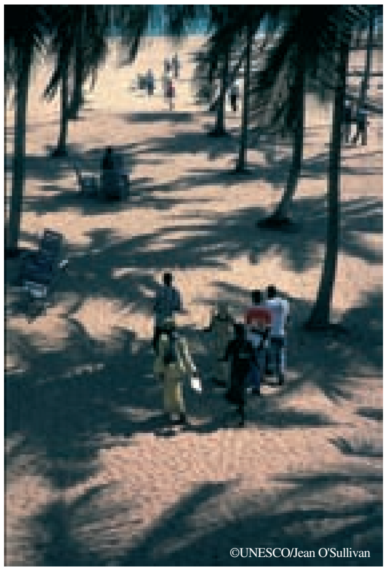
# The miracle of light



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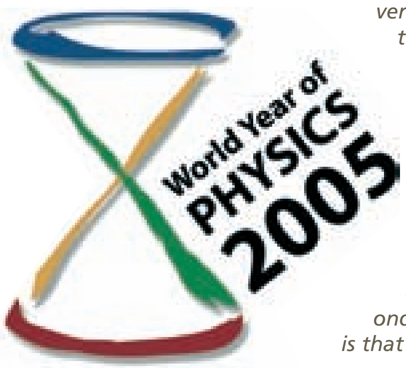
**There may be more to celebrate in the International Year of Physics than meets the eye. Indeed, the Year marks not only the centenary of Einstein's miraculous year but also the millennium of the founding of modern optics by physicist Ibn Haitham (Iraq, 965–1040). Among a number of major contributions, Ibn Haitham put experimental science on the map by decisively settling the heated debate over the basics of vision, through a remarkable series of experiments. Having pioneered the pinhole camera, he successfully explained sight in terms of light travelling into the eye rather than the other way round. This finally discredited the now absurd emission theory of Plato and Ptolemy[1], effectively rewriting centuries of scientific thought.... Here, we voyage through one thousand years of the physics of light, with a special focus on optics.**

The organizers of the International Year of Physics 2005 (originally labelled the World Year of Physics) could hardly have chosen a more elegant logo than a colourful sketch of a light-cone diagram, reminiscent of Einstein's seminal work of 1905. Light-cones, as the famous Oxford physicist Roger Penrose put it, 'represent the most important structures in space-time.' What a light-cone shows is simply how a pulse of light spreads out in space as time passes, just like ripples spread out on the surface of a pond.




*The Year of Physics logo: a colourful sketch of a light-cone diagram. The upper-cone is called the future light-cone, showing how a pulse of light spreads out in space (represented horizontally) as time passes (represented vertically). The lower-cone is called the past light-cone and is simply an extension of the future light-cone into the past. There are two basic properties of light underpinning a light-cone diagram. The first is that light travels in straight lines, which was experimentally proven by Ibn Haitham using the pinhole camera 1000 years ago. The second, also proposed by Ibn Haitham, is that light has a finite speed*

The reason why light lends itself to such elegant geometry in the first place is because of two basic properties. The first is that light travels in straight lines (ignoring the curvature of space-time), the second that light has a finite speed. These two properties lead us to the 11th century Arab physicist Alhasan Ibn Haitham, more commonly known to the West by his Latinized first name Alhazen, the founding father of modern optics.

### Ibn Haitham's light beam

In order to settle the long-standing debate over how vision worked, Ibn Haitham pioneered an experimental set-up of surprising simplicity: the pinhole camera, or *camera obscura*[2], the principle behind all photography from the earliest cameras to modern-day digital ones. His pinhole camera consisted simply of a tiny hole that led to a dark room. He placed several lamps outside the room and observed that an identical number of light spots appeared inside the room on the opposite wall. Upon placing an obstacle between one of the lamps and the hole, he observed that one of the light spots disappeared and, when he removed the obstacle, that the light spot reappeared. Crucially, he observed that each lamp and its corresponding light spot were always aligned perfectly in a straight line passing through the hole.

