# Fresnel's echelon lens

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Alongside the *Rapport contenant l'exposition du système adopté par la Commission des Phares, pour éclairer les côtes de France* [Report containing the exposition of the system adopted by the Lighthouse Commission to illuminate the coasts of France], published in 1825 by Augustin Fresnel and the hydrographer Paul-Edouard de Rossel, le *Mémoire sur un nouveau système d'éclairage des phares*[1] [On a new system of lighthouse illumination] is the founding text for understanding the history of maritime signalling. After recalling the context in which Fresnel wrote this report, we will then analyse this innovatory process, of which the famous lens was only one part.

## LIGHTHOUSES IN FRANCE IN THE EARLY 19TH CENTURY

At the time when the *Mémoire* was published, twenty or so lighthouses illuminated the coasts of France, including the prestigious Tour de Cordouan.[2] In around 1820, construction projects were instigated by Ponts et Chaussées engineers at the mouth of the Loire (Four du Croisic) and off the coast of Marseille. In 1819, the director-general of Ponts et Chaussées & Mines, Louis Becquey (1760–1849), whom Fresnel thanks at the end of his text, resurrected the Lighthouse Commission, which had been created under the Empire (April 1811). Made up of scholars, sailors and engineers, the Commission was tasked with examining the proposal of illuminating lighthouses with blue and red lights, which had been put forward by a naval officer during the Empire. More generally, it was to consider a "system" for the coasts of France in their entirety. The backdrop of war had considerably restricted its work.

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1. This is the text analysed here.
2. The Cordouan lighthouse is situated 4.5 miles out to sea on a rocky plateau in the mouth of the Gironde estuary.

Work resumed in 1818, when François Arago (1786–1853), a lecturer at the École polytechnique and a member of the Academy of Sciences and the Bureau des Longitudes, was appointed to the Commission. For assistance, he called upon a young Ponts et Chaussées engineer, Augustin Fresnel (1788–1827), who was in the process of straightening the roads of the department of Île-et-Vilaine and making various – unsuccessful – attempts to return to the capital.

> *In 1819 M. Arago offered to take charge of these experiments, provided M. Mathieu and myself were allowed to assist him. This proposition, adopted by the Commission, was submitted to M. Becquey, Director General des Ponts et Chaussées, who also approved it, and desired me to devote the greatest care to these investigations.*[3]

Over the previous few years, Fresnel had been conducting research that would enable him to present his *Mémoire sur la diffraction de la lumière* in July 1818[4]. The maritime signalling policy was a godsend for Fresnel, who found himself temporarily seconded to assist in the Lighthouse Commission's experiments on light. This was a post that provided him entry into the social circles of Parisian savants.

## MARITIME SIGNALLING AND TECHNICAL INNOVATIONS

Thanks to the admiral Antoine Thévenard, we have an inventory of the lighthouses that were in service across the world at the dawn of the 19th century: there were 130 in total, half of which were located in the British Isles. The construction of the Eddystone by John Smeaton (1759) ushered in a new era for lighthouses. Trinity House in England, the world's oldest institution charged with overseeing lighthouses (1514), the Northern Lighthouse Board (1786) in Scotland and the Commissioners of Irish Lights (1786) erected various towers illuminated by copper reflectors. These lights were fitted with parabolic or spherical reflectors, generally immobile, and lit by oil lamps.

3. English translation taken from the online translation of Fresnel's memoir [On a new system of lighthouse illumination], available online, p. 1.
4. See analysis of this memoir by Jean-Louis Basdevant, *BibNum*, May 2009.

