB}{(1-x)L} = \frac{\sin i}{\sin r}$$

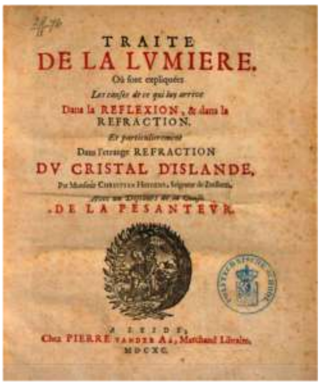
Fermat's principle entails the Snell-Descartes sine law. The fact that *i* is larger than *r* implies that light propagates faster in air than in medium

Huygens
(1629-1695)

Light is a wave propagating at a finite speed in the Aether, analogous to sound vibrations propagating in air. Huygens gave an estimate of Light's velocity based on Römer's observations. Like Descartes, he assumed that the Aether is filled with small rigid like-ball particles transmitting light vibrations.

Each point reached by the light wave can be considered as the source of a secondary wavelet, the light propagating further resulting from the superposition of all these wavelets *(Huygens-Fresnel Principle)*

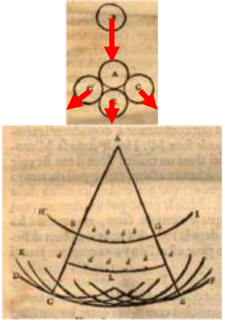




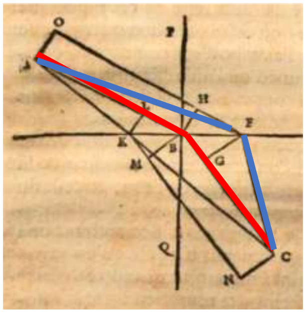
TRAITE
DE LA LVMIERE.
Où sont expliquées
Les causes de ce qui luy arrive
Dans la REFLEXION, & dans la
REFRACTION.
Et particulierement
Dans l'etrange REFRACTION
DV CRISTAL DISLANDE.
DE LA PESANTEVR.
A LEIDE,
Chez PIERRE VANDER AA, Marchand Libraire.
MDCXC.

This provides a geometrical model allowing Huygens to explain the reflexion and the diffraction laws and the linear propagation of light rays and to deduce Fermat's principle from the sine law. Huygens theory implies that light is slowed down, not accelerated, in a medium.

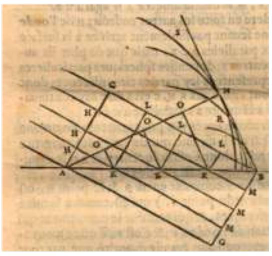
Figures of Huygens treaty illustrating his geometrical demonstrations



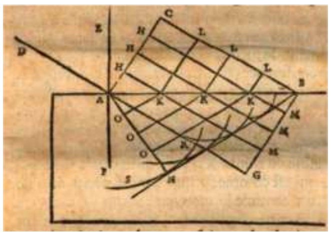
The Huygens Principle of secondary waves justified by the model of Aether particles transmitting by collision the wave motion



Fermat's least time law deduced by geometrical argument from sine's law

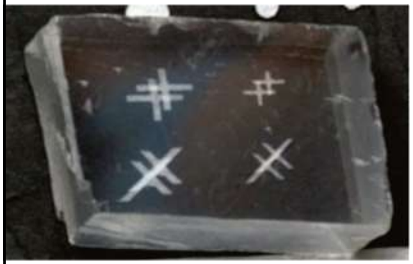


The law of reflexion



The sine law of refraction

Huygens and the strange properties of the Islandic Spath crystal ($CaCO_3$)

