PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Development of Kinetheodolites for Satellite Tracking

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The development of kinetheodolites for satellite tracking

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[Plate 5]

A typical kinetheodolite is briefly described. The early use of these instruments for satellite tracking is mentioned and the three groups set up by United Kingdom establishments for this work are described. Some of the improvements in instrumentation and observing technique made by these groups are noted, with the accuracies achieved. Some advantages of kinetheodolites are listed and suggestions are made for future development.

1. General description of a typical kinetheodolite

The kinetheodolite is like any other theodolite in that it is built round two divided circles, a horizontal circle for azimuth and a vertical circle for elevation. In general, it is operated by two observers (see figure 1, plate 5). The part which moves in elevation carries three parallel telescopes in place of the one telescope of the ordinary theodolite. The central telescope is a camera, recording on cine film, the wind-on mechanism being driven by an electric motor. The other two telescopes are elbow telescopes used by the two operators to sight the object being tracked. The circles are illuminated and can be viewed through microscopes mounted below the sighting telescopes. Optical trains of lenses and prisms enable the circles to be photographed as small insets in two corners of the frame of the film in the central camera. Each frame also records a serial number (see figure 2, plate 5).

Each exposure is initiated by an electrical pulse from a timing system. The arrival of the pulse causes four things to happen: (1) the lamps which illuminate the circles are flashed (or shutters are briefly opened in the older instruments where continuous illumination of the circles is used); (2) the main shutter of the camera is operated to photograph the object being tracked (in relation to central cross-wires); (3) after a suitable delay, the film wind-on mechanism is operated; (4) the frame serial number is changed. The repetition rate of pulses depends on the type of tracking being done, as discussed below.

Each observer has a central graticule in his telescope which appears as a pattern of black lines against the daytime sky or illuminated lines against the night sky. The illumination is by red light (as this affects the observer's dark adaptation less than white light) and the intensity is adjustable. When the target appears in the field of view of the telescope the two observers turn the instrument to follow it by means of two large handles, one for azimuth movement and the other for elevation movement. Each observer controls one handle, turning the instrument to keep his cross-wire on the target. (It is possible for one observer to operate both movements but this considerably reduces the accuracy of the tracking.)

Kinetheodolites are in use in several countries on rocket launching ranges, bombing ranges, etc.