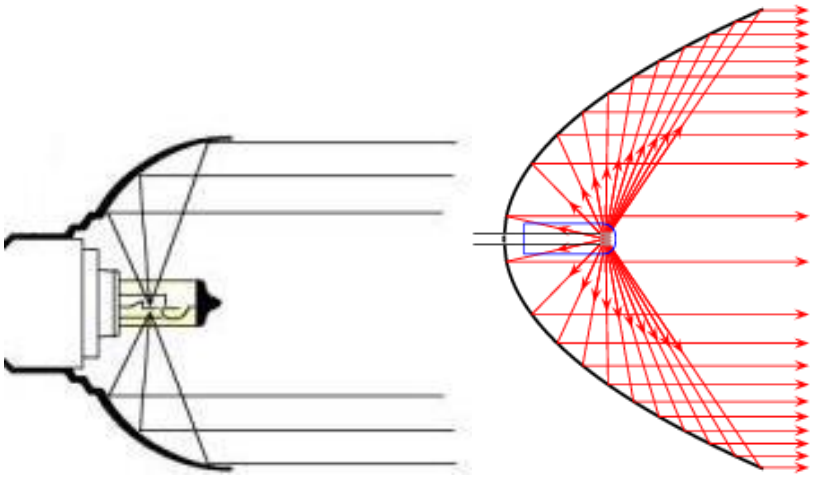

***Figure 1*: Parabolic mirror (or reflector)**
*On the left, a parabolic mirror (like those now used in some car headlights, cinema projectors, etc.); on the right, the diagram of the light rays emanating from a parabolic mirror. We can see it is a mirror or reflector because its inner surface reflects the light rays emanating from the source.*

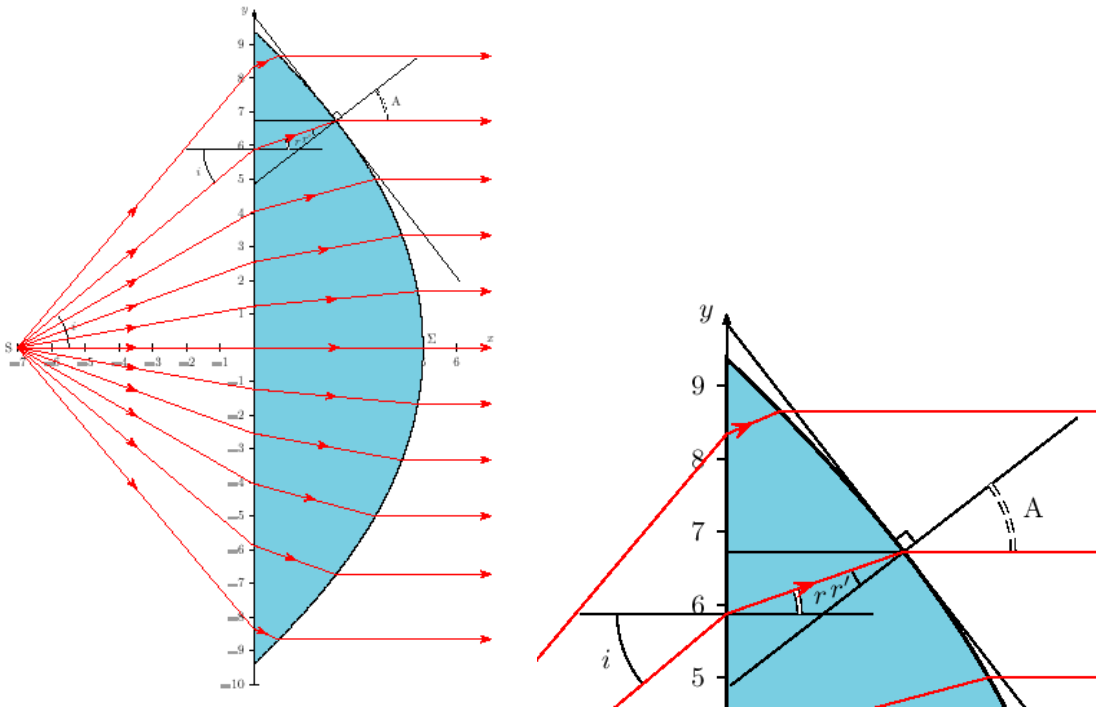


***Figure 1b*: Full plano-convex lens**
*On the left, a view of the whole; on the right, detail showing the two refractions occurring upon entry and exit of the lens. Fresnel explained the difference, from an optical point of view, between the two forms of lighting – the mirror (Figure 1) and the lens (Figure 1b): "We know that, like a parabolic mirror, a lens has the property of parallelizing the rays of light that issue from its focus and pass through it; it produces, by refraction, the same effect that a parabolic mirror does by reflection." (p. 2)*

France was not unaware of this wave of innovation from the other side of the Channel. In the 1770s, an urban lighting entrepreneur, Tourtille-Sangrain, won the signalling contract. He installed immobile spherical reflectors and oil lamps in the kingdom's civil and military towers. Scholars, artisans and engineers were all interested in the science of lighthouses. In 1782, the engineer Teulère and Jean-Charles, chevalier de Borda, a scholar and seaman, appealed to the optician Lenoir to design a silver-coated parabolic reflector. Trials of this device, which were held at Versailles in 1790, received the encouragements of the King and the applause of the court. Twelve 30-inch (812-mm) parabolic mirrors affixed to a mobile armature were installed at Cordouan in 1791. It was no accident that Fresnel chose to conduct his own experiments here: this was the place to grapple with the best techniques of the day.

