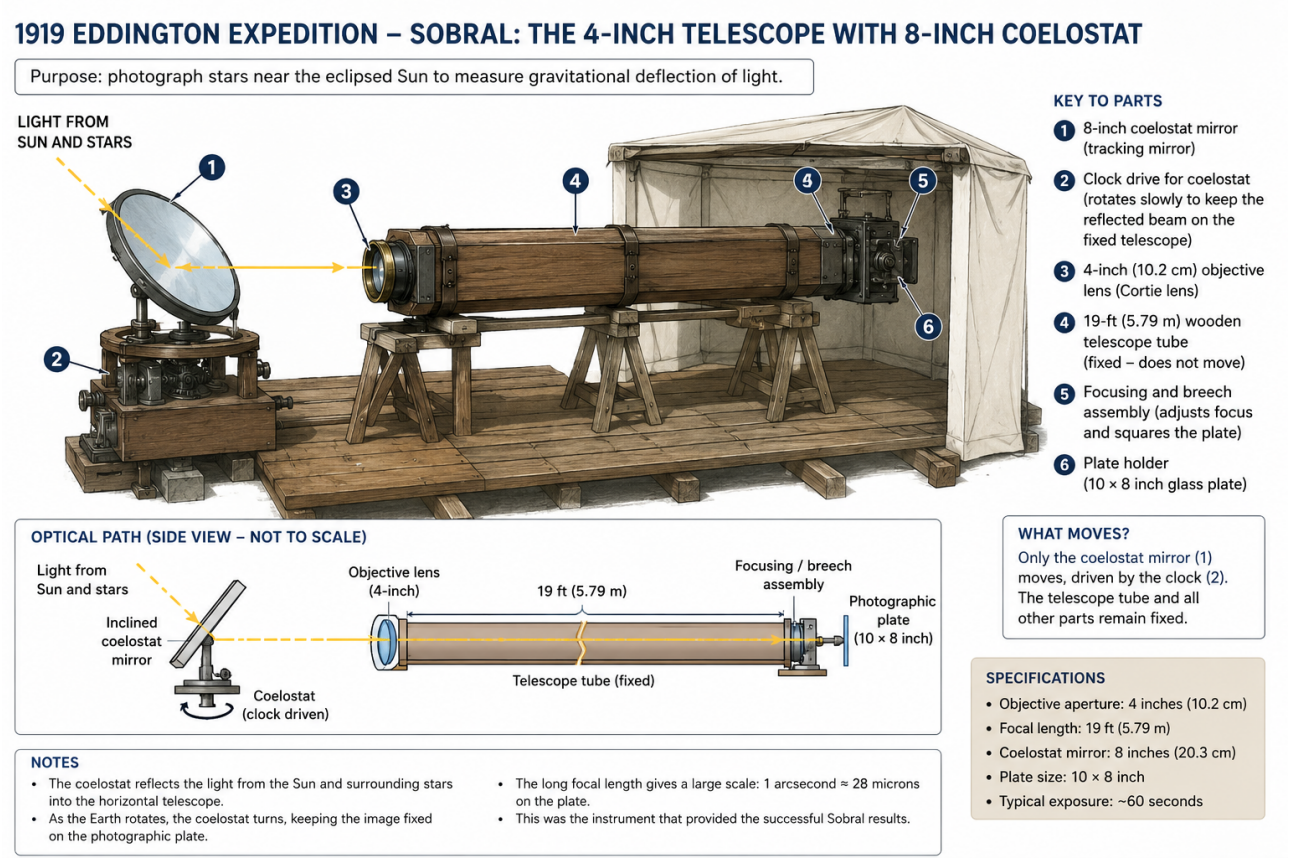


As a little test for the reader, can you spot the error in the above graphic?

Also the optics were designed so that stars across the plate come to focus as nearly as possible on the same plane. An ordinary refractor optimised for visual use does not necessarily provide such a well-corrected photographic field.

Another important feature was that it was stable in order to keep the angular separation on the sky across the plate. Remember, instead of an observer looking through an eyepiece, a glass photographic plate was placed precisely at the telescope's focal plane, and everything was designed with the photographic response of the plates in mind and to minimise aberrations that would distort the positions or shapes of stellar images.

The point about image scale is particularly important because it was effectively a precision angular measuring instrument. It converted tiny angular separations in the sky into measurable distances on a photographic plate.

The valuable precision components transported from Greenwich and Oxford were therefore principally the lens assemblies. Temporary telescope structures were constructed specifically for the expeditions.

