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

Review of Tracking Methods

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I. TRACKING

Review of tracking methods

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[Plate 1]

This paper offers a rapid and superficial survey of the main methods for tracking close Earth satellites, with comments on their virtues and limitations.

1. Introduction

The methods of tracking close Earth satellites can be divided into three main groups: radio, radar and optical. All three methods have their merits and defects, and each can sometimes outdo both the others; so, on the whole, they complement each other and are not in cut-throat competition. Consequently we can expect that all three will continue to be used.

The main virtue of radio tracking is that it offers an attractively reliable method which is independent of limitations of weather and daylight. It has a serious defect, however: it cannot function unless satellites cooperate by sending out radio signals, and in fact only about 5% of satellites now in orbit are transmitting. So radio tracking is a privilege only enjoyed by a small minority of satellites.

Radar, on the other hand, does not need either the satellite or the weather to cooperate: it is the most self-sufficient form of tracking but also by far the most costly, because massive equipment is needed if small satellites are to be observed. Also even the largest radar cannot compete with optical methods in directional accuracy.

The great virtue of optical methods is that observations of good directional accuracy can be obtained with relatively little trouble and expense, and the main defect is, of course, that daylight or clouds ruin the observations.

I shall discuss each of the methods in turn, beginning with the radio techniques.

2. Radio techniques

2·1. *Radio interferometer*

By far the most popular types of radio tracking are the interferometer and Doppler methods, and these are the only two I shall discuss. The interferometer merely measures the phase difference in the radio waves from the satellite arriving at two dipole aerials at a known horizontal distance apart, and this gives the elevation angle of the satellite in the vertical plane through the aerials. Two sets of aerials, one in a north/south and the other an east/west line, define the satellite's direction completely. The accuracy of an interferometer is limited mainly by distortion of the radio waves in the ionosphere and the best accuracy is obtained by using a fairly high frequency. The scientific satellites launched by

N.A.S.A. usually carry a radio transmitter operating at a frequency near 136 Mc/s, and all these satellites are as a matter of routine tracked by the world-wide network of some twelve Minitrack interferometer stations, placed so as to give reasonably uniform coverage of the world. A description of the operation of a Minitrack station, the one at Winkfield in England, is given by H. G. Hopkins (this volume, p. 46).

Minitrack observations have been frequently used in orbital analyses, and their directional accuracy has turned out to be between 1′ and 2′, although the instrumental accuracy would suggest that a much better accuracy than this might be achieved (see R. H. Gooding, this volume, p. 79). These Minitrack observations yield very good orbits, however, chiefly because of their excellent orbital coverage, which comes from the world-wide distribution of the stations and their immunity to daylight and cloud.

2·2. *Doppler method*

The Doppler method of satellite tracking depends upon the accurate measurement of the frequency of the signal received from the satellite and a very accurate knowledge of the transmitter frequency. The method is simple in principle. The frequency of the received signal is recorded as the satellite approaches and then passes away into the distance. The frequency is higher as the satellite approaches because of the Doppler effect and lower as the satellite recedes into the distance. The exact shape of the curve of the frequency against time depends on the orbit of the satellite, and if the frequency is measured accurately enough it is possible to deduce the orbit from the recorded frequencies. This method has been used with great success in U.S. Navy navigational satellites, and is described in detail by R. R. Newton (this volume, p. 50).

The Doppler method, like all radio methods, does run into trouble as a result of refraction in the ionosphere, but this can be largely overcome by using very high frequencies and also by using a number of frequencies which are multiples of one another. For example, the U.S. Navy navigational satellites often use the frequencies 54, 108, 216 and 324 Mc/s. By this technique the distortion due to the ionosphere can be detected and allowed for by comparing the results on the different frequencies.

The U.S. Navy system gives satellite orbits with extremely high accuracy. But the Doppler method can also be employed in a more primitive form for rather a different purpose—monitoring the transmissions from recently launched satellites. It is perhaps not widely realized how much can be done with quite simple equipment, and the example of the group at Kettering Grammar School, who monitor the signals from the Russian Cosmos satellites, deserves a mention here (see Owen 1965). They often succeed in detecting these satellites at the end of their first orbit after launch, and provide times of nearest approach during the daytime which allow the satellites to be observed optically on the first evening, before regular predictions are received.