Thus, using the pinhole camera, Ibn Haitham proved that light travels in straight lines. Further, by observing that light from different lamps did not get mixed up in going through the hole, he drew a parallel, concluding that vision occurred by means of light travelling into the eye and forming an ordered point-for-point image of the visual scene. The pinhole camera was in fact the climax of a series of observations and experiments, which meant that the eye could be studied as an optical instrument. Indeed, Ibn Haitham studied the anatomy and physiology of the eye in great detail, giving many eye parts their present-day names, for instance: the cornea, the lens and the retina.

By defining a beam of light, he was able to describe the propagation of light in a way which perfectly fitted the laws of geometry, highlighting a unique relationship between physics and mathematics. But for him, unlike his predecessors, theory had to be supported by experiment. Therefore,

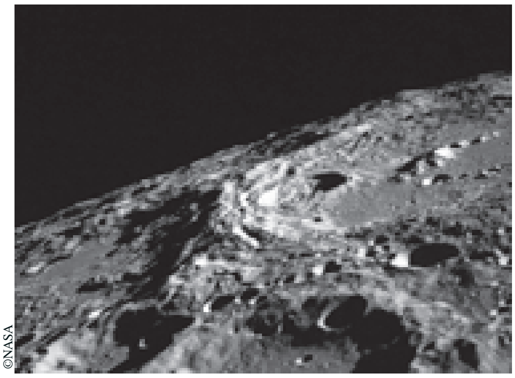
1. *The philosopher Plato (Greece, 427–347 BC) and astronomer Ptolemy (Egypt, 90–168) were both legends in their time. From measuring the position of stars, Ptolemy realized that light is refracted by the atmosphere*
2. Camera *is the Latin word for 'room' and* obscura *means 'dark'*

in order to prove his theories, he invented devices of varied complexity which were designed not merely to test qualitative assertions but also to obtain quantitative results. Regarding the phenomenon of diffuse reflection, essential for understanding vision, he showed by experiment that reflected light from each point on the surface of an illuminated object radiates in all directions in straight lines. In particular, reflected light from a visible object forms a cone of rays with its base at the object and its tip at the eye. This is the principle behind linear perspective, the foundation of Renaissance art. Artists like the Italian Leonardo da Vinci (1452–1519) used linear perspective masterfully to achieve a realistic three-dimensional sense in their paintings. Yet Ibn Haitham's influence on the development of science in Europe was still more profound. Following the revival of logic by Spanish polymath Ibn Rushd (1126–1198), the transmission into Europe of Ibn Haitham's theory of light and vision played a singular role in illuminating the European Dark Ages.

#### Science through the pinhole camera

Before we turn to the second property of light underpinning a light-cone diagram, let's take a closer look at the impact of the pinhole camera, an invention which has powered centuries of scientific thought. The pinhole camera became a standard method for generations of physicists after Ibn Haitham. Isaac Newton, for example, used it to conduct his famous prism experiment in which he analysed white light into basic colours, 'The Sun shining into a dark chamber through a little round hole in the window-shut and his light being there refracted by a prism to cast his coloured image upon the opposite wall...,' Newton explained in *Opticks* (1704). Referring to his discoveries in optics, Newton wrote in a letter to his arch-rival Robert Hooke, 'If I have seen further, it is by standing on the shoulders of giants.'

Two and a half centuries later, photographs of stars taken from the island of Principe, off the west coast of Africa, provided the proof needed to convince the international scientific community once and for all of the soundness of Einstein's general theory of relativity. Einstein had predicted that light passing near a massive object like the Sun would be deflected by an amount given by his new theory of gravity. The 1919 solar eclipse provided an opportunity for a British expedition led by Arthur Edington to test Einstein's prediction. Edington compared photographs of stars from the Hyades star cluster, seen in the vicinity of the eclipsed Sun, with photographs of the same stars when the Sun was off the visual field. The photographs confirmed the predicted shift in the stars' apparent position, turning Einstein into a celebrity.