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The Cordouan reflector was illuminated by a dual-air-current Argand lamp, named after the Swiss inventor who had developed it. In around 1820, his son-in-law Isaac Bordier-Marcet offered his expertise as a patented lamp engineer with experience in providing lighting for towns and lighthouses; like Lenoir, he sold equipment to lighthouses that were already in operation (La Hève, for example) or had been recently constructed, like Le Four, off the coast of Croisic, which was equipped with a "dual-angle catoptrics lantern", formed by two slotted-together conoids. Bordier-Marcet was responsible for installing the lanterns in the lighthouses at Fréhel, Barfleur, the Stiff lighthouse on the island of Ouessant and the Baleines lighthouse, while Lenoir won the contracts for Calais, Ailly and Saint-Mathieu.

## THE LENS: INVENTION OR INNOVATION?

Tried-and-tested techniques already existed when Arago and Fresnel set themselves this bold challenge: to radically change the technology used to light up the coasts. Into this maritime world, the two scientists would import objects and techniques from the field of scientific instrumentation. Fresnel never claimed to have invented the echelon lens, which was already used in chemistry to concentrate the sun's rays, using a device known as a "burning glass". He simply reversed the function, since the aim here was no longer to concentrate sunrays,

but to diffuse those emitted by a light source – the lighthouse's oil lamp. Step by step, Fresnel's paper reconstructs the stages in an innovatory process in which a "simple" idea – but one that was formidably complex to implement – would take shape in French lighthouses. The hagiography of the scientist holds him up as the initiator of every development in maritime signalling techniques in the early 19th century: "Augustin Fresnel was the inventor of lenticular lighthouses, just as Gutenberg was the inventor of the printing press, Galileo, the telescope, and Watt, the steam engine", wrote Léonor Fresnel in the introduction to the *Œuvres Complètes*, a veritable paean to his brother. A reading of the *Mémoire* shows that the man in question was rather more modest:

> *These ideas – of the lens in steps and of forming it of separate pieces – were not the fruit of long study; they are so simple that they readily occur to the mind. What occupied me most was the means of executing them, in this I have been ably seconded by the zeal and intelligence of M. Soleil, the optician, who bravely undertook the construction of these large lenses.* (p. 6)