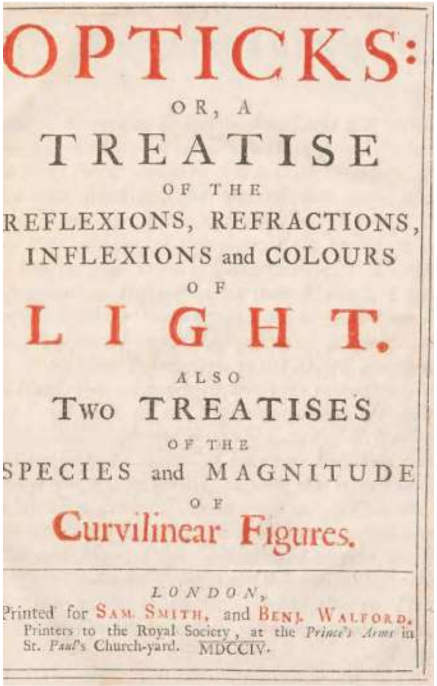


An image appears double when looked at through the crystal. A ray impinging at normal incidence gives rise to two refracted beams : one goes through without deviation: it is the ordinary beam which obeys Snell's law. The other, the extraordinary beam, is deviated at an angle. When rotating the crystal around the direction of the incident beam, the extraordinary image turns around the fixed ordinary one. If the ordinary ray emerging from the crystal is sent on a second identical crystal oriented in the same way, it goes through without deflection. If the second crystal is rotated by 90°, the ray is deviated, becoming the extraordinary ray of the second crystal. By studying this puzzling effect, Huygens discovered a manifestation of light's polarization, which will be understood one and a half century later. He also hints to the anisotropy of light propagation in some media (light propagates at different velocities depending on rays polarizations (see later).

Isaac Newton

Newton develops an opposite corpuscular theory of light

Qu. 29. Rays of light are very small bodies emitted from shining substances—such bodies will have properties that conform to the phenomena—examples—the unusual refraction of Island-Crystal appears due to some attractive virtue lodged in certain sides of the rays and of the particles of the crystal—this virtue seems not magnetical, but is similar—it is difficult to conceive how rays of light can have a permanent virtue in two of their sides



OPTICKS:

OR, A

TREATISE

OF THE

REFLEXIONS, REFRACTIONS, INFLEXIONS and COLOURS

OF

LIGHT.

ALSO

Two TREATISES

OF THE

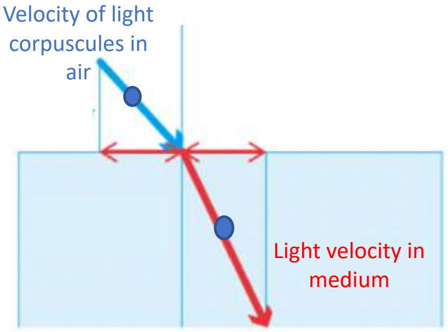
SPECIES and MAGNITUDE

OF

Curvilinear Figures.

LONDON,

Printed for SAM. SMITH, and BENJ. WALFORD, Printers to the Royal Society, at the *Prince's Arms* in St. *Paul's* Church-yard. MDCCIV.

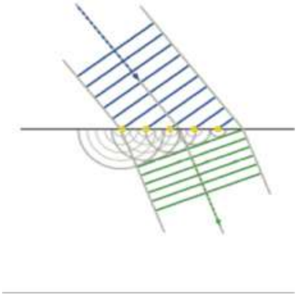


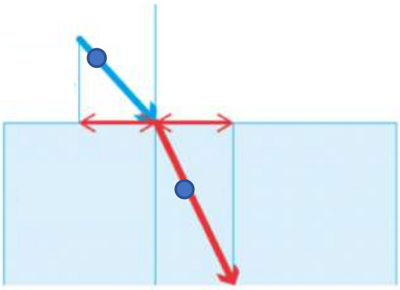
According to Newton the light corpuscules are attracted by transparent matter and are thus swifter in glass than in vacuum « in the proportion of the sines which measure the refraction of the bodies »

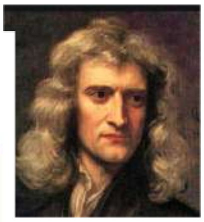
If Light be swifter in Bodies than in Vacuo, in the proportion of the Sines which measure the Refraction of the Bodies, the Forces of the Bodies to reflect and refract Light, are very nearly proportional to the densities of the same Bodies; excepting that unctuous and sulphureous Bodies refract more than others of this same density.