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*The Moon's surface. Ibn Haitham showed geometrically that moonlight can only be adequately explained using the phenomenon of diffuse reflection – that is, reflection from a rough surface*

#### Speed of light infinite or finite?

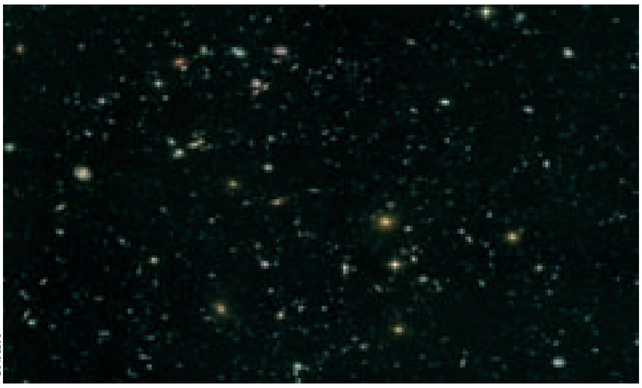
Two of the most fundamental phenomena in optics are reflection and refraction, both of which Ibn Haitham investigated through countless experiments. In explaining refraction (the bending of light as it enters or leaves a denser

## How to make a pinhole camera

Simple to make (see below), the pinhole camera helps us understand how light travels. To use the camera, simply point it towards the object you wish to observe and look at the image projected onto the screen of your camera. It is best to observe either a very contrasted or bright light, such as the filament of a lightbulb in a dark room. To avoid being temporarily blinded by the glare, simply follow the example of the first photographers and place a piece of thick, dark cloth over your head. You will see that the image projected onto the screen is upside down, which will tell you that light travels in a straight line.

To make the camera, you need a sheet of thin cardboard measuring 22 cm x 28 cm (for the rectangular body of the camera) and two sheets of waxed paper or a sheet of tracing paper measuring 5 cm x 5 cm for the screen (Step 1). With the help of a sewing needle, pierce a hole 1 mm in diameter in the centre at one end of the camera (Step 2). Once you have glued the sheets of waxed or tracing paper onto the frame of the screen, glue the screen onto the open end of the camera (Step 3).


*With the kind permission of Claire Deschênes and Judith Sévigny, CRSNG/Alcan Chair for Women in Science and Engineering (Canada): Opus programme (Useful teaching tools for science/Outils pédagogiques utiles en sciences)*



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*This view of nearly 10,000 galaxies by the Hubble Space Telescope is the deepest image of the visible universe ever achieved. Hubble's Advanced Camera for Surveys captured galaxies billions of light-years away, going back to 'within a stone's throw of the Big Bang.' This achievement comes almost 1000 years after Ibn Haitham pioneered the pinhole camera, the principle behind photography*

medium), he went against the accepted wisdom by arguing that light has a finite speed, which is the second property of light underpinning the light-cone diagram of the Year of Physics' logo. In a flash of insight, he realized that refraction was caused by the slowing down of light as it enters a denser medium. He characteristically based his proposition on an experimental model.

Quantum Electro-Dynamics (QED), the climax of the quantum revolution which Einstein kick-started in 1905, tells us that light always takes the path of least time in travelling between two points. Within the same medium, this path is simply a straight line. But because the speed of light is slower in a denser medium, the path of least time for light crossing between two mediums is no longer a straight line, causing light to bend. The theory of QED developed by Paul Dirac, Richard Feynman and others fantastically explains a wealth of optical phenomena.

Why does it not suddenly get dark when the Sun sets? The phenomenon of the twilight is so common that one hardly stops to ponder. In his book, the *Balance of Wisdom*, Ibn Haitham calculated on the basis of the duration of the twilight that the Sun is actually 19 degrees below the horizon when the twilight ends, due to the reflection of sunlight by the Earth's atmosphere. In a spectacular feat, he ingeniously used the onset of the twilight to calculate geometrically the approximate height of the atmosphere from the Earth's radius, opening a new chapter in the quest to unravel the mysteries of the universe.

## Optics masterpiece

An in-depth analysis of reflection and refraction appears in the second half of Ibn Haitham's masterpiece *Kitab Al-Manazir*, or *Book of Optics*, translated into Latin as *Opticae Thesaurus* – a revolutionary work firmly based on geometry and experiment, reforming the established optical tradition of Ptolemy. Here, Ibn Haitham decisively distinguished the study of optics (both physical and geometric) from that of visual perception, experimentally establishing optics and more generally physics as an independent science. It was in optics, rather than mechanics, that the concept of experimentation as systematic and ordered proof was first born. Ibn Haitham's *Book of Optics* must rank alongside Newton's *Principia Mathematica* as one of the most influential books ever written in physics.

'He was the greatest Muslim physicist and student of optics of all times. Whether it be in England or faraway Persia, all drank from the same fountain. He exerted a great influence on European thought from Bacon to Kepler,' wrote George Sarton in his *History of Science* (1927). There is a unique copy of *Opticae Thesaurus* in the archives of the Institute of Electrical Engineers in London, which once belonged to the celebrated French physicist André Ampère (1775–1836).

## Designing the perfect lens

According to legend, Archimedes (Greece, 287–212 BC) set invading Roman ships afire by focusing sunrays onto them using huge mirrors. Whether or not the story is true, the quest to construct a perfectly focusing mirror has inspired much research in optics since antiquity. Ibn Haitham's predecessor, 10$^{th}$ century Baghdadi mathematician Ibn Sahl, redefined the goal of this research more generally as constructing a perfectly focusing optical device. He pioneered the study of the lens, formulating the first geometric theory for lenses. Unfortunately, Ibn Sahl's work was lost for centuries.

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*The lower atmosphere illuminated orange during the twilight. Why does it not suddenly get dark when the Sun sets? Reflection of sunlight by the Earth's atmosphere means that the Sun is well below the horizon when the twilight ends. Ibn Haitham ingeniously used the onset of the twilight to geometrically calculate the approximate height of the atmosphere, using the Earth's radius. Natural phenomena like the twilight interested Muslim scientists for yet another reason. The movement of the Sun across the sky defines prayer times, whereas the birth of the new Moon marks the beginning of each month and determines annual celebrations*

## Optics: an optimal focus for active learning

UNESCO runs an Active Learning in Optics and Photonics* programme for physics teachers from developing countries. The aim is to equip university and high school teachers better to teach the optics part of the introductory physics course by using active learning and hands-on techniques and by drawing on examples from local research.

Why the focus on optics? Because optics is an area of experimental physics that is both relevant and adaptable to research and educational conditions in many developing countries. Optics has been termed an 'enabling science' because it forms the basis of many modern advances in high technology, such as the laser, optical fibres, photodetectors and sensors. Improving education in optics and photonics education will result in a skilled and well-educated workforce for emerging industries in Africa and elsewhere.

Courses have been run by UNESCO so far at the University of Cape Coast in Ghana, in September 2003 and November 2004, and at the University of Monastir in Tunisia, in April 2005. Each course attracts about 30 participants. The next course is planned for Tanzania in 2006.

The courses are run by a working group co-ordinated by UNESCO which includes UNESCO's Abdus Salam International Centre for Theoretical Physics, the International Society of Optical Engineering (SPIE), Swinburne University of Technology (Australia), the Ateneo de Manila University (Philippines), University of Oregon (Eugene, USA), University of Missouri-St. Louis (USA) and the University of Tunis (Tunisia).

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* *Also known as fibre optics and opto-electronics, photonics is the technology used to transmit, control and detect light (photons)*

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*Here, young Tunisian university instructors at UNESCO's April workshop are modelling and observing how the eye works, as well as the refractive anomalies of the eye and their correction. They are using different types of lenses supported on an optical bench*

However, recently discovered manuscripts of his work, analysed by French historian of science Roshdi Rashed, leave no doubt that Ibn Sahl was the first to discover the elusive sine law of refraction. This makes the law of refraction, together with the law of reflection – first given in full by Ibn Haitham – probably the oldest dynamic laws formulated for nature. Armed with this discovery, Ibn Sahl achieved a centuries-old goal by deriving the geometric shape of a perfectly focusing lens, otherwise known as an 'anaclastic'. What's more, he designed elaborate mechanisms for drawing his lenses and mirrors.

Yet, the basic understanding of lenses took on a whole new dimension after Ibn Haitham launched the study of their visual and magnifying properties with his *Book of Optics*. It was undoubtedly this new understanding of the lens, based on geometry and experiment, which underpinned the craft of the Dutch spectacle-makers (makers of eye-glasses) who, by holding one lens in front of another, invented the first microscope and telescope, two instruments crucial to the subsequent development of science.

### Light's dual nature: simply miraculous

Three centuries after Ibn Haitham, the Persian physicist K. Al-Farisi (1267–1319) wrote an important commentary on the *Book of Optics*, in which he set out to explain many natural phenomena. For example, by modelling a water drop using Ibn Haitham's study of double refraction in a sphere, he gave the first correct explanation of the rainbow. Al-Farisi also proposed the wave-nature of light. By contrast, Ibn Haitham had modelled light using solid balls in his experiments on reflection and refraction. Now the question presented itself: is light wave-like or particle-like?

Despite the wave theory of light becoming very dominant by the start of the 20th century, it could not account for certain experimental observations, most notably the phenomenon of the photo-electric effect, the subject of Einstein's first paper of his Miraculous Year. Einstein reintroduced the idea of light particles, now called photons, successfully explaining the photo-electric effect and thus initiating the quantum revolution. We now have to think of light as being wave-like and particle-like at the same time: light's paradoxical wave–particle duality.

In fact, duality was a key concept in Einstein's thinking at the beginning of the last century. In what is considered to be his most important work of 1905, the special theory of relativity, he showed that mass and energy are two aspects of the same thing. Indeed, stars including the Sun shine by converting mass into energy in gigantic nuclear-fusion explosions. Einstein expressed the mass-energy duality elegantly in the famous equation $E = mc^2$, where E is energy, m is mass, and c is the speed of light – a universal physical constant.

### Alhazen's Billiard Problem

The recent proof of Fermat's Last Theorem[3], hailed as one of the biggest mathematical triumphs of the 20th century, left perhaps the last of the great problems in classical geometry half-solved: Alhazen's Problem. This mathematical puzzle named after Ibn Haitham has a colourful history dating back to the time of the Greek geometricians. In his *Book of Optics*, Ibn Haitham tackled the problem in terms of optical reflection in spherical, cylindrical and conical mirrors.

It is also known as Alhazen's Billiard Problem, since it can be formulated as 'finding the point on the boundary of a circular billiards table at which the cue ball must be aimed, if it is to hit the black ball after one bounce off the cushion.' Ibn Haitham was the first to find a solution for this geometric riddle, solving it using conic sections. Indeed, mathematics was his passion, with half of all his surviving works on pure mathematics. But Ibn Haitham's mathematical genius is a story for another occasion.


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*Solar explosions. Stars including the Sun, seen here, shine by converting mass into energy in gigantic nuclear-fusion explosions. The mass–energy duality was famously expressed by Einstein as $E=mc^2$, where E is energy, m is mass, and c is the speed of light*

The brilliant mathematician Al-Khwarizmi (Iraq, 780–850) is said to have invented algebra while writing a book on how to divide inheritance based on the Quran. Al-Khwarizmi's mission as a mathematician was simple: he set out to make mathematics more systematic. Indeed, the very word 'algorithm' is derived from his name. Successive generations applied algebra to the existing branches of mathematics, giving rise to new mathematical branches. This is why algebra is considered by many as the foundation of modern mathematics.

While it became possible to express geometric problems in terms of algebra, Alhazen's Problem defied an algebraic solution for many centuries. Finally, an Oxford professor of mathematics solved it algebraically one thousand years after Ibn Haitham penned his geometric solution, drawing the curtain over a rich chapter of mathematics in time for the new millennium.

### Science's oldest puzzle

Have you ever wondered why the Moon looks much bigger when it is near the horizon? This intriguing phenomenon, known as the 'Moon illusion', is arguably the oldest unsolved scientific puzzle today. A similar effect is observed for the setting and rising Sun. The ancients wrongly attributed the illusion to the magnifying properties of the atmosphere. But is this a physical phenomenon anyway?

Surprisingly, the answer is no. The Moon illusion was correctly redefined by Ibn Haitham as being to do with visual psychology rather than physics. As has been mentioned, this clarity of thinking was key to establishing physics as an independent science. On a slightly different note, there is a famous quote in which Einstein expressed his discontent with the haziness of quantum mechanics by asking a friend: do you really believe that the Moon exists only when you

3. *Pierre de Fermat (France, 1601–1665) would intrigue mathematicians for centuries by scribbling in the margin of his copy of Diophantus's* Arithmetica '*I have discovered a truly remarkable proof which this margin is too small to contain*'. *Fermat claimed to have discovered a proof that the Diophantine equation $x^n + y^n = z^n$ had no non-zero integer solutions for x, y and z when $n > 2$. This came to be known as a 'theorem' on the strength of Fermat's scribbled note, even though no other mathematician was able to prove it for centuries*


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*Two beautifully shaped spiral galaxies in near collision. Since it is gravity which determines the large-scale structure of the universe, many physicists today seem to give special prominence to the laws governing gravity* look at it? The Moon illusion gives Einstein's rhetorical question a touch of irony.