Let's learn more about an astrograph

Firstly, it is important to distinguish an astrograph in general from the very specific *Carte du Ciel* astrographs whose object glasses were used in the 1919 experiment. By 1919 the Greenwich and Oxford instruments were already about thirty years old, but they had originally been designed for precision photographic astrometry, i.e. recording a relatively wide field of stars on glass plates so that their positions could subsequently be measured accurately. This made their optics particularly suitable for the eclipse experiment, although the instruments had not themselves been designed for eclipse observations.

A classical late-19th-century refracting telescope was principally designed for the human eye. It normally had an achromatic objective, a relatively restricted useful field, and an eyepiece. The observer looked through it, perhaps with a micrometer, and measured individual objects.

An astrograph was designed instead as a precision astronomical camera. The crucial difference was that the entire optical system was optimised to form measurable stellar images on a photographic glass plate. The standard

Carte du Ciel instrument had a photographic objective of about 33 cm (13 in) aperture and 3.43 m focal length, giving approximately 1 arcminute per millimetre on the plate. A standard plate was about 16 × 16 cm, recording roughly a 2° × 2° field.

The objective was a photographic doublet. This mattered because photographic emulsions were most sensitive toward the blue/violet part of the spectrum, whereas an ordinary visual achromat was optimised for wavelengths to which the human eye is most sensitive. A visually excellent telescope could therefore have its photographic focus in the wrong place or produce poor images across a large plate.

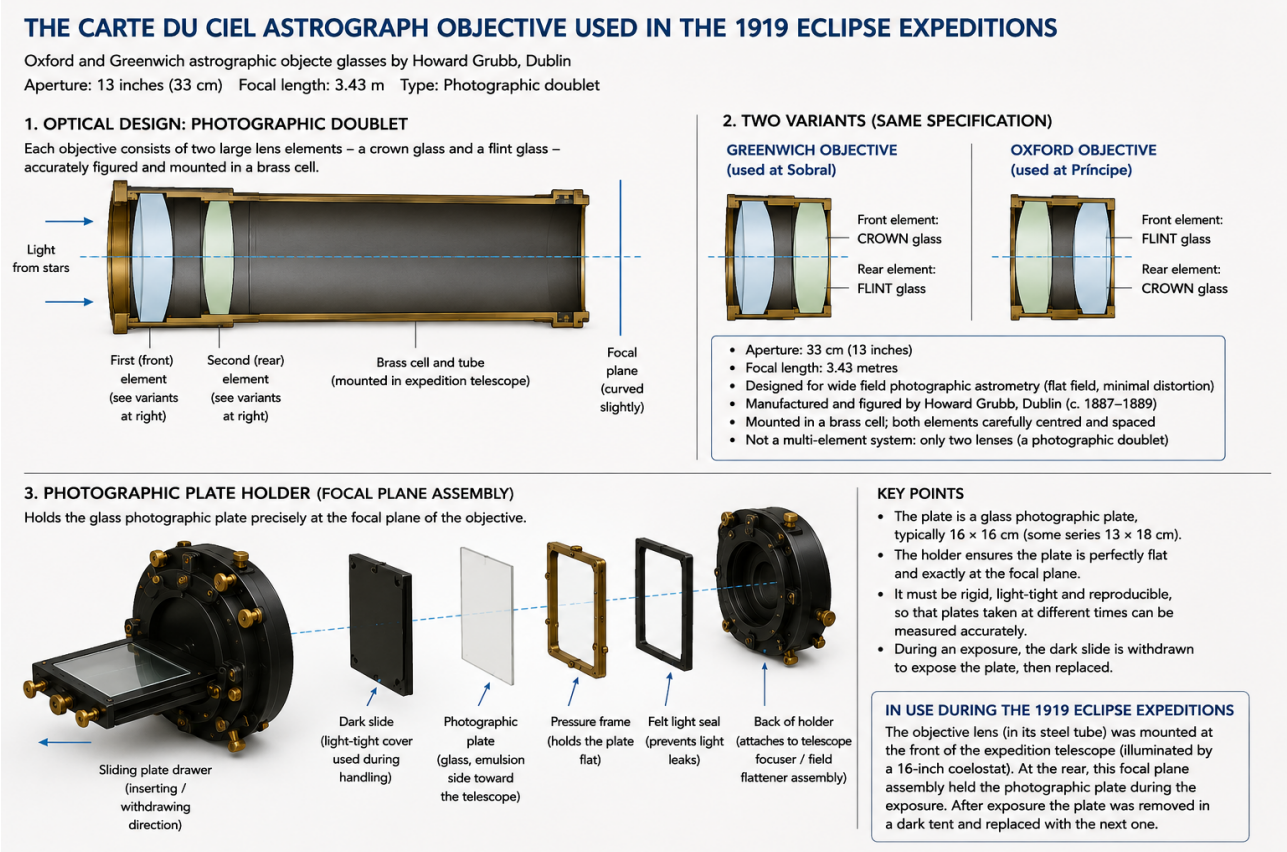
The British *Carte du Ciel* astrographs were Grubb instruments (he manufactured seven astrographs for the international programme). Importantly, these were not simple single lenses. Each object glass was a specially designed photographic doublet, with two large optical elements, one crown glass and one flint glass, accurately figured, spaced and mounted together in a metal cell. The two 1919 objectives were nominally built to the same *Carte du Ciel* specification, about 13 inches (33 cm) aperture and 3.43 m focal length, but they were not optically identical:

- Greenwich: crown-glass element in front, flint behind.
- Oxford: flint-glass element in front, crown behind.

Crown glass and flint glass are two types of optical glass with different refractive and dispersive properties. Crown glass has a relatively low refractive index and low dispersion. So it bends light moderately and separates the colours relatively little. Traditionally it was an alkali-lime silicate glass. Flint glass has a higher refractive index and

higher dispersion, and it bends light more strongly and separates different wavelengths more strongly. Historically it contained substantial lead oxide.

Because a single lens suffers from chromatic aberration. Its refractive index depends on wavelength, so blue light is bent more strongly than red light and the colours come to focus at different distances. An achromatic doublet combines two elements with opposite optical powers. The crown provides most of the required focusing power. The flint, because its dispersion is greater, can be given the opposite curvature so that it cancels much of the crown's colour separation without cancelling all of its focusing power. So two selected wavelengths can be brought to essentially the same focus, with the remaining wavelengths much closer than with a single lens.



For the astrograph, this was particularly important because you wanted tiny, sharply defined stellar images on a

photographic plate. A star is broadband light; without chromatic correction, its different colours would focus at different planes and produce a larger blurred stellar image, seriously degrading precision astrometry.

There is useful evidence of how valuable such an object glass was. Grubb was responsible not merely for buying glass but for figuring and finishing the optical surfaces and mounting the elements in their cell. Contemporary Greenwich documentation for other Grubb refractors shows just how specialised this was. Large optical glass blanks could be supplied by several different firms, but it was Grubb that figured the lenses, assembled them and made the final optical adjustments. The surviving sources consulted do not give a separate purchase price for the object glass, nor have I found firm evidence identifying the manufacturer of the raw glass blanks.

A rigid glass plate coated with photosensitive emulsion was inserted into a plate carrier at the focal plane. The rigidity of glass plate was extremely important for astrometry, since the subsequent measurement depended upon the geometrical positions of stellar images being preserved. The *Carte du Ciel* plates could also carry a *réseau*, a precisely defined grid of lines at 5-mm intervals, providing a geometrical reference when stellar positions were subsequently measured.

Check out https://www.royalobservatorygreenwich.org/articles.php?article=1057 The Greenwich astrographic telescope was actually a paired instrument. The photographic telescope was paired with a slightly smaller visual guiding telescope (10-inch objective and 3.43 m focal length). Both were rigidly connected on the same German

equatorial mounting. There was additionally a smaller 3-inch guiding telescope.

The immediate ancestor of the standard astrograph was developed at the Paris Observatory by the brothers Paul and Prosper Henry in the mid-1880s. Their logic was that when their survey reached the extraordinarily dense Milky Way, visual plotting became impractical. The success of this work helped to promote the enormous international photographic survey which became the *Carte du Ciel/ Astrographic Catalogue*. At the international Paris conference in 1887, astronomers agreed to divide the sky between participating observatories and adopted a substantially standardised photographic telescope. Initially 18 observatories undertook zones of the sky.

This standardisation is important. It was effectively a late-Victorian attempt to build a worldwide network of compatible astrometric instruments. By 1915 there were 20 participating observatories, and they had produced more than 22,000 plates.

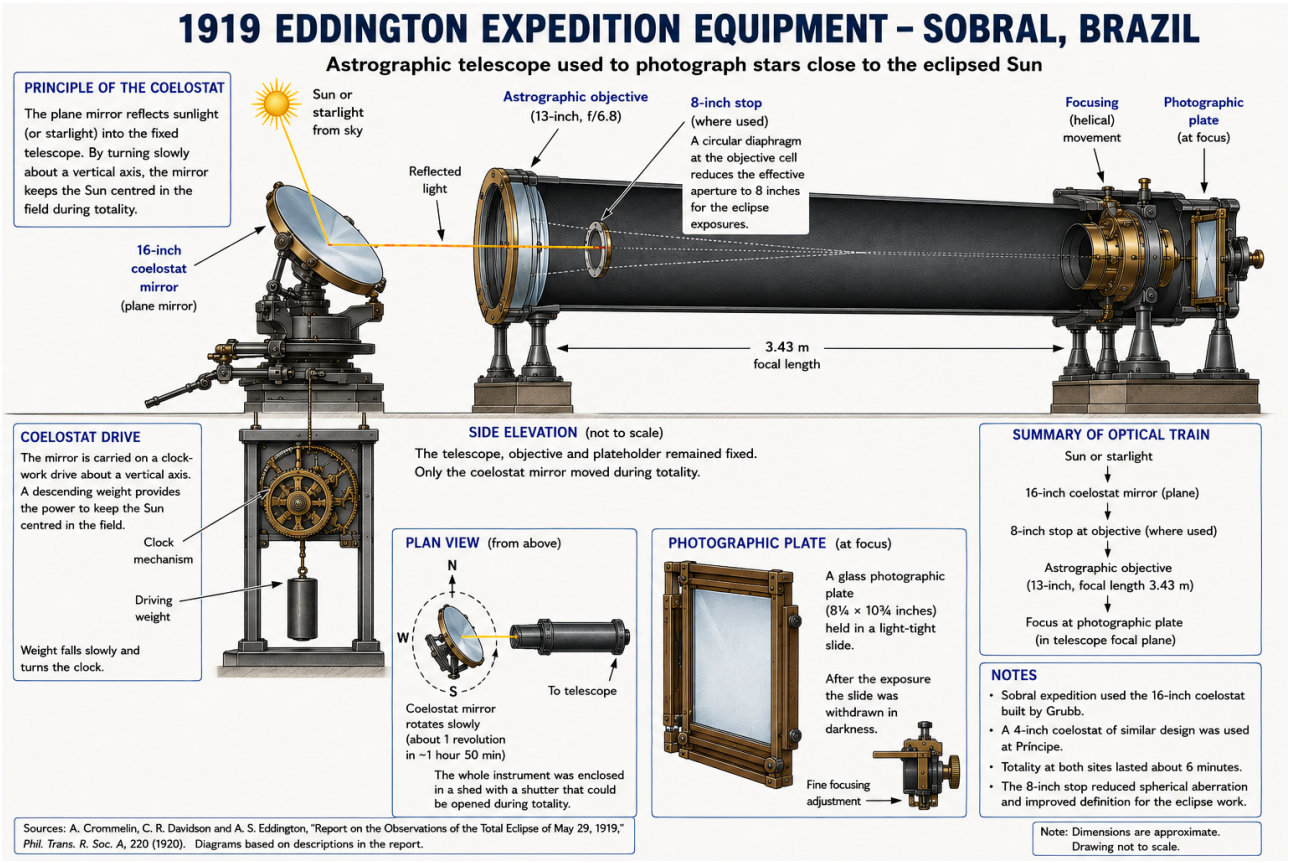
Two manufacturers dominated, Gautier in Paris, and Grubb in Dublin (ours were from Dublin). A Gautier astrograph together with its macromicromètre measuring machine cost about 35,000 French francs (perhaps €1 million or more today). A contemporary account cited in a recent historical study compares that with an annual salary for a French astronomer of roughly 300 francs.

Neither expedition transported a complete astrographic telescope. The Greenwich and Oxford astrographic object glasses were removed from their permanent observatory instruments and each was installed in a specially

constructed two-section steel tube for the expedition. At Sobral a second, independent 4-inch photographic telescope was also used; unlike the astrographs, this retained the square wooden tube in which it had previously been used for eclipse photography.

Remember - They removed probably the most optically sophisticated and valuable component of each permanent astrograph, packed it separately, kept it under the observers' personal care during the voyage, and built a new telescope around it at the expedition site.

How an expedition astrograph was constructed



Each astrographic object glass was attached to one end of a specially made steel telescope tube.