A Note on the Principle and Nomenclature of Heliostats, Coelostats, Siderostats

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A contribution of the Solar Section *Director: L. M. Dougherty*

The heliostat is defined and the reason for this study is given. After presenting the heliostat principle some practical arrangements are outlined and the important degenerate forms, the polar heliostat and the coelostat, are derived. The confusion of nomenclature and its relation to field rotation is discussed. Some notes on the utilization and the limitations of single mirror arrangements are concluded with a statement of the need for two mirror systems and a reference to the heliograph.

INTRODUCTION

The abundance of light from the Sun encourages the observer to use projection and dispersing apparatus of such size and weight that it cannot conveniently be mounted upon an equatorial telescope. To meet this situation sunlight is reflected by a plane mirror which is so mounted and manipulated that the reflected beam is fixed in direction. A mirror so used is, in general, called a heliostat. Special cases of importance within the heliostat family are the coelostat and the polar heliostat. These single mirror systems, and the name siderostat, are discussed below. There are some mechanical and optical limitations on the choice of the direction of the fixed reflected beam and, to bring it into the final desired direction, reflection at a second mirror may be required. By arranging that this beam coincides with the principal axis of the observing apparatus this latter can be stationary.

It is my personal conviction that the most desirable response to an enquirer is by reference to conveniently available publications which present the desired information in a suitable way. Library research shows that such publications do not exist to meet the enquiries about heliostats addressed to me in the office of Director of the Solar Section. That is the reason for this study. A modern illustrated discussion was given by Danjon and Couder[23] in 1935.

THE PRINCIPLE OF THE HELIOSTAT

The principle of the 'Heliostata' and a practical design were presented by Willem 'sGravesande in 1762[1]. Beautiful and very clear copper engravings of his invention are shown. His text is in Latin and, even after lifting the barrier of translation, his account is difficult to follow. The earliest account in English that I have found is Rees' *New Cyclopaedia* of 1810[2]. This too has excellent illustrations which appear to be free copies of 'sGravesande's originals.

Cornu[3] presents the principle clearly, concisely and in English. ". . . the heavenly body is regarded as a luminous point and the incident beam is regarded as a straight line which in 24 hours describes a cone around the polar axis of the instrument which is itself parallel to the Earth's axis. In order to secure fixity of the reflected beam it is necessary and sufficient that the normal to the mirror shall remain parallel to the bisector of the angle between the ray coming from the heavenly body and a given fixed direction." Figure 1 illustrates this principle. The trace of the mirror surface is denoted mm and its centre is M. The incoming ray is SM and it is reflected in direction MR which is, for convenience, shown horizontal in the figure but is not necessarily so. Further, it is emphasized that MR need not be in the meridian. PP′ is the polar axis and P′MR is arranged to be a straight line. P′L′ is an arm on the polar axis so jointed at P′ that it may be set and locked at the polar distance, p, of S. It then rotates once in 24 hours with the polar axis and,

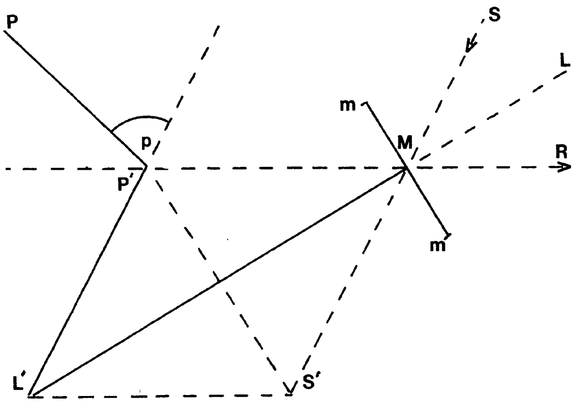

Figure 1. Diagram to show the principle of the heliostat. Notation as in text.

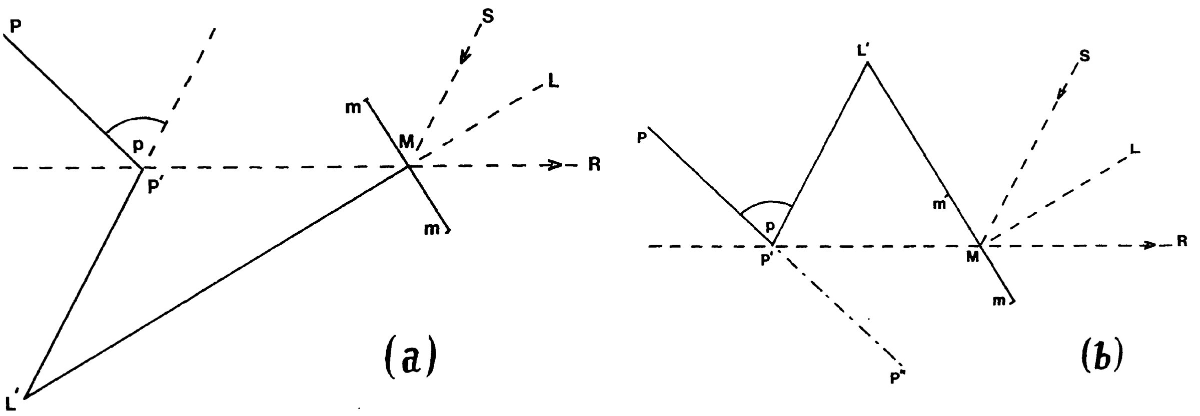

Figure 2. Diagram to illustrate (*a*) the underdrive arrangement of 'sGravesande's and Foucault's heliostats, (*b*) the overdrive arrangement.

being set initially in the hour circle of S, keeps L′P′ pointing at S. This implies that it is always parallel to S′MS. The mirror is free to rotate about two perpendicular axes in its plane, intersecting in M, and is so sited that P′M = P′L′. A sliding and rotating joint is contrived at L′. We see that P′MS′L′ is a rhombus and that LML′, a rod fixed normal to the mirror, is one of the diagonals. The diagonals of a rhombus bisect the angles through which they pass, so that L′ML bisects SMR thus meeting the necessary and sufficient heliostat condition.

Two practical arrangements are shown in outline in figure 2. Solid lines represent rods. Dotted lines and the labels conform to the presentation in figure 1. Foucault's form[4,5], called an underdrive type because of the position of rods P′L′ and ML′, is shown in figure 2(*a*). The corresponding overdrive type is illustrated in figure 2(*b*) with PP′, P′P″ and PP″ as alternative polar axes. These are the most useful heliostat arrangements for general work in middle latitudes, with the reflected beam directed into the hemisphere having the mirror at its centre and the Sun at its pole.

In passing we must credit Foucault abundantly for his two simple mechanical design features that made his heliostat so much more convenient than 'sGravesande's in construction and use. 'sGravesande had reset the observed declination by a crude mechanical device, at L′, which caused incidental alterations in length P′L′. To restore the equality P′M = P′L′, he made the polar drive and the mirror mount on separate moveable supports and used an auxiliary measuring rod in a somewhat awkward technique. During this adjustment it was necessary to maintain P′M in the required fixed direction. Foucault mounted all the parts on a common baseplate and changed the declination using a hinge joint, which could be locked, at P′. This assured the constancy of P′M = P′L′.

Drawings showing mechanical details of an underdrive heliostat at Mount Wilson and an overdrive type at Tucson are given by Pettit[6]. The heliostat designer should inspect these.

Figure 3 shows in outline two arrangements with the fixed beam directed into the hemisphere away from the Sun. Silbermann[7] realized the arrangement of figure 3(*b*) but his linkage was, of necessity, complicated. In general, these arrangements give large angles of inclination between the normal to the mirror and the incident and the reflected solar rays. This is undesirable as the distortion caused by surface imperfections of the mirror become great at such

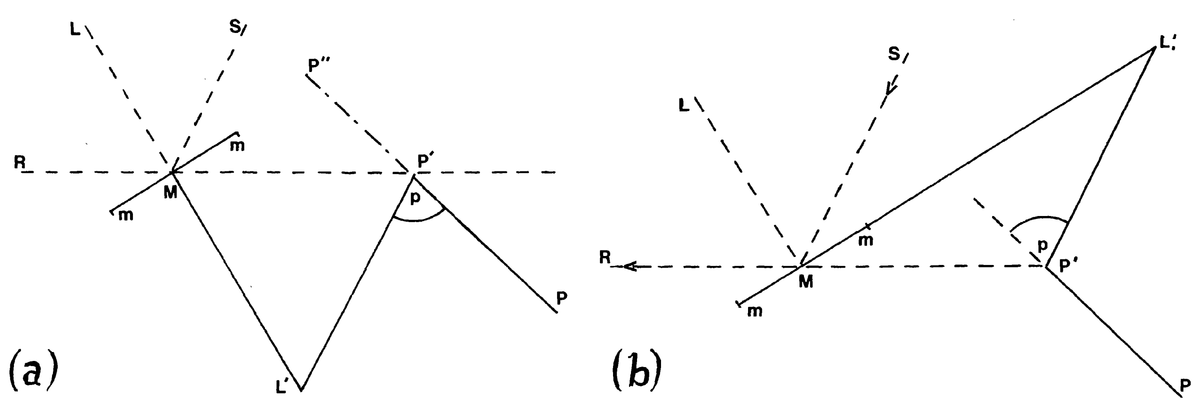

Figure 3. Diagram to illustrate (*a*) the underdrive and (*b*) the overdrive arrangement of Silbermann's heliostat.

angles. In general, the need to direct a final beam of sunlight into this hemisphere is best met by other arrangements which are discussed below.

ROTATION, DIRECTION AND NOMENCLATURE

The terms heliostat, coelostat and siderostat are much misused by interchange. Additionally it is not uncommon today for a coelostat and second mirror to be designed. The first paragraph of this paper, following 'sGravesande, defines a heliostat. Unfortunately the name is not well chosen because, except in the one special case of the coelostat, such mirrors do not make the Sun stand still! The centre of the field, M, as seen by the observer, remains fixed in direction RM but the rest of the field rotates about that axis. This means that the Sun's disk, seen in the heliostat, is rotating. To add to this difficulty the rate of rotation varies and in some cases reverses! Polar heliostats have a constant rate of rotation and the coelostat has zero rate. These are discussed below. A useful, but very mathematical, account of field rotation rates is given (in German) by Hartmann[9]. Very shortly after Foucault's death in 1868 it was reported[10] ". . . there exists, in the papers that he left, several sketches dated November 1861, and the name *siderostat*". These sketches showed a heliostat in the arrangement of figure 2(*a*). In 1900 we find Cornu[11] writing, "The well known instruments known as the heliostat and the siderostat. . . ." In the same paper he needs to define both of these instruments. I quote from his paper, "*Siderostat.* — This name is used to designate the apparatus specially constructed for the purpose of sending a reflected beam towards the southern horizon . . . *Heliostat.* This instrument sends the reflected beam in the direction of the northern horizon". Notice that he does not specifically define either instrument. This is understandable because by his implied definition 'sGravesande's heliostat was a siderostat! Cornu wrote this paper towards the end of a brilliant lifetime's work in optics. His writing was always elegant and precise. It is unlikely that he would use the words he did on this occasion without good reason. I speculate that his choice of words on this occasion arose from his very human desire to honour his countryman together with a reluctance to utter an illogical definition. A few years earlier Stoney[12], in an extensive note concerning heliostats, had referred to all those he mentioned, including 'sGravesande's, as 'siderostats'. Foucault's eminence had ensured the popular and confusing use of his nomenclature. Siderostat, which implies that a star, a point source, can be made to stand still would seem to be a more apt name. Nevertheless 'sGravesande, the inventor, chose heliostat and we must, as a proper courtesy to him, classify all devices with the same optical principle under that name. Sidgewick[13] (1955) partly repeats Cornu's definitions without comment and compounds the confusion by loose wording and inadequate statements. This is regrettable as his book is today commonly and conveniently available.

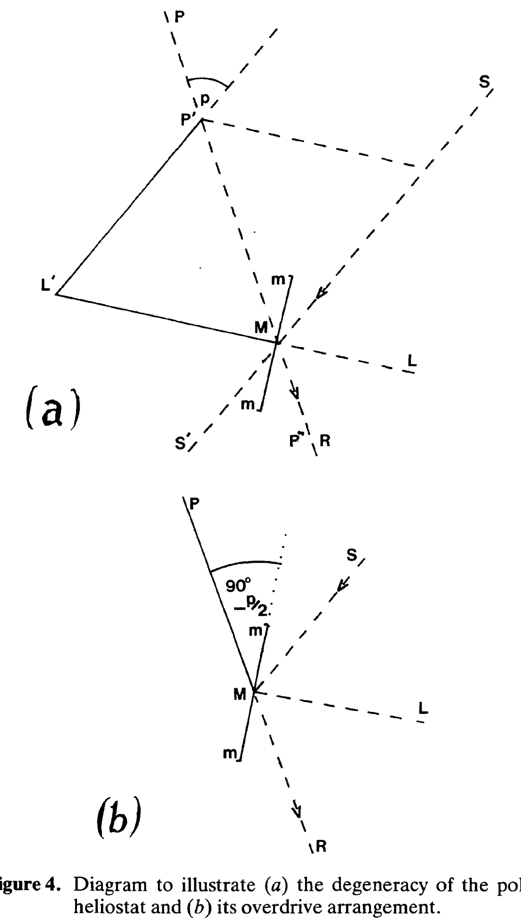

Figure 4. Diagram to illustrate (*a*) the degeneracy of the polar heliostat and (*b*) its overdrive arrangement.

POLAR HELIOSTATS

As the chosen fixed direction of the reflected beam is brought into parallelism with the Earth's axis the heliostat degenerates into a polar heliostat. Consider figure 4(*a*) SM is the incident and MR the reflected beam. The normal is ML which is produced to L′. P′L′ is erected parallel to SM and we see immediately that PP′ is collinear with MR. The design realization of this is to discard the linkage P′L′ and ML′ and fit the mirror into a fork on the end of the polar axis. This brings P′ into coincidence with M. See figure 4(*b*). A little consideration of the geometry and the optics shows that the plane of the mirror is inclined at an angle of $90°-p/2$ to that axis, where p is the Sun's polar distance. The reflected beam, DAR, is 'downwards', towards the observer's depressed pole. This is the overdrive arrangement. The underdrive arrangement is with MR 'upwards', towards the elevated pole. This arrangement should be drawn for middle latitudes, as an exercise for the reader, and the arrangement for an observer on the equator should also be considered. Notice that the parameters of the polar heliostat do not include the observer's latitude.

This is to be expected as the direction of the Sun is being referred to the Earth's axis, a line in a space, and not to the observer's horizontal co-ordinates.

The inclination of the beams to the normal to the mirror in figure 4(*b*) is $\frac{90^\circ + \delta}{2}$, so for the Sun the maximum and minimum values are 56°·75 and 33°·25. The larger of these values indicates that a mirror of good surface figure is required. This high inclination also foreshortens the effective aperture of the mirror so that the reflected beam is elliptical in cross section with a minor axis 5/9ths only of the diameter of the mirror. Similar values are associated with the arrangement having the reflected beam directed to the elevated pole.

The mechanical simplicity of a polar heliostat makes it particularly desirable. Further it has the optical property of a constant angular velocity of the field of view at one revolution per day[14].

THE COELOSTAT

Let us now choose to make the unused diagonal of the polar heliostat of figure 4(*a*), the normal to the mirror. We then have the arrangement of figure 5(*a*). As the diagonals of a rhombus are perpendicular to each other the normal to the mirror now moves in the plane of the equator and the plane of the mirror is parallel to the Earth's axis. L′O rotates about PP″ once in 24 hours and L′M = 2 L′O thus ML′ rotates once in 48 hours about a line parallel to PP″ through

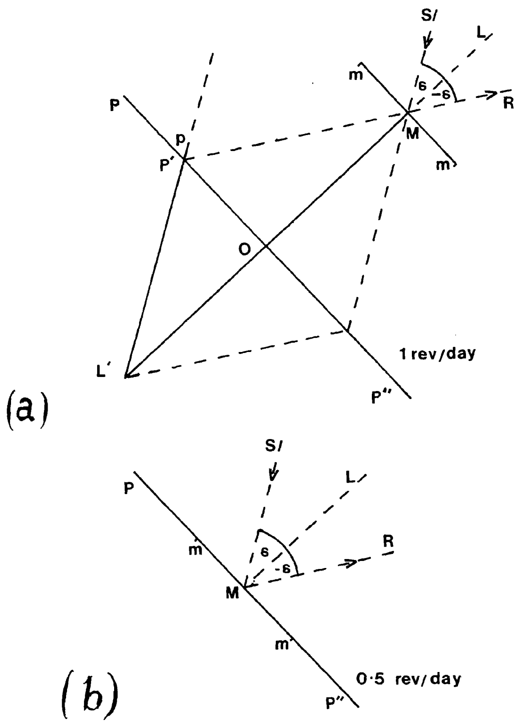

Figure 5. Diagram to illustrate (*a*) the degeneracy of the coelostat and (*b*) its arrangement.

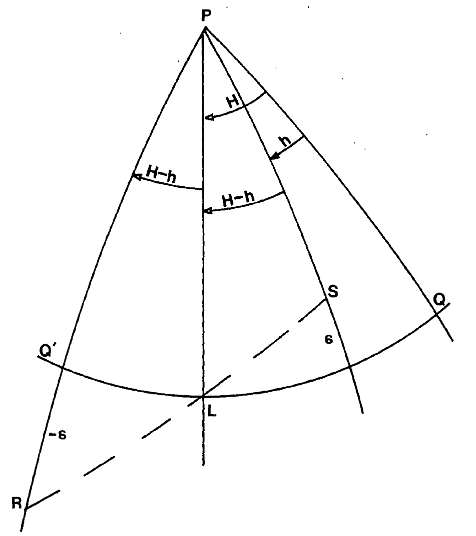

Figure 6. Diagram to illustrate the relation of the coelostat to the celestial sphere.

M. This apparatus can be mechanically simplified by discarding the linkages and moving the mirror, keeping it parallel to the polar axis until M coincides with O. PP″ then lies in the plane of the mirror. The polar axis must now be driven at one rotation in 48 hours. This is shown in figure 5(*b*). The great value of this arrangement of a heliostat is that, as shown by Lippmann[15] who introduced it, the field is non-rotating. Cornu[16] presents a mathematical discussion of this condition. The stationary field property led Lippmann[17] to name this arrangement the coelostat.

Figure 6 shows S, L and R on the celestial sphere, seen from the 'outside', as with a star globe. QQ′ is the equator, PM is the observer's meridian, and the hour circle, hour angle = H, of L is shown. We see by the elementary laws of reflection, that for the Sun's equatorial co-ordinates (h, δ), the co-ordinates of R become ($h' = 2H - h$, $-\delta$). We can set h' by a suitable choice of H but we have no control over the declination of R. To utilize the stationary field of the coelostat we must, in general, use a second mirror to reflect MR into the final desired direction. For a specific observation of short duration, such as photography of totality during a total solar eclipse, it may be possible to set the observing apparatus in such an altitude and azimuth that it receives the reflected beam direct from the coelostat mirror. This very special case is discussed by Smart[18].

SIMPLE HELIOSTATS

Veio[19] denotes heliostats other than those above as *simple heliostats*. This seems to be a misnomer. In general, the mathematics[20] and the practical realization of heliostats other than the three special cases discussed above, is extremely complex. McMath and Mohler[21], following Danjon and Couder, use the name *uranostats*.

PRACTICAL EXPERIENCE FOR DESIGNERS

A heliostat designer holding a small mirror is an altitude/azimuth mounted heliostat. The experimental use of such an arrangement will soon show that, without excessive reduction of effective aperture, it is practicable to place the reflected beam into any direction within the hemisphere having the Sun at its pole. Many observers will recall making such an experiment, for non-scientific purposes, during childhood. The experimenter may take station at the proposed site of the heliostat and reflect the beam into the altitude/azimuth of the proposed observing apparatus. An exercise of this kind, carried out near the date of an equinox and near the time of day most convenient for subsequent daily observations, will indicate any optical constraint, and any physical obstruction, to the proposed arrangement.

SUMMARY

The uranostat, which reflects a beam into the hemisphere containing the Sun, is simple to construct. It can be realized with a practicable drive system if it is used at small hour angles only.

Foucault's heliostat, commonly called a siderostat, is suitable for reflecting a beam into the hemiphere containing the Sun. There are two mechanical arrangements of this; the underdrive and the overdrive. The choice of mechanical arrangement is a drawing board exercise and is largely a function of the type of driving clockwork and the supports. The field rotates at a changing rate which is a minimum when the Sun lies in the plane of symmetry of the apparatus. This arrangement is of value as a single mirror system only.

The Polar Heliostat is the degenerate heliostat in which the reflected beam lies in the polar axis. This is towards the elevated pole in the underdrive arrangement and towards the depressed pole in the overdrive type. This heliostat is mechanically simple. The field rotates at the constant rate of one revolution per day. In solar practice the overdrive arrangement is likely to be less disturbed by thermal convection than the underdrive arrangement. It is useful as a single mirror system if the observing apparatus can conveniently be placed in the polar axis and may be of value in certain cases of two mirror systems.

The coelostat is the degenerate heliostat in which the polar axis lies in the plane of the mirror. It is mechanically the simplest system and is the only heliostat to have a non-rotating field. It can be used as a single mirror system for short time intervals in special cases, but in general the fixed declination of the reflected beam makes it of value in two mirror systems only.

Heliostats reflecting into the hemisphere away from the Sun are of little value to the solar observer.

TWO MIRROR SYSTEMS

For fixed beams in or near the vertical, or otherwise into the hemisphere away from the Sun, practical systems use a coelostat and a second mirror. In some special cases a polar heliostat with second mirror is of value. I contemplate discussing these in the near future.

The *heliograph* is a hand driven, altitude/azimuth heliostat and second mirror system that was sometimes used for army signalling up to the time of the Boer war. It is now long obsolete but is of much interest. A fascinating description of this equipment and its operation may be found in an army signal training manual[22]. The item does not have any possible astronomical application.

HISTORICAL

There are four historical heliostats held in the Science Museum, London. A further heliostat from the same establishment is on loan to Liverpool Museums. The Museum of Science, Oxford, has a much modified mechanism that may have once been part of a 'sGravesande heliostat, and a Silbermann type is in the Planetary Science Division, Observatoire de Paris, Meudon. I would be glad to hear from any member who would be willing to prepare colour slides, sketches and descriptions of any of these.

A paper on the practical realization of single and double plane mirror systems is in preparation.

I am grateful to Colin A. Ronan for drawing my attention to reference 8 and to G. Clout, of the Imperial War Museum, for tracing the description of the heliograph and its operation.

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An Introduction to Transistors and Diodes

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Modern transistors can be designed to do many different things. They can amplify a minute radio-frequency signal, or provide a large amount of direct current. Almost all of them are made using either germanium or silicon. Silicon transistors are more robust than germanium ones, and should be used by beginners, though germanium transistors have some special properties which can be very useful in some applications.

An 'ordinary' transistor usually consists of a small metal or plastic cylinder, out of which sprout three thin wires. These wires are connected internally to the collector, emitter and base respectively. The collector is analagous to the anode in an electronic valve, whilst the emitter and base are similar in action to the valve's cathode and grid. Transistors are represented in circuits by the symbols shown in figure 1. They come in two kinds. Those which like a positive driving voltage are called NPN (figure 1a); those which like a negative voltage are called PNP (figure 1b). In both cases the direction of flow of the current from positive to negative is shown by the arrow on the emitter. Unlike the valves which they replace, transistors will work well on small voltages; it is unusual to find more than 20 to 30 volts in a transistor circuit, and in many cases a 1½-volt battery provides more than enough power.

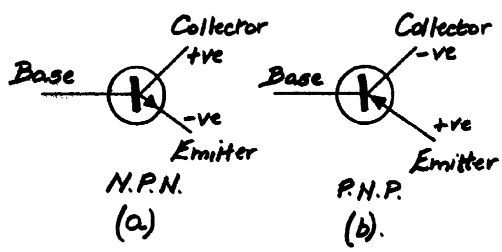

Figure 1

How does a transistor work? It is, in fact, an electrical valve or switch. If a voltage is applied between the collector and emitter, then the current flowing in and out of these two terminals can be controlled by applying a small voltage to the base. Great care must always be taken to control the currents flowing in a transistor, particularly in the base–emitter circuit; it is only too easy to melt the very delicate internal connections.

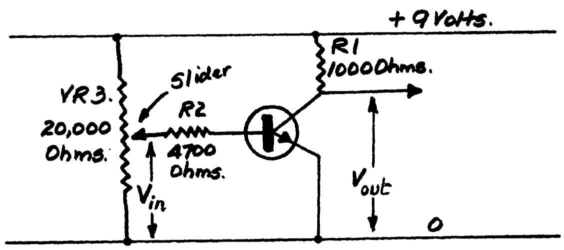

Figure 2

Figure 2 shows a typical silicon NPN transistor circuit. The 1000-ohm ('1 K') resistor R1 is known as the collector load; it controls the maximum current that can flow in the collector–emitter circuit. R2, the base resistor, limits the current that can flow in the base–emitter circuit, in this case to a maximum of 9/4700 amps (1·9 milliamps); this minute current will be much more than enough to operate the device. VR3 has a resistance of 20 000 ohms (20 K); at one end of it the voltage will be 9 volts, at the other end it will be 0 volts; the slider picks off any convenient voltage and applies it to the base, through R2.

Imagine that the slider on VR3 is at the low-voltage end of the resistance. The voltage on the base, V_{in}, will be zero, the transistor will be shut off, and the resistance inside it between the collector and emitter