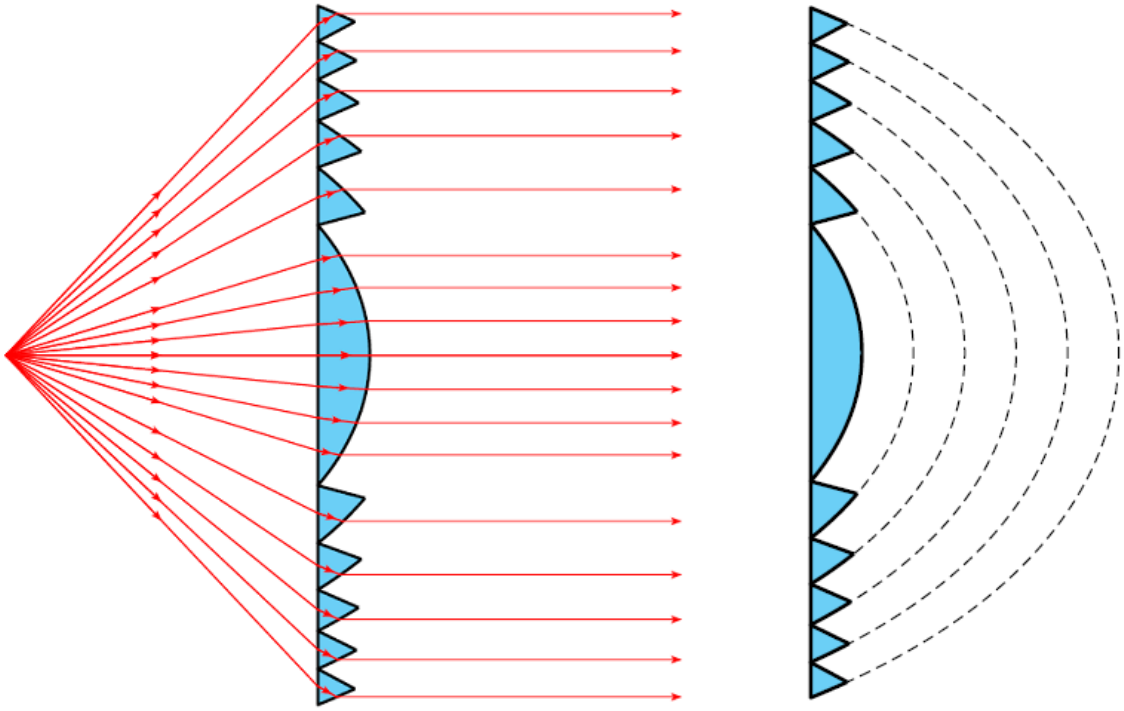

***Figure 2*: Diagram of Fresnel's echelon lens**

*As Fresnel notes: "But if the exterior surface of the lens* [the full plano-convex lens, Figure 1b, left] *be divided into concentric rings* [Figure 2 above, right]*, and if, from the small lens in the centre and the rings which surround it, all the useless portion of their thickness be removed* [giving the above left-hand figure]*, leaving only enough to permit of their being solidly united at their thinnest edges, the parallelism of the rays emerging, from the focus can also be obtained (p. 3)." For each ray, the two angles of refraction visible on the right of Figure 1 are conserved on the left of Figure 2, because the two*

*optical surfaces of refraction are also conserved:*[5] *the plane side on entering the lens, the curved side on exiting it. Only the length of the optical path inside the lens is reduced (hence Fresnel's remark on the "useless portion of their thickness").*

The use of glass, the brittleness of which Fresnel knew would be criticised (p. 17), was not a given. There was a significant shift in scale between the lenticular devices and the scientific instruments manufactured by the optician Soleil. The latter had accepted the order for Cordouan,[6] and indeed this was the first step towards the creation of a maritime signalling market, without which no innovation could have developed. In his *Mémoire*, Fresnel recounts the problems that Soleil encountered – gluing the pieces of glass together, for example. In his correspondence, he recalls at length his negotiations with Saint-Gobain, who, after much persuasion, finally agreed to supply a crown-glass, whose greenish tint is familiar to all those who have seen a large lenticular optic.

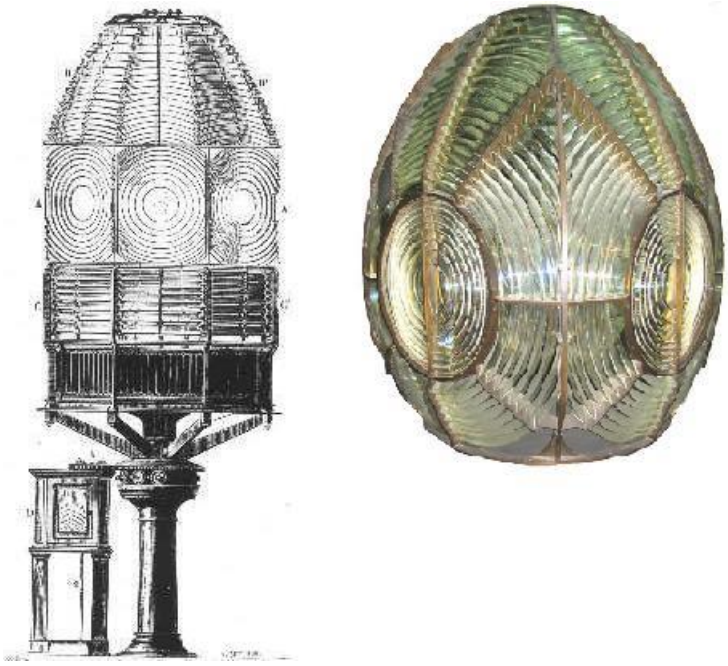

***Figure 3*: Fresnel's echelon lens, used in lighthouses in the past (left, image: École des Ponts) and in the present day (right).** *Fresnel's description of "his" lens goes as follows: (on the central section, p. 9) "All the light intended for the illumination of a lighthouse is united in one single flame. This flame is surrounded by eight square lenses set vertically, the centres of which are situated in the same horizontal plane as the single light … they thus form around the brilliant object a vertical prism having a regular octagonal base"; (on the upper section, p. 13) "I accomplish this easily, without changing any of the general arrangements of the eight lenses, by utilizing the rays passing out above them, which would otherwise be lost. For this purpose I employ eight additional*

