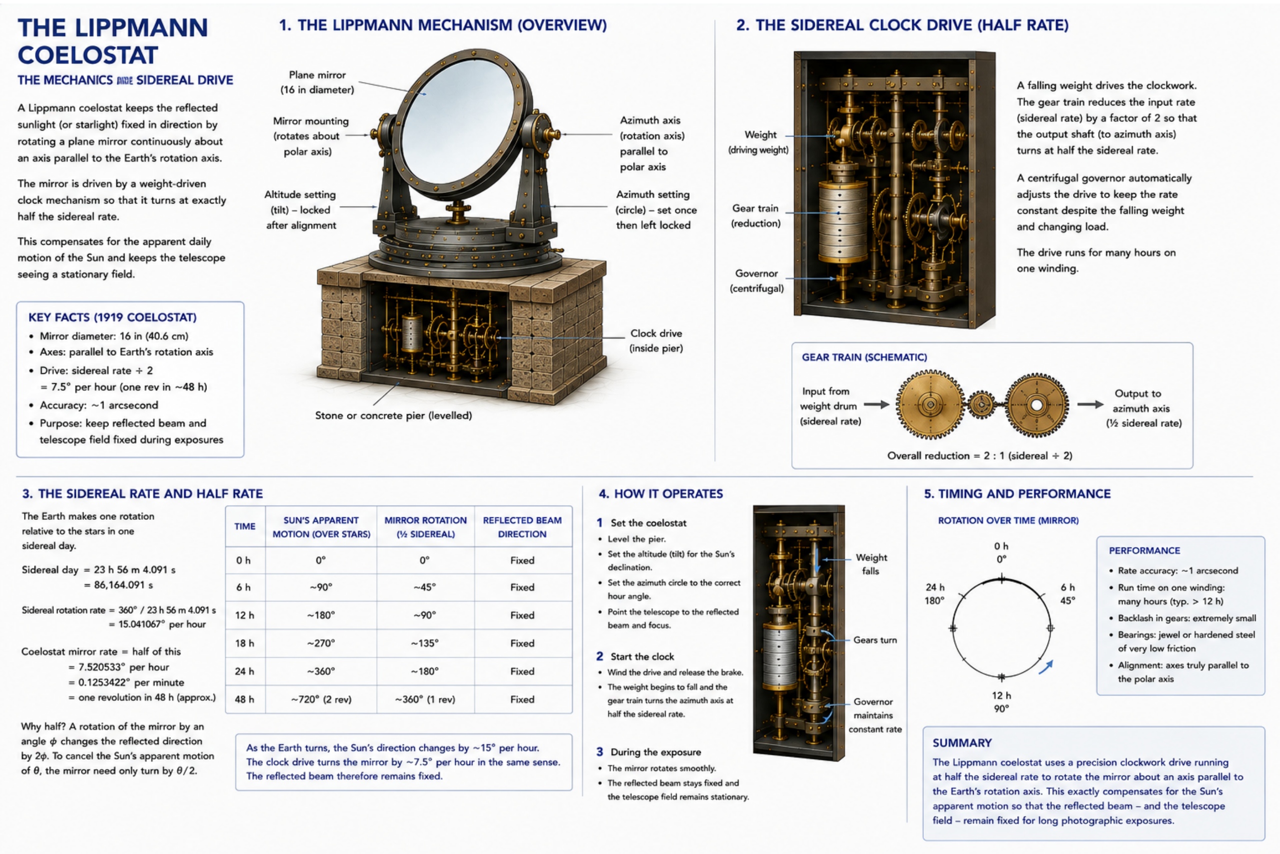
Because a tube more than 3 m long would have been inconvenient to transport, each tube was manufactured in two sections, which could be bolted together after arrival.

At the rear of the tube was a rigid wooden breech piece containing the photographic apparatus. This allowed adjustment of the focus, adjustment to make the photographic plate perpendicular to the optical axis ("squaring on"), and included a plate holder and locating screws. These locating screws were particularly important because they ensured that successive photographic plates occupied the exact **s**ame focal plane.

Why a coelostat was required



These long telescope tubes were not mounted so that they tracked the Sun across the sky. They remained stationary.

Instead, incoming light from the Sun and surrounding stars first struck a clock-driven (re-silvered) flat mirror called a **coelostat**. As the Earth rotated, the coelostat mirror rotated slowly so that it continued to reflect the same region of sky along the fixed horizontal axis of the telescope.