FIGURE 1

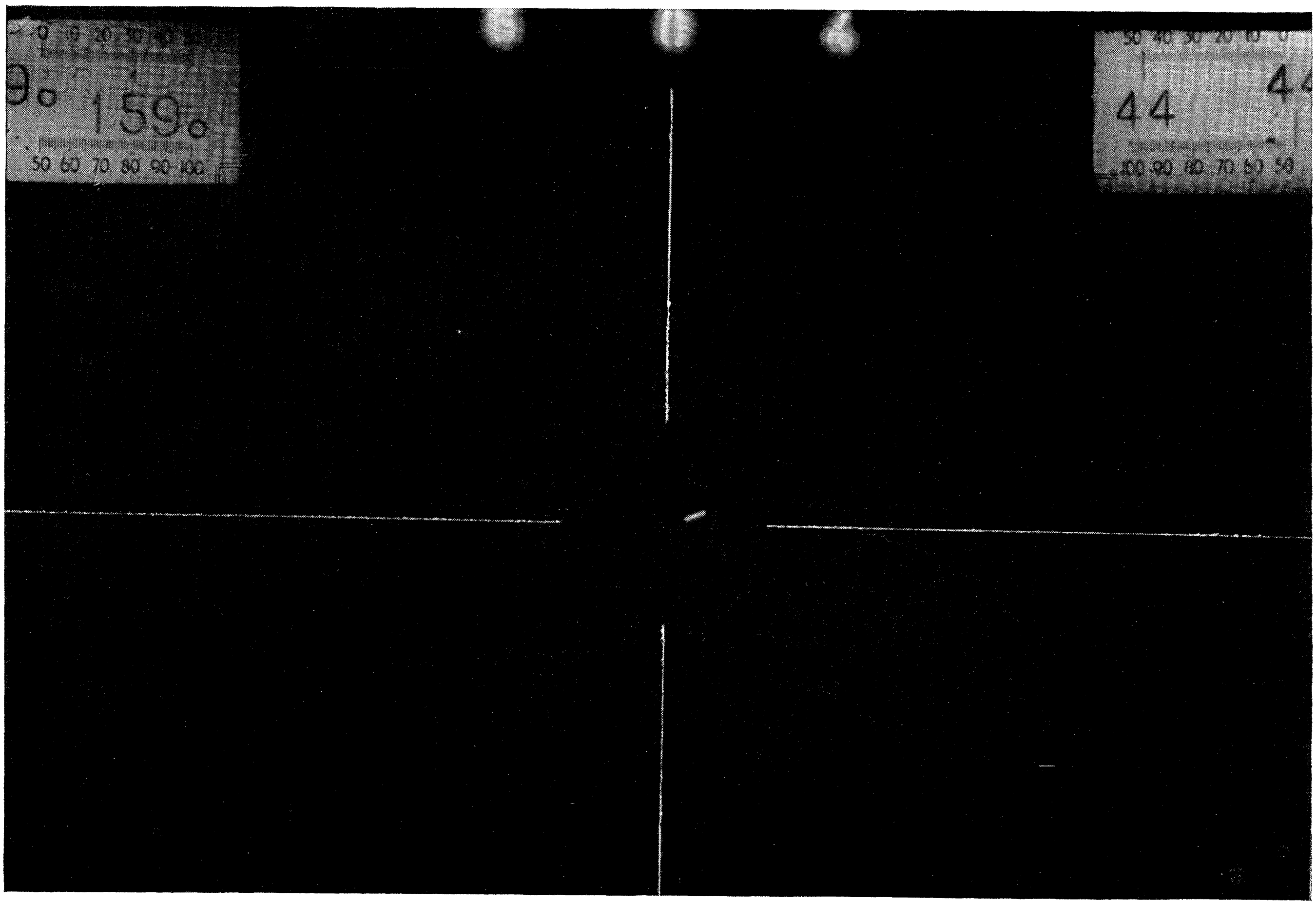

FIGURE 2

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2. Early satellite tracking by kinetheodolites

When the first artificial Earth satellites were launched, in 1957, there was a lack of instruments suitable for optical tracking. Kinetheodolites were obvious possibilities, however, and they were quickly brought into use in the United Kingdom, in the United States of America, and probably elsewhere also.

In the U.K., observations of Sputnik 2 were made at several Royal Aircraft Establishment ranges. Details of the observations were reported by Merson & Nuttall-Smith (1959); a more general description of the work has been given by King-Hele (1961).

For this early U.K. work two temporary modifications were made to the kinetheodolites. First, because satellites were fainter objects than the rockets, bombs, and aircraft on which kinetheodolites had previously been used, it was necessary to increase the exposure time on the object and to use the fastest possible photographic emulsions. This created problems for the observers operating the kinetheodolites, as it called for steadier movement of the tracking handles. Secondly, because satellites moved slower than the other objects and were therefore visible longer, it was found best to decrease the repetition rate from 300 to 60 frames/min or less. Attempts to record the satellite Sputnik 3 drew attention to two limitations of the kinetheodolite for satellite tracking: the aperture of the sighting telescope was too small for the observer to acquire and follow the satellite except when its visual magnitude was near its maximum (about +5); and the camera was incapable of recording any image except in the most favourable circumstances of satellite brightness and accurate tracking.

3. Kinetheodolites modified for satellite tracking

Following the early work by the R.A.E., arrangements were made for the development of kinetheodolite tracking by other U.K. establishments, using old R.A.E. kinetheodolites which had been rejected for range use. Initial modifications to the kinetheodolites to make them more suitable for satellite tracking were effected by the R.A.E. and some assistance in maintenance has been given to the operating stations from time to time. Three groups were set up successfully (after several delays).