Huygens vs Newton: two conflicting theories

Huygens







Newton

Light is a wave….

propagating slower in water than in air

Both theories explain the sine law, but with opposite arguments which make contradictory predictions about light velocity in matter

….or a flux of particles

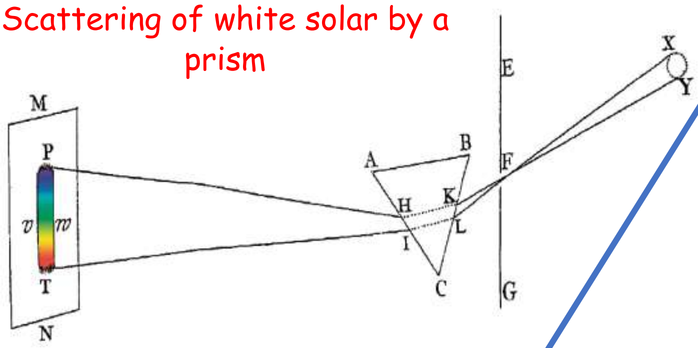
….flying swifter in water than in air

sin (i)/sin(r)= c(air)/c(water)
Huygens

sin (i)/sin(r)= c(water)/c(air)
Newton

Newton studies of colors

Scattering of white solar by a prism



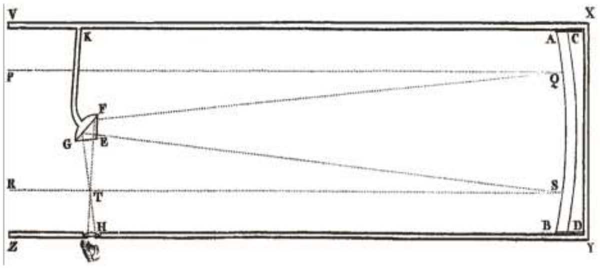
Light's particles of different colors have slightly different velocities in transparent medium (dispersion). Newton assumes that blue rays (more dispersed than red ones) propagate faster than red ones. The wave theory predicts the opposite.

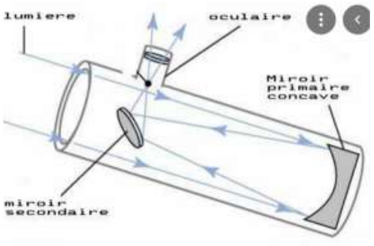
Newton rings observed in white light

Experiments done with great precision, but Newton could not really explain them because particle theory cannot account for interference effects

« light particles undergoing "fits and starts" of easy and difficult reflections »

Newton invents the reflecting telescope





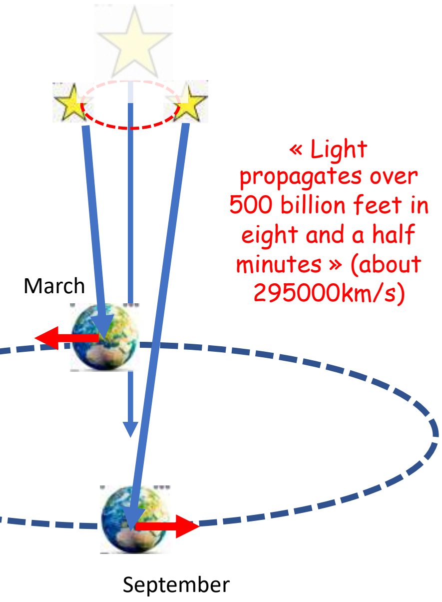
Light reflected on parabolic mirror is concentrated in the focal plane and deflected by a small mirror towards an eyepiece lens.

Advantages over the Galilean refracting telescope:
No chromatic aberrations (reflection laws are independent of color)

No spherical aberration (parabolic mirrors focus parallel beams better than spherical lenses, as a consequence of Fermat's principle). Resolution limited by size of mirror. Large sizes more easily achievable for mirrors than for lenses.

Light velocity measured by the aberration of stars

James Bradley (1693-1762)



« Light propagates over 500 billion feet in eight and a half minutes » (about 295000km/s)

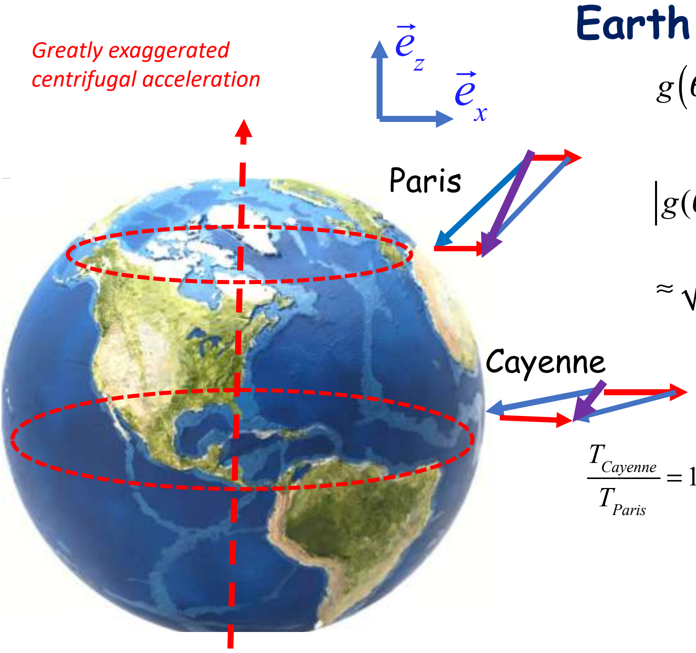
In Earth's frame of reference, the velocity vector of the light coming from a distant star appears oriented at an angle varying according to the season (the case of a star in a direction normal to the ecliptic is represented on figure). The inclination of the star light ray expressed in radian is equal to the ratio of the Earth velocity on its orbit to light's velocity, an angle very close to 10^{-4} radian, i.e. *20 arc-seconds.* The apparent annual motion of the star is thus a small circle having a diameter of 40 arcseconds. If the star is in a different direction, its motion is seen as elliptical. This aberration effect - independent of the star distance to the Earth - is different from the parallax one, which is only a fraction of an arcsecond for the closest stars. In 1727 Bradley measured the star aberration and used it to give an evaluation of light's velocity much more precise than the Römer-Huygens one.

A related scientific quest: the determination of the shape of the Earth

Jean Richer who performed in 1672 the measurement of Mars parallax in Cayenne also observed that his Huygens pendulum was beating slower than in Paris, accumulating a delay of about 3 minutes per day. Huygens hypothesized that this was the result of a decrease of gravity around the equator due to the centrifugal acceleration caused by the daily rotation of the Earth.

This acceleration, in a direction normal to the rotation axis, is similar to the one experienced in a merry-go-round. Huygens had found that this acceleration, to which all bodies are submitted in a rotating reference frame, is equal to ω^2R, where ω is the angular velocity of the frame and R the distance from the rotation axis. Observing its effect on gravity was the first non astronomical evidence that the Earth was not a Galilean reference frame ("a pur si muove" as Galileo is supposed to have said)…

Effect of centrifugal acceleration on rotating spherical Earth



$$g(\theta_L) = -\left(g-\omega^2 R\right)\cos\theta_L \vec{e}_x - g\sin\theta_L \vec{e}_z$$

$$\left|g(\theta_L)\right| = \sqrt{(g-\omega^2 R)^2\cos^2(\theta_L) + g^2(1-\cos^2(\theta_L)}$$

$$\approx \sqrt{g^2 - 2\omega^2 gR\cos^2(\theta_L)} = g\left(1 - \frac{\omega^2 R\cos^2(\theta_L)}{g}\right)$$

$$g(\theta_L) = g(1 - 0{,}003436\cos^2\theta_L)$$

$$\frac{T_{Cayenne}}{T_{Paris}} = 1 + 0{,}00172\left[\cos^2(\theta_{L,C}) - \cos^2(\theta_{L,P})\right] = 1 + 9{,}66\times 10^{-4}$$

Expected pendulum delay per day in Cayenne: 83 seconds
(if Earth was a homogeneous sphere)

Richer's pendulum slowing down and Galileo's relativity of motion

In his famous book « Dialogues Concerning the Two Chief World Systems » Galileo analyses the relativity of motion, stating that in boat moving at constant speed, no mechanical experiment can tell an observer whether he is moving or still:

> *« You will discover not the least change in all the effects named, nor could you tell from any of them whether the ship was moving or standing still. »*

This metaphor was used by Galileo to justify that the Earth could be moving in the Universe without us noticing it. In a Galilean reference frame moving at constant speed, the only way to feel the « motion » is to look outside (at the stars).
Galileo added that one could however feel the motion if the boat was pitching forward or backward, accelerating one way or the other. One then feel the inertial forces associated to these accelerated reference frame motions. The rotation of the Earth, corresponding at Equator to an acceleration about 3.10^{-3} time the Earth gravity, makes a reference frame attached to the ground slightly non-Galilean.
Richer, with the help of Huygens clock, is the first to have noticed that small effect and observed, without looking at the stars, that the Earth is moving.

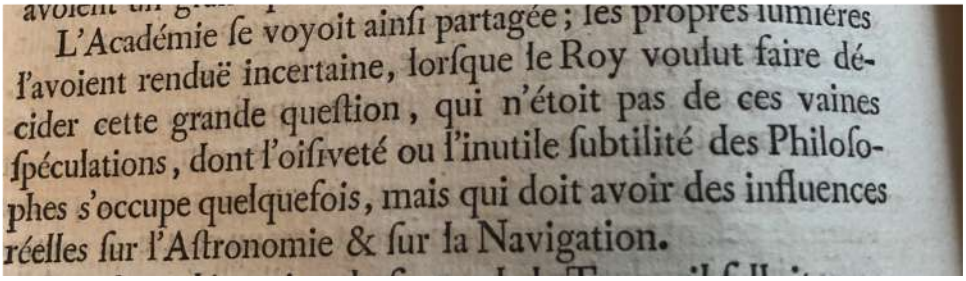
The observed delay (3 minutes) was much larger than the one expected from the direct effect of the daily centrifugal acceleration: Huygens and Newton made the hypothesis that the centrifugal force also changed the figure of the Earth, flattening it at the poles and giving it the shape of an orange-like ellipsoïd. Points around the equator, being further away from the center of the Earth that at higher latitudes, should experience a reduced gravity, an effect which had to be added to the direct centrifugal force.

At the same time, Cassini father and son, who were Royal astronomers in Paris, claimed that the Earth was indeed an ellipsoïd but that it was narrowed at the equator, with its great axis pointing towards the poles. It was looking more like a lemon than like an orange! They based their conviction from their measurement of one degree of the Paris meridian that they found slightly smaller in the North of France than in the South. In 1735, the French Academy of Sciences decided to settle the controversy by an actual measurement.

Maupertuis
(1698-1759)

La Condamine
(1701-1774)

A sentence in Maupertuis' report to the Academy

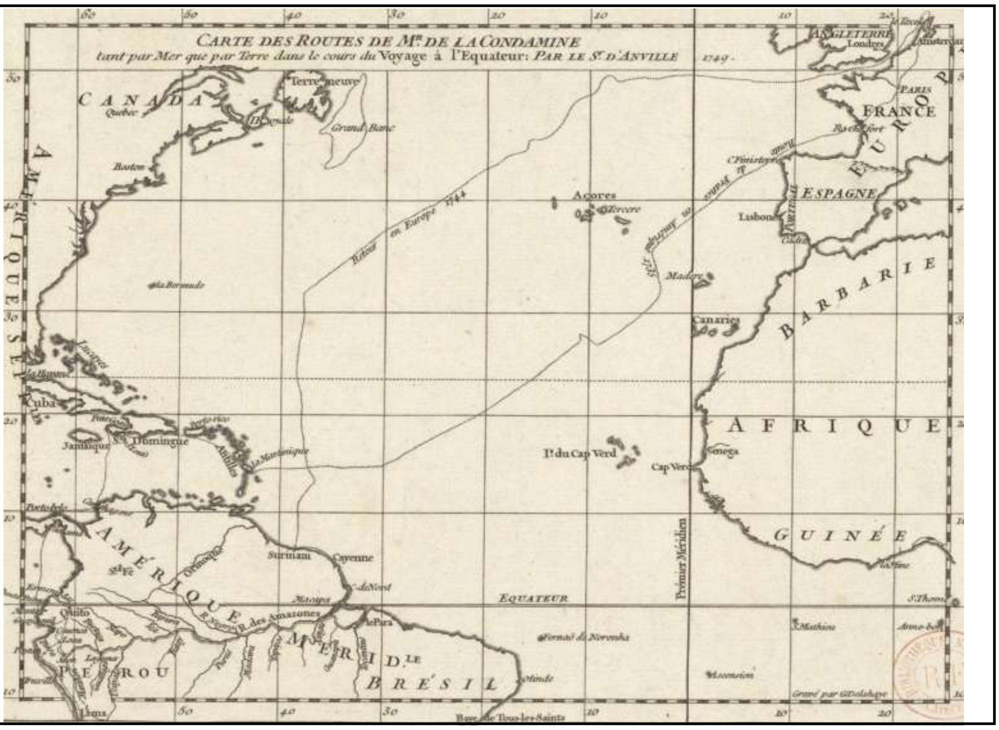


L'Académie ſe voyoit ainſi partagée ; les propres lumiéres l'avoient renduë incertaine, lorſque le Roy voulut faire décider cette grande queſtion, qui n'étoit pas de ces vaines ſpéculations, dont l'oiſiveté ou l'inutile ſubtilité des Philoſophes s'occupe quelquefois, mais qui doit avoir des influences réelles ſur l'Aſtronomie & ſur la Navigation.

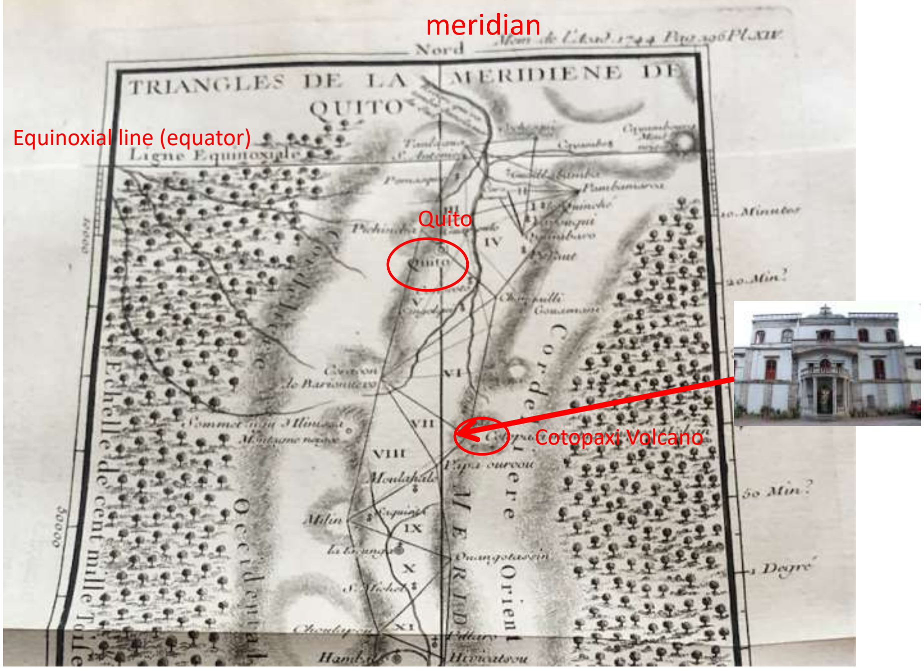
"The Academy was thus split on this issue (*oblateness or prolateness of the Earth*)*. Its own lights on this question have left it unable to decide, when the King expressed His will to resolve this big question which was not one of the vain speculations whose idleness or useless subtlety sometimes keeps Philosophers busy, but a question which must have real influences on Astronomy and Navigation".*

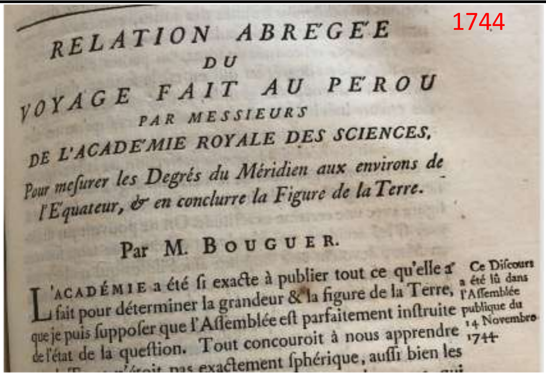
One team was sent to Lapland (Maupertuis, Celsius), the other to Peru (La Condamine, Bouguer) to measure a one degree of latitude difference on a meridian at points as far from each other as possible, thus decreasing errors from measurements performed at points too close in latitude.

The eleven year journey of La Condamine



Triangulations to measure the degree of longitude along Quito’s meridian





1744

RELATION ABREGÉE
DU
VOYAGE FAIT AU PÉROU
PAR MESSIEURS
DE L'ACADÉMIE ROYALE DES SCIENCES,
Pour meſurer les Degrés du Méridien aux environs de l'Équateur, & en conclurre la Figure de la Terre.

Par M. BOUGUER.

L'ACADÉMIE a été ſi exacte à publier tout ce qu'elle a fait pour déterminer la grandeur & la figure de la Terre, que je puis ſuppoſer que l'Aſſemblée eſt parfaitement inſtruite de l'état de la queſtion. Tout concouroit à nous apprendre pas exactement ſphérique, auſſi bien les

Ce Diſcours a été lû dans l'Aſſemblée publique du 14 Novembre 1744.

Short report about the voyage made in Peru by the gentlemen of the Royal Academy of Sciences to measure the degree of the meridian near the Equator and deduce from it the shape of the Earth

1737

DES SCIENCES. 389

LA FIGURE DE LA TERRE
DÉTERMINÉE
PAR MESSIEURS DE L'ACADEMIE ROYALE
DES SCIENCES,
Qui ont meſuré le Degré du Méridien au Cercle Polaire.

Par M. DE MAUPERTUIS.

J'EXPOSAI, il y a dix-huit mois, à la même Aſſemblée, le motif & le projet du Voyage au Cercle Polaire; je vais lui faire part aujourd'hui de l'exécution. Mais il ne ſera peut-être pas inutile de rappeller un peu les idées ſur ce qui a fait entreprendre ce Voyage.

Di a été l'Aſſ publi 13 N 1737

A value close to the ones calculated by Huygens and Newton

”Congratulations for having flattened the Earth and…the Cassinis!”
(Votaire to Maupertuis)

The shape of the Earth determined by the fellows of the Royal Academy of Sciences who have measured the degree of the meridian at the Polar Circle

The Earth is oblate!

$$\frac{R_{equator} - R_{pole}}{R} \approx 0.003$$

Mission of the French Academy of Sciences conducted by La Condamine and Bouguer who measured the degree of longitude at equator to evaluate the oblateness of the Earth.

La Condamine visited the hacienda in 1742 and observed an eruption of the Cotopaxi volcano.

EN ESTE MONUMENTO HISTORICO SE ALOJO CARLES MARIE DE LA CONDAMINE CON EL PROPOSITO DE ESTUDIAR LA ERUPCION DEL COTOPAXI EN EL MES DE JUNIO DE 1742.

EL MARQUES DE MAENZA DUEÑO DE ESTA HACIENDA FUE SU ANFITRION.

UNA AMISTAD FECUNDA NACIO DE ESTE ENCUENTRO QUE TUVO COMO MOTIVO UN IMPORTANTE ACONTECIMIENTO TELURICO

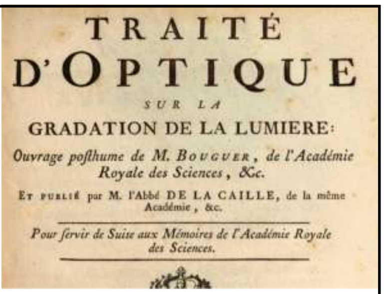
HOMENAJE DEL GOBIERNO FRANCES EN EL 250 AVO ANIVERSARIO DE LA VENIDA DE LA MISION DE LA ACADEMIA DE CIENCIAS DE PARIS AL ECUADOR

HOMMAGE DU GOUVERNEMENT FRANCAIS AU 250 EME ANNIVERSAIRE DE LA VENUE DE LA MISSION DE L'ACADEMIE DE SCIENCES DE PARIS EN EQUATEUR

Pierre Bouguer
(1698-1758)

The birth of photometry

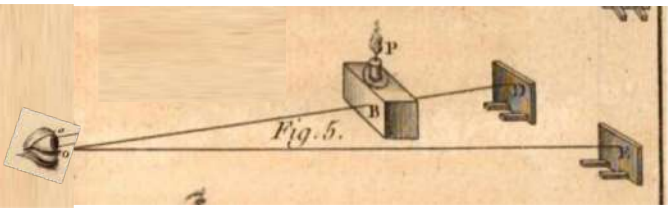
How to define and measure the luminous intensity of a light source or a light-diffusing body? Pierre Bouguer, who had measured the meridian in Ecuador and investigated the variation of gravity with altitude in the Andes mountains has also been a pioneer of photometry. His work - exposed in his posthumously published «Traité d'Optique» – has been influential.



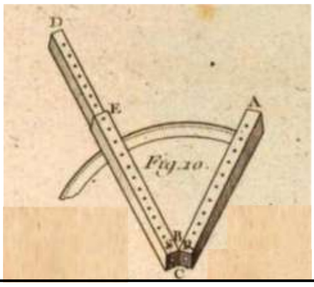
TRAITÉ
D'OPTIQUE
SUR LA
GRADATION DE LA LUMIERE:
Ouvrage poſthume de M. Bouguer, de l'Académie Royale des Sciences, &c.
Et publié par M. l'Abbé DE LA CAILLE, de la même Académie, &c.

Pour ſervir de Suite aux Mémoires de l'Académie Royale des Sciences.

Apparatus used by Bouguer to compare the luminous intensity of two screens illuminated by a candle, one seen directly the other through a thick transparent body.

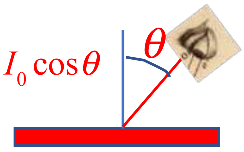


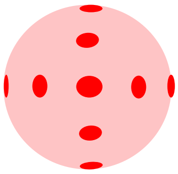
Bouguer's apparatus measuring the angular dependence of the light intensity radiated toward the eye by an extended source



The Bouguer-Lambert cosine law

$$I(\theta) = I_0 \cos\theta$$





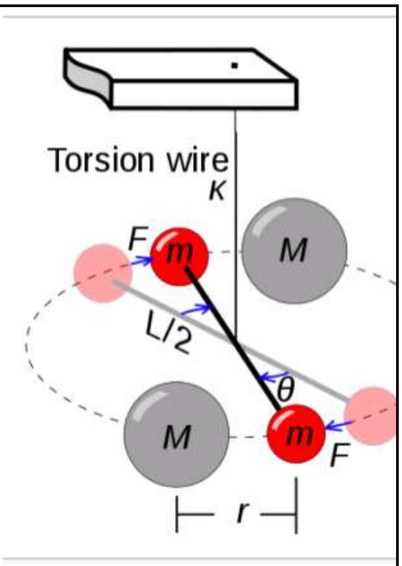
The light intensity emitted by an element of a diffusive surface in a small solid angle along a given direction varies as the cosine of the angle of this direction with the normal to the surface. Bouguer corrected wrong statements by previous scientists which did not take the cosine variation into account. He remarked that spherical sources like the sun would, without this cosine term, appear as much brighter at their edge than at their center, which is not the case.

A circular area at the center of the solar disk (latitude and longitude 0°) appears as an ellipse at points on the sphere of latitude or longitude θ different from 0, its apparent area decreasing as cosθ. Since the intensity radiated by a surface element is also proportional to cosθ (Bouguer-Lambert law) the luminance of the sun (intensity received by the eye per unit apparent area) is independent of θ: the sun appears as a disk of uniform luminosity.

Other Bouguer's discoveries: he confirmed the $1/r^2$ variation of the intensity of the light emitted by a point source (already stated by Kepler), he found that transparent media attenuate transmission at a rate proprtional to their thickness (Beer-Lambert law), resulting in a transmission decreasing exponentially with the thickness of the transmissing medium.

Henry Cavendish
(1731-1810)

The eighteen's century ends with another important measurement of the Earth: its mass indirectly estimated by Cavendish who determined the gravitational constant G by measuring the force exerted by two large masses M on two test masses m attached to a torsion balance.



$$F = G\frac{mM}{r^2} \rightarrow G = Fr^2 / mM = 6.67\times10^{-11}\, Nm^2kg^{-2}$$

$$g = GM_E / R_E^2 \rightarrow M_E = g\frac{R_E^2}{G} \approx 6\times10^{24}\, kg$$

The experiment also yields the mass of the Sun:

$$M_S \approx 2\times10^{30}\, kg$$

The history of light in the 17th and 18th century reveals permanent features of scientific research

Link between basic science and technology: the first quantitative discoveries about light required the invention of novel measuring devices (clocks and telescopes).

The importance of quantitative precise measurements: the estimation of velocity of light as well as the discovery of the oblateness of the Earth were made possible only when the instruments became able to keep the time with a precision of a few seconds per day and to measure angles with precision of the order of one arcsecond.

The invention of simple models to explain disparate and complex phenomena: Fermat's principle of least time is a good example

The role of chance and serendipity: Galileo failed to measure the velocity of light, but contributed to the invention of instruments which made this measurement possible 60 years later. Richer went to Cayenne to measure the parallax of Mars and discovered the variation of gravity with latitude.....

These features will again be illustrated by the the revolutionary advances of the science of light in the 19th century.

Grazie

End of Lecture 1