Each astrograph was fed by a 16-inch coelostat.

The advantage was mechanical. Only the mirror had to track the sky, and the 3.43 m long telescope itself could remain fixed on a rigid support.

The disadvantage was that the coelostat became part of the precision optical system. Any deformation or instability of its supposedly flat mirror could affect the stellar images and their scale on the plate. This subsequently became particularly important at Sobral.

The additional 4-inch Sobral telescope

Sobral was given a second, independent photographic telescope.

This was a 4-inch objective lens with a focal length of 5.79 m that had previously been used during a 1914 eclipse expedition in Sweden. The 4-inch objective was already fitted to a square wooden tube, and was fed by a separate 8-inch coelostat belonging to the Royal Irish Academy.

Although the 4-inch instrument had only half the working aperture of the stopped-down astrograph, it had a much longer focal length, namely 5.79 m rather than 3.43 m. Consequently, the same angular stellar displacement produced a larger physical displacement on its photographic plate.

In practical terms this meant that with the 4-inch telescope's 5.79 m focal length, Einstein's 1.75″ solar-limb deflection would correspond to (just) 0.049 mm on the photographic plate. But with the shorter 3.43 m focal length of the larger astrographic telescope, the same angular deflection would produce only 0.029 mm.

The smaller telescope therefore had a potentially important astrometric advantage, namely a greater linear plate scale for the gravitational displacement.

Photographic plates and preparation

The stellar positions were recorded on glass photographic plates, not film.

They were commercial gelatin-silver dry photographic plates, i.e. accurately cut sheets of glass carrying a thin light-sensitive photographic emulsion. Surviving Ilford Special Rapid material is catalogued explicitly as a glass-plate negative.

The emulsion contained microscopic silver-halide crystals, principally silver bromide in plates of this period, suspended in gelatin. Exposure to light created a latent image.

Chemical development converted the affected grains into metallic silver, and fixing removed the remaining unexposed silver halide. The resulting plate was therefore a negative, bright objects such as stars became small dark deposits of metallic silver when the plate was viewed directly.

For astrometry, glass had a major advantage over flexible film, i.e. dimensional stability. The astronomers eventually wanted to measure differences of only tens of micrometres.

A rigid glass substrate gave a much more reproducible geometrical surface than flexible sheet or roll film.

They deliberately took plates from two manufacturers. That turned out to be a very sensible precaution.

Remember - The experiment ultimately depended upon determining stellar-image positions on a 20 × 25 cm piece of glass to a tiny fraction of a millimetre. Einstein's hypothetical solar-limb displacement of 1.75″ corresponded to only about 0.049 mm.

The original report says that during the preparations at Sobral it became apparent that one kind of plate was unsuitable under the hot climatic conditions. A photographic emulsion is gelatin, which responds strongly to temperature and humidity. In tropical conditions it can soften and swell, making processing more difficult, and the mechanical properties of the emulsion can deteriorate.

Remember - Plate holders along with the plates were also parts of telescope's metrology. For the expedition astrographs, the report says they obtained **1**8 plate carriers for each telescope. At the breech of the new steel tube was a wooden structure incorporating the focusing and plate-positioning mechanism. Exact locating of the plates was important because if one side of a 16-cm plate sat slightly farther from the objective than another, stellar images could change shape or focus across the field.

What equipment therefore actually went to each site?

The main Sobral system consisted of the Greenwich 13-inchastrographic object glass, with an 8-inch working aperture, a 3.43 m focal length, and a clock-driven 16-inch coelostat.

Sobral also had a 4-inch Cortie object glass with a 5.79 m focal length, and a separate 8-inch coelostat.

In Príncipe they only had the Oxford 13-inch astrographic object glass, stopped to an 8-inch working aperture, 3.43 m focal length, with a clock-driven 16-inch coelostat.

Having a secondary astrograph in Sobral proved crucial. The large Sobral astrograph suffered severe image degradation during the eclipse, whereas the supposedly supplementary 4-inch telescope produced sharp stellar images and ultimately provided the strongest measurement of the experiment.

Expedition to Sobral

The Sobral party left England on 23 March 1919 and arrived at Sobral on 30 April, travelling first by sea, then by local steamer and finally by train (total 38 days).