(a) *Kinetheodolite Section, Meteorological Office*

(Site position: 35° 50·1′ N, 14° 26·5′ E, height 134 m)

Kinetheodolite 40/873 was received at the radio-sonde station on the airfield at Qrendi, Malta, in June 1960. The Kinetheodolite Section was set up in June 1960 with a staff of

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Description of plate 5

Figure 1. Kinetheodolite. This is the instrument at Earlyburn, with sighting telescopes of 95 mm aperture.

Figure 2. Frame of kinetheodolite film. The satellite image, slightly off centre, is of Echo 1, 1960ι1. On this occasion the instrument was left stationary and the length of the trail corresponds to the duration of the exposure. Azimuth (top left) reads 159·31° and elevation reads 44·47°.

two. Kinetheodolite 40/873 was replaced by 40/746 in December 1961. The staff was increased to four in January 1964. This group has concentrated on observation rather than instrumental development and has recorded well over 3000 transits of artificial satellites, mostly using the photovisual mode (see below). Most of the observations have been fully reduced.

(b) Satellite Section, Royal Greenwich Observatory

(Site position: 50° 52·1′ N, 0° 20·8′ E, height 38 m)

Kinetheodolite 40/872 was received at Herstmonceux Castle in March 1963. The Satellite Section was set up in October 1963 with a staff of three, plus two part-time observers. Some observations were made in 1963 during the training of the observers. The observing programme proper started in January 1964 and has continued up to now, though sometimes with reduced staff. This group has used mainly the normal (photographic) mode of observation. Over 1300 transits have been recorded. Not all the observations have been reduced yet. Several instrumental improvements have been made and considerable attention has been paid to prediction methods, including the production by computer of look data for all three kinetheodolite stations.

(c) Satellite Tracking Section, Royal Observatory, Edinburgh

(Site position: 55° 44·0′ N, 356° 46·3′ E, height 282 m)

Kinetheodolite 40/771 was received at the Observatory in March 1960. The Satellite Tracking Section was set up in October 1960, with a staff of two. The kinetheodolite was used at a temporary site during the winter of 1960/61, mainly for training of the observers. In the summer of 1961 it was transferred to the Observatory's Earlyburn Outstation, some eighteen miles south of Edinburgh. Early in 1963 kinetheodolite 40/771 was replaced by kinetheodolite 40/873. The staff was increased to three in October 1963 and to four in August 1964. This group has stopped observation on several occasions in order to concentrate on experiments with a view to instrumental development. Over 1500 transits have been recorded, nearly all in the photovisual mode. Not all the observations have been reduced yet.

Correspondence between these groups, occasional visits by members of one group to another, and two meetings of a Kinetheodolite Observers Committee have meant that improvements made by one group have been available to the others. The major modifications made to the kinetheodolites and to the techniques of tracking by the three groups are described below.

4. Kinetheodolite control unit

The kinetheodolites were originally designed to record frames on cine film at a repetition rate of 300 (or in some cases 240) frames/min. An early modification to the kinetheodolite made by the R.A.E. was to operate it through a control unit which reduced the repetition rate to 60 or 30 frames/min. The M.O. group has used the 60 frames/min rate and the R.O.E. group the 30 frames/min rate up to now. The R.G.O. group has designed and constructed another control unit. This provides a variable frame rate. Before tracking begins, a rate appropriate to the satellite concerned can be selected; this can be 60, 30, 15, 10, 6, 3, or 2 frames/min. The control unit also provides a variable exposure time. For the slower repetition rates an audible warning of the operating pulse is given. The unit has been more fully described by Grimwood (1965).

5. Larger sighting telescopes

The standard kinetheodolite sighting telescopes have an aperture of about 60 mm. With these it is possible to see satellites as faint as magnitude +8, but only in unusually good conditions. A need for improved light-grasp was soon felt. The R.O.E. group was able to obtain from the Royal Radar Establishment a pair of sighting telescopes of aperture about 95 mm. These were fitted to the kinetheodolite and have proved to be very satisfactory, enabling satellites as faint as magnitude +10 to be tracked. The R.G.O. group also fitted a similar pair of sighting telescopes and has improved the method of mounting to eliminate some of the difficulties found by the R.O.E. group.