2·3. *Radio tracking of space probes*

If radio signals from very distant satellites or space probes are to be received, the main requirement is for a large and sensitive aerial to detect the very weak signals. This meeting is concerned mainly with close satellites, so I shall not discuss this topic further. However, to repair this omission, J. G. Davies (this volume, p. 67) describes the tracking of the Russian Luna satellites with the Jodrell Bank radio telescope.

3. Radar techniques

The basic radar method consists of having a large dish which sends out radio waves in a very narrow-angle beam and detects the small fraction of them reflected from the satellite. The angular accuracy of radar is not likely to equal that obtainable by optical methods, but of course the satellite's distance and rate of change of distance can be measured, as well as the direction. The 45 ft. satellite tracker at the Royal Radar Establishment, Malvern (figure 1, plate 1), operating on a wavelength of 10 cm, is the major radar of this type in Britain and W. A. S. Murray (this volume, p. 41) gives a more detailed account of its work. The N.A.S.A. deep-space network has 85 ft. dishes in U.S.A., Australia, South Africa and elsewhere. These are used mainly for tracking space probes, but they are converted into radars at times.

The U.S. Air Force radar network is, as far as I know, the only one which tries to keep track of all satellites in orbit. All the methods used by the U.S. Air Force are not made public, but several of their sensors are of the same type as the Fylingdales early-warning station in Britain. The main purpose of this radar is to track ballistic missiles rising over the eastern horizon. Satellites are also detected if they are large enough, though they will usually be disappearing over the horizon, as they travel from west to east.

Radar is vital to any comprehensive surveillance system because it is not upset by daylight or clouds and can keep a continuous check all round the clock. However, radar has several defects. The first of these is its cost. To detect and track satellites visible in 7×50 binoculars costing about £20 you need a radar with a dish at least 40 ft. in diameter costing perhaps £200000 and requiring quite a large staff to run it. The second defect is that the radar's performance deteriorates rapidly with increasing distance because of the fourth-power law. So it is much better for low satellites than for very distant ones. Another limitation is that some constructional materials are almost transparent to radio waves of the wavelengths used, and satellites made of materials like fibreglass are very difficult to detect. The fourth trouble is that the directional accuracy can never approach the standard achieved by cameras, and the fifth difficulty is that most radars require very accurate predictions, because the beam is so narrow, whereas with a camera or visual observations the field of view can be quite wide, perhaps 10°.

In view of these limitations it is obviously a good idea to try to combine the virtues of radar and the radio interferometer. For this the requirements are: (1) a very powerful transmitter of radio waves; and (2) very sensitive aerials which pick up the reflected rays and indicate the direction. The transmitter and the receivers can, however, be physically quite separate and need not look like a dish at all. This is the system adopted by the U.S. Navy in their Spasur network (King-Hele 1966). There is a series of transmitting stations in an east/west great circle across the southern United States near latitude 33° N, and the reflexions from satellites are picked up at four receiving stations, each like an ordinary radio interferometer station. The transmitter has a very flat fan-beam, less than 1° wide in the north/south direction but with a very wide east/west spread, so that the beam serves as a fence which any satellite must cross. As it crosses, it reflects some of the radiation and if more than one of the interferometers obtain a measurement of the satellite's direction, its position over the Earth can be found from the intersection of the lines from the two stations. This is another of the important sources of information for the U.S. Air Force's Space Detection and Tracking Organization.

To sum up radar, then, we might say that it is expensive and beyond the reach of most purely scientific organizations. But it is indispensable to surveillance, and the scientists engaged in orbital analysis are greatly indebted to the U.S. Air Force for keeping track of all the satellites and sorting out the pieces of debris, which might otherwise have caused great confusion; and also for making available predictions and orbital information which greatly help the scientific tracking organizations.

4. Optical techniques

4·1. *Introduction*

Optical tracking differs in its techniques from radio and radar tracking, partly because of the difference in wavelength, but also because most of the Sun's energy is emitted as light. Sunlight has dictated the whole course of biological evolution, not only through its control over climate but also because it has made us develop eyes rather than aerials in our heads. Since sunlight is so strong we can detect even the tiny fraction reflected from a satellite to a particular eye or camera on the ground, provided the sky background is dark; so optical tracking does not have to rely on man-made radiation, like radio and radar.

However, reliance on sunlight does mean that optical observers are troubled by the presence of the Earth's shadow. If the sky has to be dark, the shadow height above the observer must be at least 100 km; and of course if the satellite has to be illuminated, the shadow height must be less than the satellite's height. For a satellite at a height of say 400 km, there is usually only an hour or an hour and a half during the evening when it is suitably placed for observing, and this generally means that only one transit per evening can be observed optically, unless the satellite is well above 500 km. The situation is, of course, even more difficult with low satellites at 200 km height. As a result of these limitations there are usually only two quite small arcs on the orbit where the satellite can be observed optically. This means that the coverage of the orbit is often rather poor with optical observations.

These are the main difficulties and disadvantages. However, most scientific work on orbital analysis has been done with optical observations, because they can be quite easily made, and because they can also be very accurate.

I shall describe first photographic and then visual techniques.

4·2. *Photographic methods*

4·2·1. *Possible techniques*

Photographic tracking is simple enough in principle. The camera is designed to record on photographic plate or film both the image of the satellite and the images of the stars among which it passes. The exact direction of the satellite can be found by measuring its distance from several of the reference stars on the photographic plate.

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FIGURE 1. The 45 ft. diameter satellite tracking radar at the Royal Radar Establishment, Malvern. (Reproduced by permission of the Controller, H.M.S.O.)

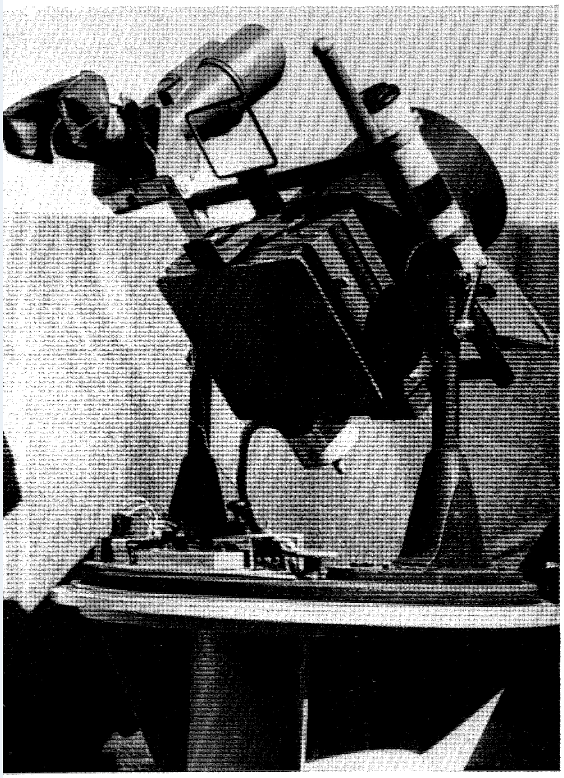

FIGURE 2. The Russian NAFA 3C/25 camera, much used for satellite tracking. The aperture is 10 cm.