The instruments were erected on the racecourse at Sobral.

The two independent photographic systems were the Greenwich astrographic, and the auxiliary 4-inch instrument. But preliminary observations showed that the 4-inch instrument could record seven of the stars required for the deflection measurement.

Problems discovered before the eclipse

Tests of the astrographic system revealed serious astigmatism, caused by the 16-inch coelostat mirror. This was partially corrected, but the remaining defect made it clear that the observers would have to return to Sobral in

July to obtain comparison photographs of the same star field after the Sun had moved away from it.

The images from the 4-inch telescope were better, although not quite perfect, and comparison photographs would also be required for this instrument.

Two makes of photographic plate had been taken to Brazil, but preliminary work showed that one type was unsuitable in the hot climate.

Another practical problem was that the coelostats and their clock drives were found to be very sensitive to wind. The 16-inch coelostat was particularly troublesome. Its drive produced a marked periodic oscillation of the image, with a period of approximately 30 seconds. The planned exposure times with the astrographic telescope were therefore shortened.

Eclipse day — 29 May 1919

The morning of the eclipse was rather cloudier than usual, but as totality approached a large clear region reached the Sun approximately one minute before second contact, the beginning of totality.

The total contact lasted 310 seconds.

With the astrographic telescope, 19 photographic plates were exposed, using alternating exposure times of 5 and 10 seconds.

With the 4-inch camera, eight plates were exposed, each for 28 seconds.

Development was carried out during the cooler night-time hours over the following days and was completed by 5 June.

The astrographic photographs were successful in that 12 stars appeared on a number of the plates, and at least seven appeared on all but three plates. The difficulty that subsequently emerged was not the number of stars recorded but the quality and scale of their images.

The expedition left Sobral on 7 June, and returned on 9 July specifically to obtain the necessary comparison photographs of the eclipse star field, now visible at night without the Sun.

Photographs taken with the 4-inch telescope

The auxiliary 4-inch telescope ultimately produced the most satisfactory photographs, and seven stars were measured.

It is important that the experiment did not directly measure a displacement of 1.75″. Einstein's 1.75″ prediction applied to a hypothetical light ray grazing the solar limb. The seven measured stars lay farther from the Sun and therefore had smaller predicted displacements, with both an (x) and a (y) component depending upon each star's position relative to the Sun.

Thus there were 14 coordinate measurements, two coordinates for each of seven stars. For many of these, the observed and calculated values agreed quite closely. For example, one calculated displacement of +0.74″ was observed as approximately +0.83″. Other individual measurements showed considerably larger residuals, for example, in one case a calculated value of approximately

−0.32″ corresponded to an observed value of approximately +0.19″.

The result was therefore not obtained by expecting every individual coordinate measurement to reproduce Einstein's prediction exactly. The complete pattern of stellar displacements was reduced statistically, together with the required plate constants.

From the 4-inch photographs the authors obtained a gravitational deflection equivalent to approximately 1.98'' for a hypothetical ray at the solar limb, compared with Einstein's prediction of approximately 1.75''. This became the strongest result of the expedition.

Photographs taken with the astrographic object glass

The second Sobral system used the Greenwich astrographic object glass, stopped to an 8-inch aperture and fed by the 16-inch coelostat. Although these photographs recorded more stars, the stellar images on the eclipse plates were badly out of focus, whereas photographs subsequently obtained with the same system returned to good focus. The investigators concluded that the optical system had changed during the eclipse observations and considered heating of the coelostat mirror by the Sun the probable explanation.

This presented a serious problem because a change in focus could also produce a change in the scale of the photographic image. A change of scale causes the whole star field to expand or contract on the plate and can therefore imitate part of the radial displacement being sought. When the astrographic eclipse plates were reduced in the ordinary way, the mean value obtained for the gravitational coefficient was approximately 0.86'', considerably below the result obtained with the 4-inch telescope and close to the approximately 0.87″ value associated with the earlier half-deflection prediction.

However they then applied an alternative reduction in which the scale change was inferred from the change of focus of the telescope. On that assumption the same astrographic observations gave a solar-limb deflection of approximately 1.52''.

The important point is therefore not that the 0.86″ result was mathematically transformed into 1.52″. The two numbers resulted from different assumptions about an instrumental parameter that the defective eclipse photographs could no longer determine reliably, i.e. the change in scale between the eclipse and comparison photographs.