5. In the configuration shown in Figures 1 and 2, the tangents at a particular point on the curved interface are parallel, since the circles are concentric, as Fresnel notes.
6. On the contract signed with Soleil, Fresnel states: "Mr Director General des Ponts et Chaussees came to the assistance of the manufacturer, and by paying a certain amount in advance, encouraged him in the new undertaking, to which he devoted all his energies, assuring its success from the outset." (p. 22)

*trapezoidal lenses of 0.50 of a meter focal distance, which are placed above the four-wick burner in the form of a truncated octagonal pyramid, like a dome or roof, through the upper opening of which the chimney of the lamp passes."*
*The modern-day echelon lens (to the right, in crown-glass) can be described in very similar terms: the principle of eight central lenses and eight upper trapezoidal lenses (which are a little more rounded) remains the same; the only thing that has disappeared is the "upper opening" to release smoke, since oil lamps are now a thing of the past!*

## THE LENTICULAR APPARATUS: A TECHNICAL SYSTEM

The apparatus installed at Cordouan was not made of lenses alone; it was a complete "system", comprising an optical device, a source and a rotating apparatus, the whole thing being required to operate every day, far from Paris and its scholars. That is why Fresnel considers the question of the light source, which must be as localised as possible:

> *It was necessary, in order to make the most advantageous use of the lenticular apparatus, to produce a central light of great brilliancy and of small dimensions. M. Arago and myself have succeeded in solving this problem in a satisfactory manner by carrying out the idea of M. Rumford in regard to multiple wicks …*

At the end of the 19th century, this text would sometimes be dug out as evidence of a prophetic presaging of the use of new energy sources such as electricity and gas.

Thanks to the calculations and empirical observations of numerous observers in Paris and on the coast, Fresnel demonstrated that his device had a better optical performance – i.e. the ratio between the light output obtained and the raw materials consumed. Cautious and shrewd, Fresnel avoids mention of the investment cost of lenticular devices, which was significantly higher than that of the reflectors with which they were in competition. He also makes use of practical arguments:

> *But, another very important advantage, which will suffice to give the preference to lenses, even though their effect should not be superior to those of the reflectors, is the permanency of the glass and the durability of its polish. The cost of keeping the lenses in order will be almost nothing, and their cleaning will give much less trouble than reflectors, which must be frequently rubbed with red oxide of iron to keep up their polish.* (p. 16)

Léonor Fresnel would write long instructions for the lighthouse keepers, specifying down to the tiniest detail how to install and maintain the delicate pieces of apparatus designed by his brother Augustin.

## FROM LIGHTHOUSE TO NETWORK

By mentioning the characteristics of the light, and whether it should be immobile or periodic, Fresnel reminds us that the aim was not simply to design a single apparatus, but rather a system of around fifty large lighthouses, as described in the report of 1825. The language used to describe the characteristics of the lights – "eclipse" – is the language of the sky. The historian Jules Michelet (*The Sea*, 1860) perfectly summarises this controlled celestial system when he writes:

> *To the sailor, who steers by the stars, this invention gave him, as it were, a new heaven and added constellations. Planets, fixed stars, all were created anew … and in those newly invented constellations there was even an improvement upon the celestial lights, in the variety of color, intensity and duration, of their glow and of their flashing.*[7]

The issue of range, linked to the light output, as well as the variety of signals used by the different lighthouses, was thus fundamental in terms of limiting the number of points that needed to be illuminated and navigational errors due to the confusion of two identical lights. The hypothetical idea of a specific signal for each light being too complex, a decision was made to adopt a slim-lined "grammar". Fresnel writes:

> *For this reason I have sought to attain the same end, by so arranging an apparatus, that the intervals between its flashes shall be of unequal periods according to the idea of M. Sganzin, Inspector General des Ponts et Chaussees.* (p. 21)

Three options were selected: fixed; a one-minute eclipse; and a 30-second eclipse. The aim here was to hone the rotation machines – borrowed from the art of watchmaking – by making them continuous.