6. Photoelectric recording

Experiments were performed by the R.O.E. group with a photomultiplier as satellite recorder in place of the kinetheodolite film. The photomultiplier was mounted behind a small hole and produced a signal only when light from a satellite or star passed through the hole. With the existing optical system of the kinetheodolite it was difficult to get any signal from objects fainter than magnitude +6. The size of the hole (which of course determined the positional accuracy of the arrangement) could not be reduced indefinitely and with the existing optical system the practical limit to accuracy was about 0·02°. To eliminate the effects of changing sky brightness, two holes were used, one on the optical axis of the instrument for the satellite and one well off-axis for the sky background. A chopping mechanism was used to switch rapidly from one to the other; the resulting alternating current from the photomultiplier could be more easily amplified and interpreted than a direct current. To have made this method effective on the satellites of magnitude +10 which were to be tracked would have required major optical modifications.

7. Photovisual mode

Kinetheodolites were designed primarily for daytime use. The optical system is not suitable for recording any save the brightest satellites. An object fainter than stellar magnitude +4 can be recorded on the film only by increasing the exposure time; and this calls for superlatively good tracking. If the images are very faint much time is required to find them on the film during film reading. The R.O.E. group found that if the tracking had been fairly good it was possible to obtain satisfactory results by ignoring the images completely and using only the scale readings. The accuracy of this mode was given as only 0·1° by Veis (1963) but the R.O.E. group have shown that the accuracy is much better than that. The time required for film reduction is less than if images are measured.

This mode of using the kinetheodolite has become known as the photovisual mode (in distinction to the photographic mode, in which the object being tracked is photographed and the tracking error can be measured on the film). A small modification to the camera allows the film to be used twice (an economy devised by G. A. Ramsden of the R.O.E.

group). An important feature of the photovisual mode is that the film is not essential; if another method of recording the scales could be introduced, the central camera would be unnecessary.

The M.O. group adopted the practice of reporting the scale readings as they were, omitting those which obviously suffered from bad tracking errors. A method of marking the bad values was devised (by R. J. Adams of the M.O.). A push button was mounted below the elevation sighting telescope; when this was pressed (by the elevation observer) the lamp illuminating the elevation scale was switched off. If the observer lost sight of the object being tracked because of cloud, faintness of the satellite, etc., the lamp was switched off till good tracking could be resumed. This indication of bad tracking usually started one or two frames too late, but this could be allowed for in the reduction.

The R.O.E. group has investigated various methods of smoothing all the values. The present data-reduction procedure is tedious but does not require any special skill on the part of the person performing the reduction. Although at present the smoothing procedure requires several man-hours per transit, the method could be programmed for a computer. As it is comparatively easy now for a kinetheodolite to record as many as 50 transits in one night, speedier data reduction is an obvious requirement.

Visual observations, in which the observer notes by eye the position of the satellite with respect to the background stars and records the time by means of a hand-operated stop-watch, are limited in accuracy mainly by the observer's personal reaction time and its variations. The effect of any given inaccuracy in timing is clearly proportional to the satellite's apparent velocity. In a kinetheodolite the background reference is not a star field but the graticule in the eyepiece. If the tracking is fairly smooth (that is, if the observer is turning his handle steadily) and if the rate is approximately correct, then the satellite's observed velocity with respect to the graticule is very low. The observer's reaction time errors are therefore much less significant than when the background reference is a star field.

The R.O.E. group has experimented with the use of a tape recorder for comments made by the observers during the kinetheodolite run. When the lamps illuminating the scales are flashed, a sharp 'click' is heard, followed about a tenth of a second later by a 'clunk', which is the noise of the film wind-on mechanism. The observer notes where the satellite was in relation to his cross-wire at the moment of the click. Before the next click, which comes 2 s later, he says whether his cross-wire was ahead of the satellite or behind it and by how much, using 0·01° as the unit. There is a gap in the cross-wire which is 0·10° wide and it is fairly easy to use this to assist in estimating short distances from the centre of the graticule with an accuracy of about 0·01°. The record of the satellite transit then consists of three items: (1) an observing record sheet which relates each frame number to a known time of the clock and so to any standard time with which the clock is compared; (2) the length of film with its numbered frames, each bearing an elevation value and an azimuth value; (3) the tape with the click-clunk of each frame being recorded and also the observer's comments on the tracking accuracy. The reduction procedure involves the correction of elevation and azimuth values for instrumental errors and refraction, and the smoothing of these values using the taped comments to remove the effect of tracking errors; a detailed description has been given by McInnes (1966*b*).