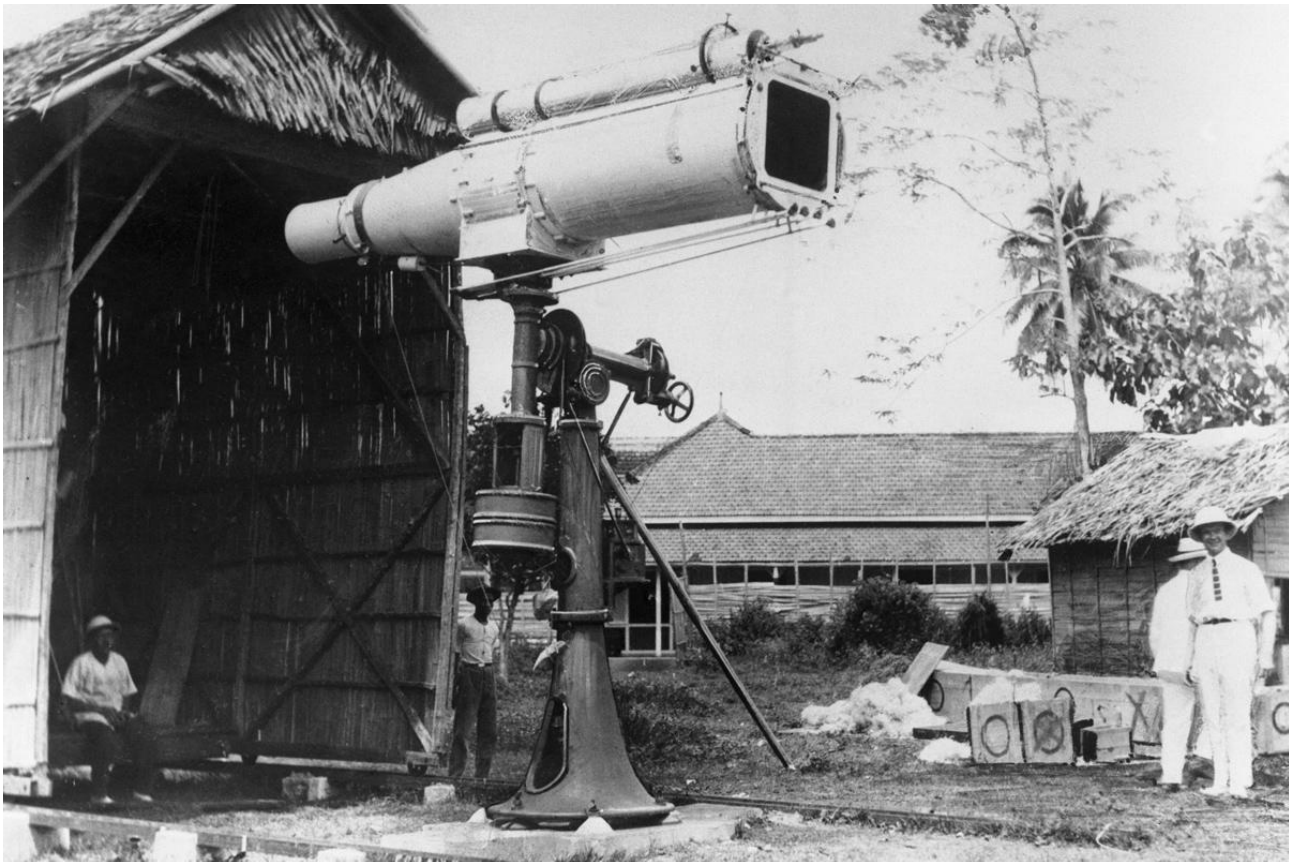
For this reason the authors regarded the Sobral astrographic result as substantially less reliable than the result from the 4-inch telescope.

Expedition to Principe

Eddington and Edwin Cottingham left on 8 March 1919, and landed at Santo António on Príncipe on 23 April (total 46 days). Eddington selected Roça Sundy, a cocoa plantation in the north-west of the island, at about 500 ft above sea level.

Príncipe had only one telescope system, with the Oxford astrographic having a 13-inch objective with a 3.43 m focal length. Tests also demonstrated that images obtained with the full aperture were substantially poorer. Eddington therefore used an 8-inch stop in front of the Oxford objective for all eclipse and comparison work. The telescope was fed by a clock-driven 16-inch coelostat. The clock weight descended into a pit, sufficiently deep to allow the drive to operate for 36 minutes without rewinding.