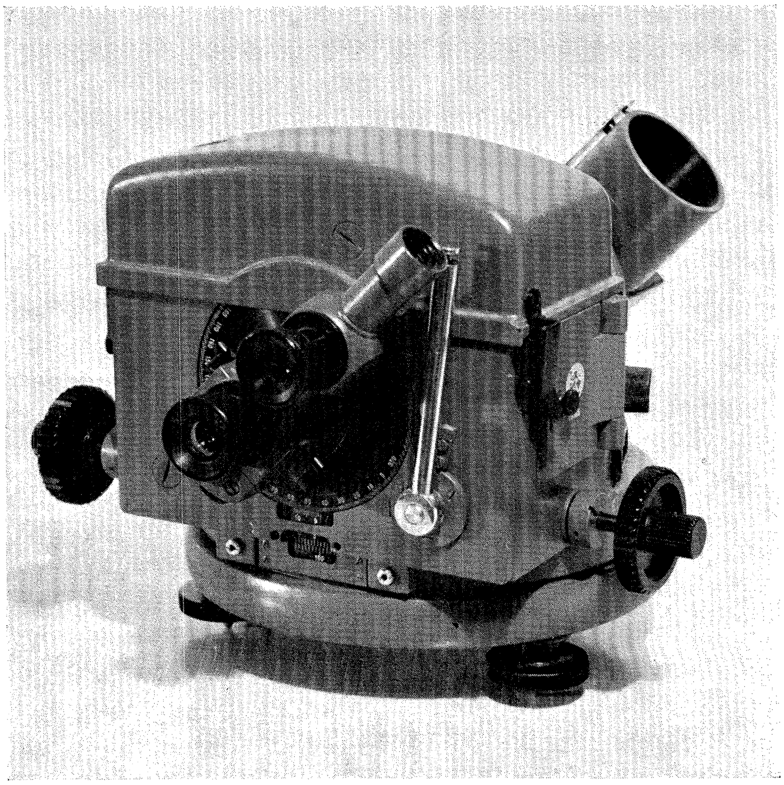

FIGURE 3. One of the theodolites used for satellite tracking at Jokioinen, Finland.

(*Facing p.* 8)

In practice there are several choices of system (Veis 1963). The first method is to operate with the camera stationary. The stars then trail slowly across the field of view, at not faster than $\frac{1}{4}$°/min, while the satellite moves rapidly across, at perhaps 20°/min. The trails of the satellites and stars may be broken perhaps two or three times by shutters, so as to yield time and positional observations at two or three points on the track. The second method is to make the camera follow the stars, which will then appear as dots while the satellite track is a broken line.

A possible snag with both these methods is that the track of the satellite may be very faint, unless the camera is an extremely large one. So another procedure is to follow the satellite and to allow the stars to trail. This demands a more elaborate mounting for the camera, but it does allow much fainter satellites to be observed.

To obtain the best of both worlds the camera can be made first to follow the stars and then to follow the satellite. This 'oscillating' mode of tracking can be (but rarely is) used by the Baker-Nunn cameras.

4·2·2. *Baker-Nunn cameras*

The Baker-Nunn satellite tracking cameras developed and used by the Smithsonian Astrophysical Observatory have made a dominant contribution to the optical tracking of satellites, and F. L. Whipple & C. Lundquist describe their recent work (this volume, p. 14). The Baker-Nunn camera has an aperture of 50 cm and can photograph satellites down to a magnitude of about 12 with a directional accuracy of about 4″. These are the 'precisely reduced' observations: 'field-reduced' observations, which are read off by the camera crews, are also widely used, and have an accuracy of 1′ to 2′ (D. W. Scott & D. H. D. Warren, this volume, p. 111).

A network of 12 Baker-Nunn cameras has been operating since 1958 and the number of observations obtained, chiefly of faint satellites in long-lived orbits, has averaged about 5000 per month in the last two years. Timing is by a crystal clock, giving an accuracy of about 2 ms and the field of view is 30° along the satellite's track and 5° perpendicular to it.

4·2·3. *Hewitt cameras*

The camera developed by Hewitt at the R.R.E., Malvern is similar in several respects to the Baker-Nunn camera, but it is not a tracking camera; so the mounting is simpler but it is not possible to record such faint satellites. The aperture is 61 cm, greater than the Baker-Nunn, and there is a field-flattening lens near the focal plane so that the images are reflected on to a photographic plate and not on to a film. The Hewitt camera can observe slow-moving satellites down to a magnitude of about 10 or fast-moving satellites down to a magnitude of about 7. The accuracy of the camera is about 1″, and is better than the Baker-Nunn because it uses a glass photographic plate instead of a film, which is not free from distortion. There are two of these cameras, one at Evesham and one at Edinburgh; their work is described by J. Hewitt (this volume, p. 26) and a photograph of one of the cameras is given as figure 1 of his paper.

4·2·4. *Small cameras*

There is no essential difference between the large cameras just described and many types of smaller camera used for satellite observation. The smaller cameras usually depend on lenses rather than on mirrors, and having smaller apertures they cannot record such faint satellites. One of the most widely used small cameras is the Russian NAFA 3 C/25 which has an aperture of 10 cm and a wide field of view (figure 2, plate 1). The accuracy is almost as good as can be obtained with the larger cameras (Massevitch 1961), but the satellites must be much brighter if they are to be recorded. Another widely used camera is the Minitrack optical tracking system which is installed at Minitrack radio tracking stations. This camera has an aperture of 20 cm and its performance is rather similar to the NAFA.

Various other small cameras have been developed, often with ingenious methods for improving performance by rocking or rotating the camera or photographic plate.

4·2·5. *Astronomical telescopes*

Satellites can, of course, be photographed with the aid of astronomical telescopes. The main difficulty is that these telescopes have very small fields of view, perhaps 1° in diameter. This difficulty can be overcome, however, as is shown by the work done by K. Fea (this volume, p. 200) with the 24 in. telescope at the University of London Observatory. These observations can be just as accurate as those from cameras designed solely for satellite photography.

4·2·6. *Kinetheodolites*

The cameras so far discussed depend upon measuring the satellite's position relative to the stars. The kinetheodolite, on the other hand, keeps its feet firmly planted on the Earth, and could operate even if a thick interstellar fog appeared and blotted out all the stars. In a kinetheodolite the satellite's direction is determined from the angle between its image and the cross-wires defining the axis of a small telescope. The direction of the telescope itself is measured relative to the Earth in terms of its elevation above the horizon and its azimuth direction.

Kinetheodolites are less accurate than large cameras but somewhat easier to operate and are capable of yielding a large number of observations on one transit if necessary, and also of observing fairly bright satellites in conditions when faint stars are not visible. The accuracy of a kinetheodolite is about 30″ in direction and 5 ms in time. At present there are three kinetheodolite tracking stations in the British network, at the Royal Greenwich Observatory, Herstmonceux, at the Royal Observatory, Edinburgh, and in Malta.

As well as taking photographs of the satellite, a kinetheodolite can be operated in the photo-visual mode to observe satellites which are too faint for their images to be recorded on film. The operators of the kinetheodolite keep the centre of the cross-wires pointing at the satellite and the satellite is assumed to coincide with the centre of the cross-wires. The accuracy is about 1′. These techniques are discussed in more detail by B. McInnes (this volume, p. 32) and a photograph of a kinetheodolite is given as figure 1 of his paper.

4·2·7. *Photocells and lasers*

There are other methods of optical tracking, which have so far not been of much importance statistically but may be in the future. The first of these is the use of photoelectric cells to detect the passage of a satellite across a shaped slit in front of the telescope

(Fea & Newton 1964). This ought to be a valuable method, but so far has not been much used.

Lasers are however very promising because they can combine the directional accuracy of optical methods with the range measurement of radar (Lehr, Maestre & Anderson 1966). Some difficulties have been encountered, however. The first main difficulty has been in providing the extremely accurate predictions required, and the second difficulty is that the satellite must be fitted with special corner-reflectors if the reflexions are to be detected, so that laser tracking is confined to a very small minority of satellites. However, these defects may well be overcome in future years.

4·3. *Visual methods*

4·3·1. *Theodolites*

Theodolites, like kinetheodolites, yield observations relative to the Earth, in terms of azimuth and elevation.

In its simplest form a theodolite is merely a small telescope mounted on a stand and with scales indicating elevation and azimuth. The observer watches the satellite, times it with a stopwatch at the moment when it crosses the intersection of the cross-wires in the centre of the field of view, and takes the reading of the scales at this time. Most visual observers find it better to make observations relative to the stars rather than using a simple theodolite, but there are some observers who use this method.

Much more satisfactory is the semi-automatic theodolite (Muller 1966), which is half way between a simple theodolite and a kinetheodolite. The observer has only to press a switch when the satellite is in the centre of the field of view. The dial readings are automatically recorded and a mark is made on some timing record. This is really just the same as a kinetheodolite in the photo-visual mode. A very great number of satellite observations have been made by the theodolite stations at Jokioinen in Finland and Meudon in France. The theodolites used have rather small apertures, 6 cm at Jokioinen (see figure 3, plate 1) and 7 cm at Meudon, and observations are usually made on the brighter satellites, though objects down to magnitude 8 can be observed quite readily. Their directional accuracy is about 2′.

4·3·2. *Observations relative to the stars*

The majority of visual observers, especially those in Britain, prefer to make observations relative to the stars. This is undoubtedly the simplest and cheapest of the methods of observation and can give good directional accuracy. The best observers achieve a directional accuracy of 1′ to 2′. The eye is also a very keen detector of light, so that with quite small 7×50 binoculars the visual observer can rival the large camera or the large radar in detection capability.

Almost every observer has a different method for visual observing, depending on his temperament, environment and the optical instrument used. Some observers, the majority perhaps, prefer to use binoculars, while others prefer telescopes. Some observers prefer to make one observation, while others prefer to make two or three observations per transit. All I can do is to try to give a rough picture of the typical procedure, with the proviso that there are wide variations between individuals. The first requirement in making visual observations, as in all other optical observations, is to obtain predictions of the satellite's track. These are provided in Britain by the Radio and Space Research Station (D. E. Smith, this volume, p. 100). Once the observer has predictions, he will usually plot the predicted track in a small star atlas, such as Norton's *Star Atlas*, and probably choose the region where he is going to make the observations, perhaps near some bright and easily recognizable star. For most visual observers their observing is a spare-time activity in the evening. For most of them it is a matter of going out into the back garden a minute or two before the satellite comes and training the binoculars or setting the telescope on a part of the sky where the satellite's track is passing.

The actual track of the satellite will probably differ slightly from the predicted track, and of course the predicted timing may be in error too. Observations are taken by waiting until the satellite passes a convenient pair of stars and estimating the point where it crosses the line between them, say seven-tenths of the way up from A to B. As the satellite passes this point the observer starts his stopwatch. Then if he has a split-action stopwatch, he can stop the auxiliary hand as the satellite passes another convenient pair of stars. After marking the position of the satellite roughly on the star atlas the observer goes in and stops the stopwatch against a time signal, very often in Britain the Post Office time signals, which can be obtained by telephone. The exact position of the satellite is then plotted in a large star atlas such as the Becvar Star Atlases, or calculated from star catalogues, such as the Smithsonian star catalogue. Fuller descriptions of the methods are given by King-Hele (1966).

Analysis of these observations (Scott 1967) has shown that the best observers achieve an accuracy of about 0·1 s in time and 1′ to 2′ in direction. These directional accuracies are similar to the field-reduced Baker-Nunn observations and the Minitrack observations, and are quite accurate enough to determine good orbits. The main snags about visual observations so far have been that there are not enough on any particular satellite and their poor coverage of the orbit, which is particularly bad in the southern hemisphere. Both these difficulties are now gradually being overcome.

Visual observers with 11×80 binoculars or 5 in. telescopes can see satellites down to magnitude 9 or sometimes 10, and larger telescopes allow observation of even fainter satellites.

Because they are so cheap and simple, visual observations also have about a dozen other uses (King-Hele 1966), ranging from satellite identification to re-entry patrols.

Many people think that a first-class knowledge of the stars is needed in order to become a visual observer. This is not so. I have been observing for many years, but I still cannot recognize more than about a dozen constellations and it is quite possible to work from star maps without ever knowing the names of any stars or constellations.

5. Conclusions

To conclude, I ought to provide some comparisons of the various methods. This is very difficult because the different methods have different virtues and defects, as explained earlier. The only reasonable comparison that can be made is of the accuracies, which are summarized in table 1, in probable order of decreasing cost. If we take a satellite at 1000 km height as typical, its rate of angular travel is about 20′ per second, so that 1′ is covered in 50 ms. The timing accuracy is therefore more than adequate for most of the instruments, but can be the main source of error in visual observations, especially with low satellites.

Table 1. Approximate accuracy of various methods

	directional (min of arc)	timing (ms)	range (km)
40 ft. radar	5	1	1
Minitrack radio	1 to 2	1	—
Baker-Nunn precisely reduced	0·06	2	—
Hewitt camera	0·02	1	—
Baker-Nunn field-reduced	1 to 2	2	—
kinetheodolite photographic	0·5	5	—
kinetheodolite photovisual	1	5	—
theodolite (semi-automatic)	2	10 to 100	—
visual, relative to stars	1 to 2	100	—

References (King-Hele)

Fea, K. & Newton, A. C. 1964 *Planet Space Sci.* **12**, 261–71.

King-Hele, D. G. 1966 *Observing Earth satellites.* London: Macmillan.

Lehr, C. G., Maestre, L. A. & Anderson, P. H. 1966 *Smithsonian Astrophys. Obs. Spec. Rep.* no. 211.

Massevitch, A. G. 1961 *Space Research II*, pp. 102–14. Amsterdam: North-Holland.

Muller, P. 1966 *Cospar Inf. Bull.* no. 30, pp. 15–20.

Owen, K. 1965 *Flight int.* **88**, 144–5.

Scott, D. W. 1967 *Planet Space Sci.* **15**, 775–785.

Veis, G. 1963 *Space Sci. Rev.* **2**, 250–96.

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FIGURE 1. The 45 ft. diameter satellite tracking radar at the Royal Radar Establishment, Malvern. (Reproduced by permission of the Controller, H.M.S.O.)

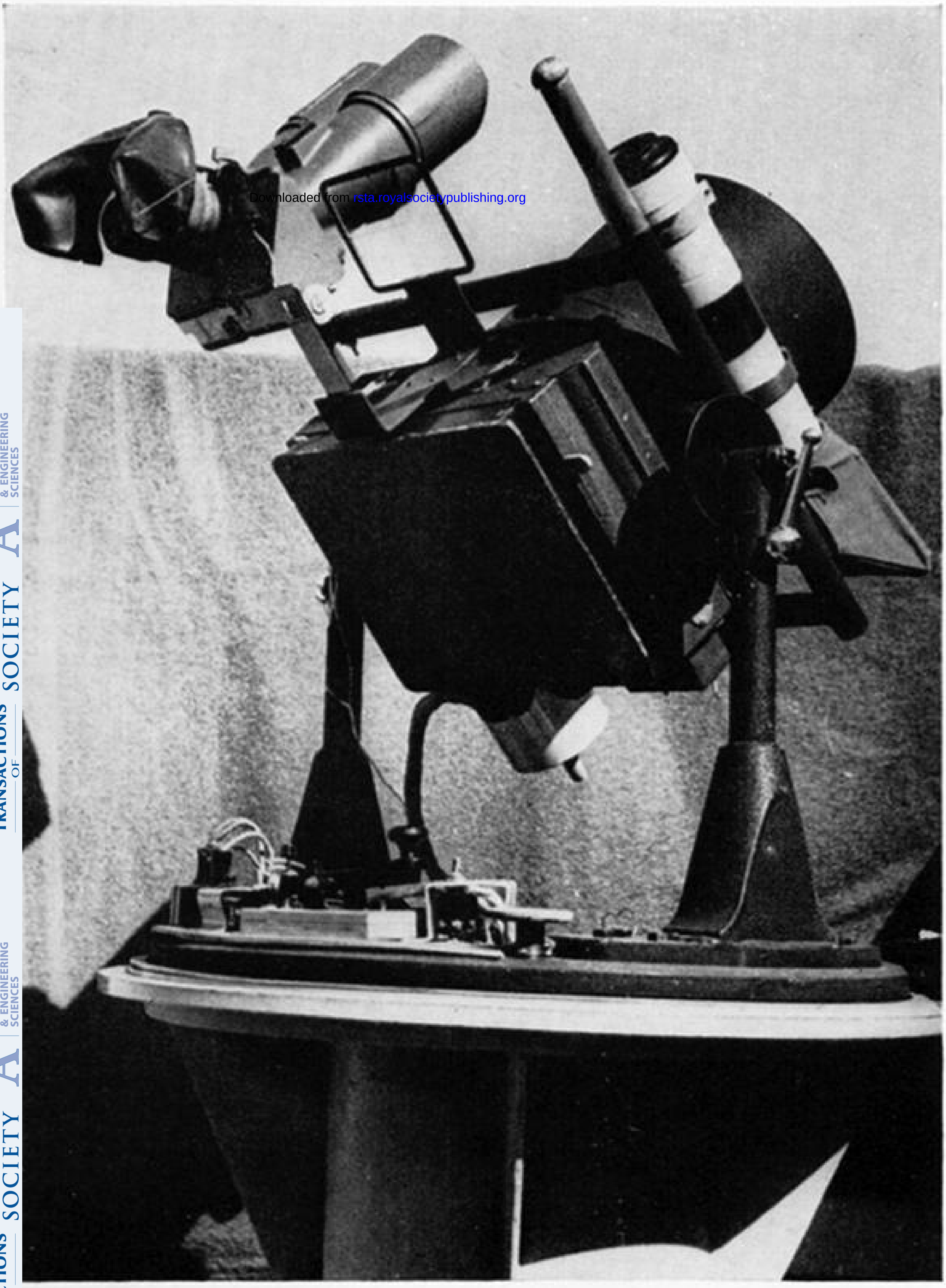

FIGURE 2. The Russian NAFA 3C/25 camera, much used for satellite tracking. The aperture is 10 cm.

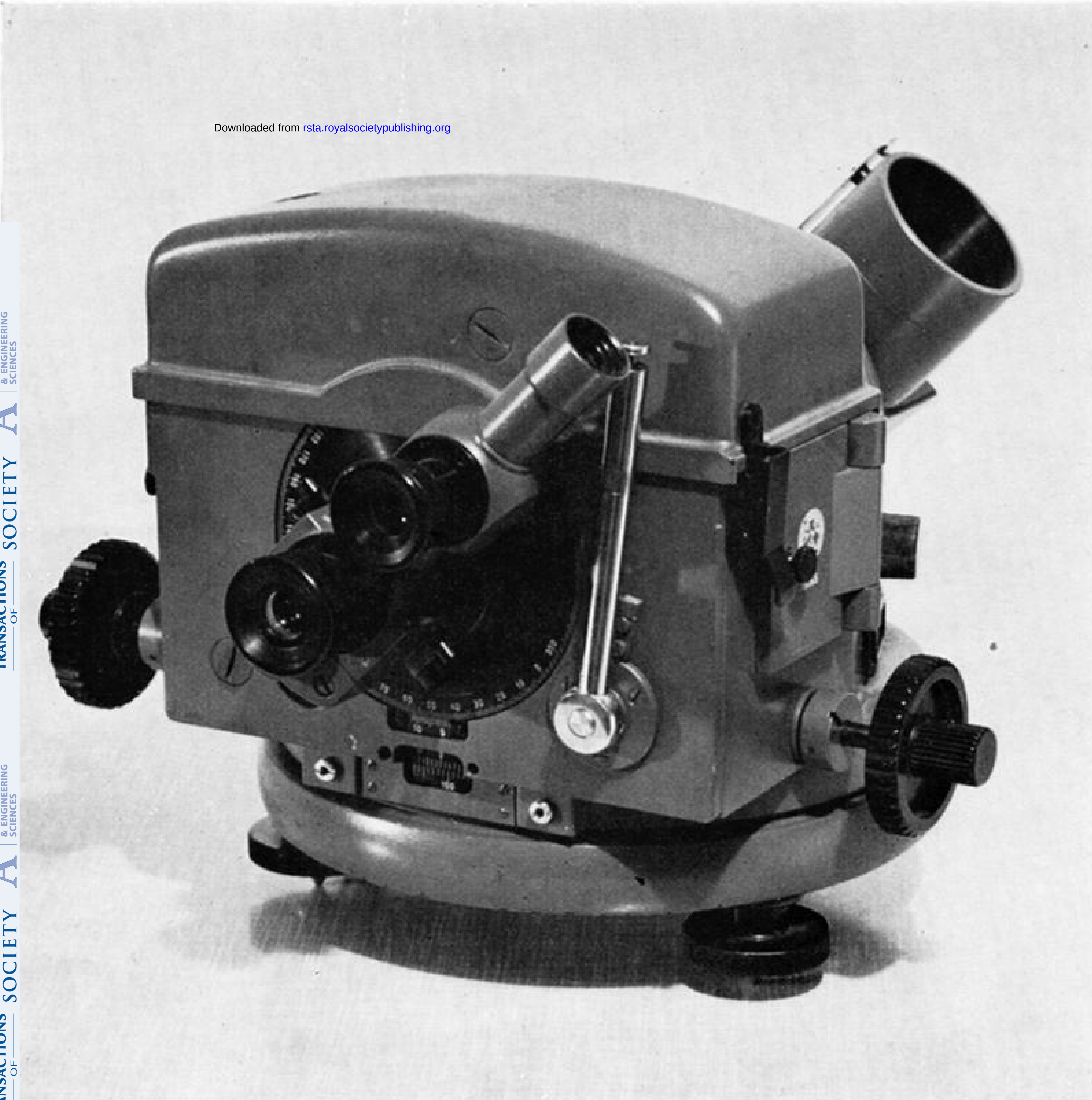

FIGURE 3. One of the theodolites used for satellite tracking at Jokioinen, Finland.