8. Calibration

Instrumental corrections for the kinetheodolites used on bombing ranges are normally obtained by means of observations of terrestrial reference objects of known azimuth. Star observations may be used, as described by Marchant (1964). Because the satellite tracking kinetheodolites are used at night, star observations are always used, along with observations of terrestrial reference objects. The addition of the improved sighting telescopes at R.O.E. and R.G.O. has introduced additional instrumental errors; a description of the calibration procedure has been given by Russell & McInnes (1966).

9. Positional accuracy

The scales of a kinetheodolite can be read to about 0·003° (10″). The various instrumental corrections can be made to within that accuracy. This leaves the tracking error. In the photographic mode this is measured; for good images it is usually possible to claim a standard deviation of about 0·003° for elevation, 0·003° sec$E$ (where E is the elevation) for azimuth. For the photovisual mode, the tracking error is eliminated by the smoothing procedure. The R.O.E. group uses 0·01° as the unit of measurement and thereby limits the accuracy. For a well-tracked object with good taped comments a standard deviation of 0·01° is usually claimed.

It is, of course, the residuals resulting from orbital determination which are the real test of accuracy achieved. The residuals so far announced for kinetheodolite observations support the estimates of accuracy made by the observers. For example, a recent orbital determination by Scott (1966) used 40 photovisual observations by the R.O.E. kinetheodolite and the mean a.b.c. residual was 0·007°; (a.b.c. stands for 'average in best conditions', and is the arithmetic mean of the best 70 % of the residuals of the observations from one observing station). The same determination used 22 observations (mainly photographic) by the R.G.O. kinetheodolite, giving a mean a.b.c. residual of 0·008°. The accuracy achieved depends to some extent on the apparent angular velocity of the object being tracked and poorer accuracies are to be expected on faster-moving satellites.

10. Timing accuracy

The greatest observed angular velocity is about 2°/s. The positional accuracy likely to be achieved on such a fast satellite with a kinetheodolite, in the photographic mode, is about 0·01° or worse; for the photovisual mode it may be about 0·04°. The timing error which is equivalent to a positional error of 0·01° is 0·005 s and for 0·04° it is 0·02 s. The time of each scale flash is therefore required with an accuracy of, say, half these values, that is about 0·002 s for the photographic mode and 0·01 s for the photovisual mode. Most satellites tracked by the kinetheodolite are moving much more slowly, a typical speed being 0·3°/s. The timing accuracy required is correspondingly less. The R.G.O. group uses Observatory time pulses. (As the R.G.O. is responsible for the nation's time service, including the standard time signals broadcast by MSF Rugby, these pulses are highly accurate and are constantly rated in terms of a large number of broadcast signals and in terms of star transit observations.) The R.O.E. group uses a small crystal chronometer rated against broadcast time signals. The time of the chronometer can be converted to MSF Rugby and so to UT 2 or any other time system with an accuracy of 0·005 s or better, except on rare occasions when it has been impossible to obtain good broadcast signals for a period of several days. The M.O. group uses a system similar to the R.O.E. one. In general, the accuracy of a kinetheodolite record from any of the three stations is limited in position rather than in time.

11. Advantages of kinetheodolites

While no instrument is ideal and there is an obvious case to be made for other optical satellite tracking instruments, there are some advantages of the kinetheodolite which are worth detailing.