A particular sector of the coelostat mirror, judged to have the best optical figure, was deliberately used for both the eclipse and the check photographs.



The above photo is of (I think) the Oxford astrographic, but not as used in Principe.

The comparison problem

Príncipe presented an important experimental difficulty that differed from Sobral. At Sobral, the observers could return in July and photograph the same star field after the Sun had moved away. Eddington could not conveniently do this at Príncipe because the eclipse occurred in the afternoon, so the same field would not occupy a suitable position in the night sky for many months. Instead, photographs of the eclipse field had already been obtained with the same Oxford objective at Oxford before the expedition.

Eddington also photographed a separate check field containing Arcturus both at Oxford and at Príncipe. It was selected to have nearly the same declination as the eclipse field and was photographed at Príncipe at the same altitude in the sky. The purpose was to reveal systematic differences caused by the coelostat, transportation of the objective, temperature, atmospheric refraction or other differences between Oxford and Príncipe.

These check photographs became particularly important because they allowed Eddington to determine the change of photographic scale between Oxford and Príncipe.

Eclipse day — 29 May 1919

The weather was much worse than at Sobral, with a heavy thunderstorm. The Sun appeared briefly but was soon covered again. About half an hour before totality the crescent Sun became intermittently visible through drifting cloud. Totality was calculated to last just over five minutes.

Eddington and Cottingham obtained **1**6 photographic plates. Unfortunately, cloud covered the Sun during most of totality. Only during the final part of totality did the cloud become sufficiently thin for stars to appear on the photographs.

What was actually recorded

Of the 16 eclipse plates, only a few were useful. The crucial stars were κ¹ Tauri and κ² Tauri, because their positions relatively close to the Sun gave them among the largest predicted gravitational displacements. Fortunately, both appeared on the later plates.

However, after examining the complete photographic series, Eddington concluded that only two eclipse plates were sufficiently good to provide a trustworthy determination. Thus, although 16 eclipse photographs had been exposed, the final quantitative result depended essentially upon two photographic plates and five useful stars.

Measurement

The Príncipe plates had to be compared with the Oxford reference plates, and for each star, small differences in the (x) and (y) coordinates were measured. This was important because the photographic scale at Príncipe was slightly larger than at Oxford, corresponding principally to an increase in effective focal length associated with the approximately 40°F temperature difference between the two sites. After these corrections, they obtained a solar-limb deflections of approximately 1.61" (I think with an error of ±0.30"), as compared to Einstein's prediction of 1.75". So the Príncipe measurement was consistent with Einstein's full prediction, although substantially less precise than the result obtained with the 4-inch telescope at Sobral.

Eddington's own conclusion was appropriately cautious. He felt that the accuracy was sufficient to provide a “fairly trustworthy confirmation” of Einstein's theory and to make the approximately 0.87″ half-deflection very improbable.

It's worth noting that Príncipe almost failed because of the weather, but was still considerably better than the large Sobral astrograph. Its focus remained stable, its systematic behaviour had been tested with a separate comparison field, and Eddington had an independent determination of the photographic scale. For that reason, despite the very limited number of usable stars and plates, the authors considered the Príncipe result scientifically meaningful.