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How did the tide of the history of techniques turn in favour of Fresnel's device? The *Mémoire* relates the process by which the innovation was given the go-ahead at a crucial experiment held on the evening of 13 April 1821. That evening, the Lighthouse Commission, installed "at the very top of Montmartre to judge the effect produced" by the competing apparatuses, came out in favour of the lenticular – or Fresnel – system, as opposed to the parabolic projectors of his competitors. A few months later, observers in Châtenay watched the light shine

7. Jules Michelet, *The Sea*, New York, Rudd & Carleton, available online.

from the device installed on the roof of the Arc de Triomphe, some 15 miles away. Were the "judges" – scientists and engineers, like Fresnel – impartial? As early as May 1821, Isaac Bordier-Marcet observed with a certain amount of bitterness that the die was already cast. The newspaper *Le Journal du commerce* published the account of "this skilled lamp constructor", who, while not questioning the radiant brightness of the lens, felt that the comparisons had been partial and unrepresentative of the real conditions in which the apparatuses would be used. As for Lenoir's reflectors installed at Cordouan, they were dismantled in 1823.

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The lighting market was around 40 years old when Fresnel developed his lenticular system (it dated back to the early 1780s). This was a process that combined an innovation – the lens and its fabrication – with progress that had already been achieved in the field of lamps and rotation mechanisms. Reducing his contribution to the lens alone does not take into account his concrete innovatory work, as described in the *Mémoire*. There are ideological reasons for this simplification: to demonstrate the relevance of a French-style engineering education, in which science and technique are closely intertwined. The lenticular theory, a breakthrough innovation in the field of lighthouse technology, is evidence that can be adduced in favour of this argument.

**Fresnel versus Buffon**

Fresnel credited Buffon (1707–1788) with the invention of the echelon lens: "Buffon was the first to suggest echelon lenses for increasing the power of burning-glasses while diminishing their thickness." Yet while he cites and recalls this precedent at length (p. 3–5), this is to better emphasise his own invention, which consists in making the echelon lens out of several pieces of glass, in contrast with sculpting a single bloc of hemispherical glass, which is what Buffon imagined: "it is evident that he proposed to make them of a single piece of glass which would render their fabrication almost impossible … Buffon had not thought of constructing his lenses in several pieces". Indeed, Fresnel's tone towards Buffon is rather caustic: "It is easily understood why, *twenty-five years after*[8] having invented these lenses and notwithstanding his earnest desire to possess one, the same scholar who invented the beautiful mirror of

8. It is Fresnel who emphasises "twenty-five years after".

Archimides,[9] the construction of which was much more complicated and much more expensive, was unable to procure an echelon lens three feet in diameter, it was because he had not thought of making them of several pieces." To further underline this difficulty, Fresnel invokes a witness (Charles) who had heard said (from Rochon) that he "had seen a small echelon lens measuring 12 to 15 inches in diameter and made out of a single piece of glass, originating from Buffon's study". A small-sized lens, made out of a single bloc: these details are mentioned to limit the scope of Buffon's invention, which remained theoretical. Fresnel is conscious that, in terms of the echelon lens, what can be attributed to him, as opposed to Buffon, is "precisely that which renders the invention practicable on a large scale".

## EPILOGUE: LENSES TODAY

Fresnel's echelon lens found an immediate application in lighthouses, whose lighting system – in conjunction with the system as a whole – it revolutionised. It was also used experimentally in embryonic railway security in order to illuminate the locomotives using small catadioptric lanterns. One hundred and twenty years later it would find a new use in the mass production of cars (although it should be noted that parabolic reflectors are still used in some modern vehicles). An invention with a destiny all of its own, the lens would thus come to have an application that the inventor himself had – quite understandably – not envisaged. Indeed, this application served to vindicate Fresnel and the hopes he had placed in echelon lenses:

> *Not only will they be useful for the illumination of lighthouses, but they will doubtless be of use in the advancement of science … May we not, at some future time, owe to these burning-glasses discoveries as surprising as those with which the voltaic pile has enriched chemistry?* (p. 22)

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*(November 2008)*

*(Translated by Helen Tomlinson, published January 2017)*

9. Fresnel is certainly referring to Buffon's echelon lens here.