(a) *Divided circle reference system*

Because the position of the satellite is measured by reference to the instrument's own divided circles, it is not necessary to be able to record the star background. This means that, provided the object being tracked is bright enough to be seen by the observers, accurate measurements can be made in bright moonlight, twilight, or even daylight. The R.O.E. group has successfully recorded more than a dozen satellite transits at times when the depression of the Sun below the horizon was less than 10°. For example, Polyot 1 (1963–43A) was tracked on 1 December 1965 at 16 h 43 min UT, when the sun was only 7·4° below the horizon; the observers estimated its magnitude as +5 steady. It has been estimated by McInnes (1966*a*) that kinetheodolite tracking of the brightest artificial satellites is possible even in daylight.

(b) *Speedy re-setting and complete freedom of movement*

The pointing direction is very easily and quickly changed and the track followed is not constrained in any way. This means that if a prediction is discovered to be wrong, a correction can be immediately applied. This is very important when observations are being attempted of an object near decay, which is likely to be bright enough for acquisition by the unaided eye but which may well pass several degrees away from the predicted point. It frequently happens that two objects are expected at the same time but with such doubt in the predicted times that either may come first. In this case, a watch can be kept for both objects with binoculars by the two observers and the kinetheodolite used first for the object which comes earlier and then also for the later one. On a night with a great deal of cloud, when the clear areas of sky are changing position rapidly, the predicted satellite path can be scanned and the record made at any cloudless part. On occasion satellites have been tracked successfully through thin and patchy cloud when stars were visible only for the briefest intervals. It also means that an artificial satellite acquired unexpectedly can be tracked (if the observers so decide) as easily as if predictions had been prepared. As has been shown by Eberst (1966), the data given by the kinetheodolite record are particularly suitable for the calculations leading to identification of the object.

(c) *Altazimuth mount*

There are certain advantages in an altazimuth mount. Most satellite prediction methods give the path of the satellite in altazimuth coordinates, an extra calculation being required to give right ascension and declination. The effect on the position of the path if the satellite is late or early is easier to visualize in altazimuth. Any altazimuth instrument can be set up at any site, which is not the case for mounts related to declination and therefore to latitude.

(*d*) *Human eye as receptor*

Because the observer is watching the satellite as the transit is recorded, its visual characteristics can be studied (comments being conveniently recorded on tape with the click-clunk of the camera motor providing a time reference). The importance of visual characteristics for discrimination between objects in similar orbits, for detection of changes in spin rate, and for other such purposes has been emphasised by King-Hele (1964). The system of telescope plus human brain is an extremely powerful one in several respects. A 95 mm aperture telescope and a dark-adapted eye can detect a satellite of magnitude +10, which requires something like the 600 mm aperture *f*/1 system of the Hewitt camera for photographic recording. The eye very quickly adapts to different levels of background sky brightness, which pose difficult problems for both photographic and photoelectric systems. By noting the direction and speed of movement, the brightness, and the flashing characteristics, if any, the human observer can usually quickly appreciate whether the object acquired at any given point is in fact the predicted object or another satellite which has happened to cross that point at the predicted time. To make an automatic system able to discriminate in this way is very difficult.

(*e*) *Cost*

The capital cost of a kinetheodolite observing station is small compared with that of other types of observing station achieving similar results. The running costs are at least as low as for comparable stations. The kinetheodolite is therefore a suitable instrument for a network. The importance of a well-constructed network of observing stations for general orbital studies is being increasingly realized.

(*f*) *Potentiality for automation*

A major problem with nearly all optical tracking instruments is the time and human effort required for data reduction. There is an obvious need for more automatic instruments.

Those involved in kinetheodolite tracking have been concerned about this for some time; see, for example, suggestions by McInnes (1964). It is considered that a satisfactory solution to the problem would be provided by the construction of an instrument similar to the kinetheodolite but with digital readout of the elevation and azimuth scales. Manually controlled variable-speed motors should give smoother tracking. An elaborated version of the M.O. group's push button mounted near each sighting telescope could replace the tape recorder and allow each observer's estimate of offset to be recorded in the same form as the digital readout of azimuth and elevation. The R.G.O. group's control box would suit this system very well.