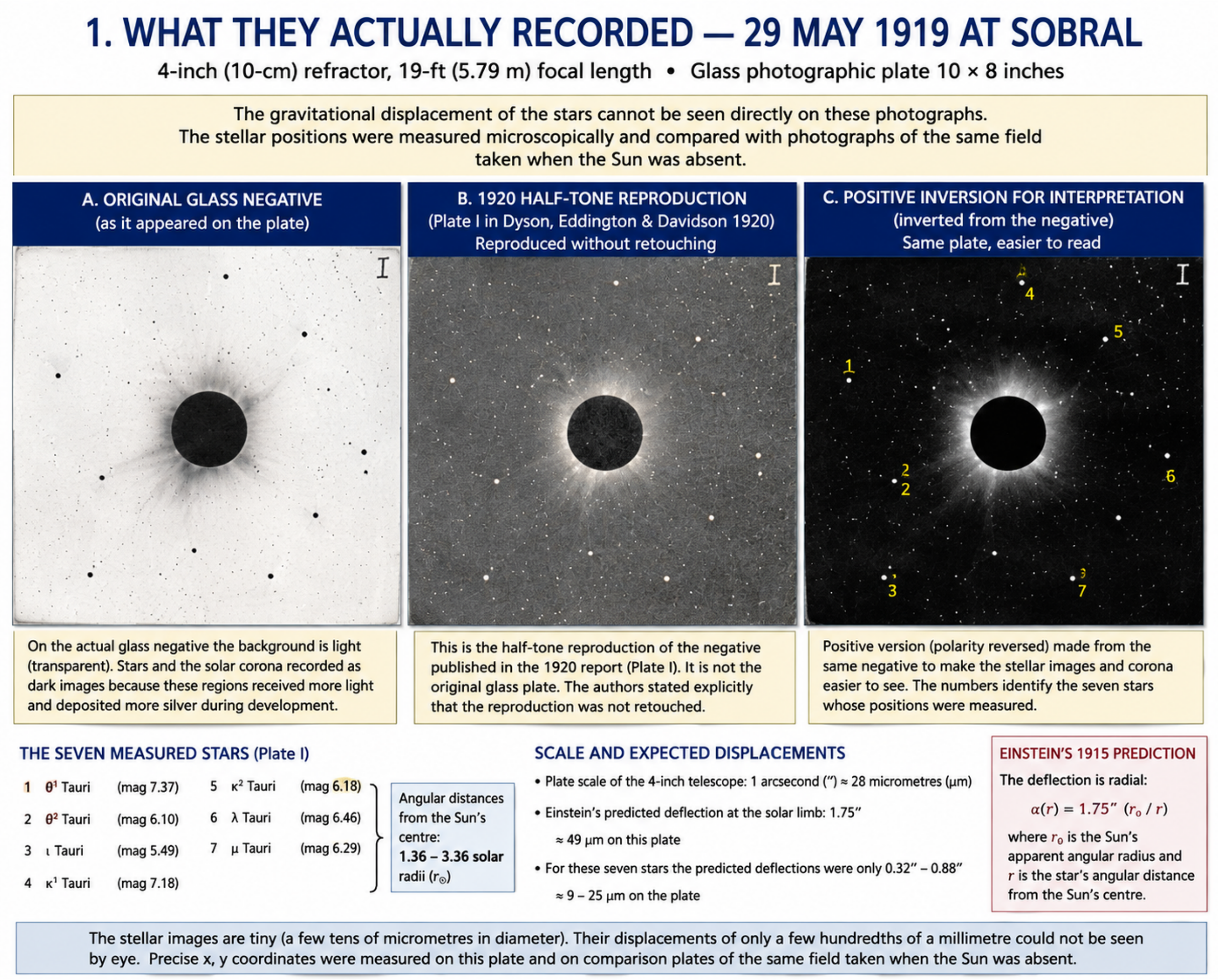
Conclusions

The authors considered the Sobral 4-inch telescope to provide by far the most reliable result because of its superior stellar images and larger photographic scale. It gave a solar-limb deflection of 1.98″ ± 0.12″. The Príncipe observations, seriously affected by cloud, gave 1.61″ ± 0.30″ and were given substantially less weight. The Sobral astrographic telescope gave 0.93″, but the authors rejected this as unreliable because of the instrumental and scale problems associated with its badly focused eclipse images.

The two results considered reliable were therefore consistent with Einstein's general-relativity prediction of 1.75″, rather than the approximately 0.87″ half-deflection. The individual Sobral 4-inch stars also showed approximately the predicted increase in deflection with decreasing distance from the Sun.

The authors concluded that there was little doubt that light was deflected in the Sun's gravitational field by approximately the amount predicted by Einstein, although they explicitly recommended that the experiment should be repeated at future eclipses. They also recommended abandoning coelostat mirrors for such precision measurements and instead using telescopes on equatorial tracking mounts, thereby removing an unnecessary optical element and potential source of systematic error.

How the results were analysed



At Sobral the 4-inch telescope, on the original negative, the exposed stellar images and corona appeared dark against the relatively clear glass. The familiar published image is a half-tone reproduction, while a positive reverses the tones for easier viewing. The relativistic displacement cannot be seen by eye. The seven useful stellar images had predicted shifts of only about 0.32–0.88″, corresponding to roughly 9–25 μm on the plate.