One can easily test the Moon illusion by taking pictures of the Moon near the horizon and comparing them with pictures of the Moon near the zenith. Most people are astonished to find that the size of the Moon in the photographs remains almost exactly the same!

A mind-bending explanation for the Moon illusion was given by Ibn Haitham in his *Book of Optics*. First, he proposed what is now called the Size–Distance Invariance Hypothesis (SDIH), basically explaining why an object would appear to be larger if it is perceived to be further away, an effect purely to do with visual processing in the brain. Indeed, most present-day explanations of the Moon illusion are based on some version of Ibn Haitham's SDIH. Second, he explained why the dome of the sky appears flattened; in other words, why the stars near the horizon seem to be further away than the stars directly above. Paradoxically however, most people say that the large horizon Moon actually seems closer; that's why little children are sometimes seen to jump in an attempt to catch it! It is precisely this paradox which many present-day researchers are trying to resolve.

## The search for quantum gravity

One of the intended goals of the International Year of Physics is perhaps to inspire another paradigm shift, which might well be needed in order to solve the central problem in physics today: finding a theory for quantum gravity. That theory needs to unify quantum mechanics with general relativity (the theory of the very small and the theory of the very large). If we reflect on the last 1000 years of science, comparing Einstein's paradigm shift at the beginning of the 20th century, which established modern physics, with Ibn Haitham's paradigm shift at the beginning of the last millennium, which established physics on experimental grounds, one thing strikes us: the central theme for both was light, not gravity.

Interestingly, many physicists today seem to give special prominence to the laws which govern gravity, since, as famous Cambridge physicist Stephen Hawking explains, 'it is gravity which determines the large-scale structure of the universe.' We can still ask however: does the curious similarity between the paradigm shifts in physics of 100 years ago and 1000 years ago give away any clues about the nature of the paradigm shift which might solve today's central puzzle of quantum gravity?

## Over the Moon!

Today, in celebration of Ibn Haitham, who correctly explained the nature of the Moon's surface, a lunar crater has been named after him. Alhazen crater lies near the eastern rim of the Moon's near side (Latitude: 15.9° N, Longitude: 71.8° E). Another lunar crater celebrates Einstein: Einstein crater lies along the western limb of the Moon (Latitude: 16.3° N, Longitude: 88.7° W). It is a fitting coincidence that, on the Moon, Alhazen crater lies in the east whereas Einstein crater lies in the west, beautifully reflecting their birth places back on Earth – Basra in Iraq and Ulm in Germany.

*Seen from the Moon, the Earth shining 'moonlike'. It is a fitting coincidence that, on the Moon, Alhazen crater lies in the east, whereas Einstein crater lies in the west*

Einstein once said, 'It has always pained me that Galileo did not acknowledge the work of Kepler.' But has the work of Ibn Haitham, which established experiments as the norm of proof in physics, been properly acknowledged? Let's make the centenary of the miraculous year a celebration of one thousand years of physics – from Ibn Haitham to Einstein – and a celebration of light, the universal metaphor for knowledge.

H. Salih, M. Al-Amri and M. El Gomati[4]

*The historical content of this article is based primarily on original writings of Ibn Haitham, as well as on the analysis of Roshdi Rashed, recipient of UNESCO's Avicenna Gold Medal.*

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4. *H. Salih is affiliated to York Probe Sources Ltd at the University of York (UK), M. Al-Amri to the Department of Physics, King Khalid University in Abha (Saudi Arabia) and M. El Gomati to the Department of Electronics at the University of York. All three authors are affiliated to the Foundation for Science Technology and Civilisation (UK). The authors are grateful to those who made valuable suggestions during the preparation of this manuscript, especially David Wilkinson of Central Science Laboratories in York*