The author is grateful to his colleagues in the Royal Observatory, Edinburgh, and in the other kinetheodolite groups for many stimulating discussions of the matters dealt with in this paper.

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FIGURE 1

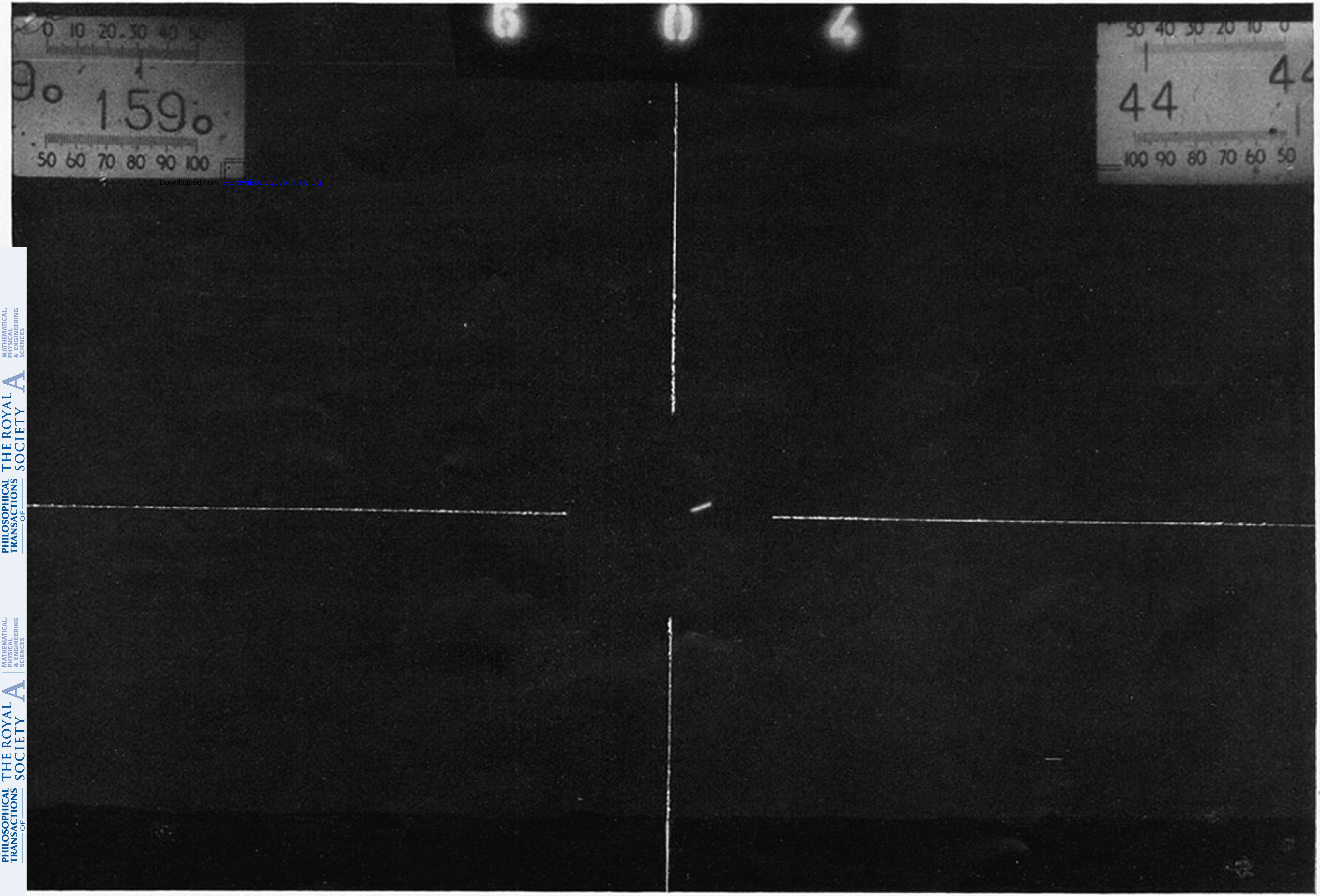

Figure 2

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES