Large Flux-Collectors for Infrared Astronomy

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[Plate 14]

1. Flux collectors and field imagers

Astronomical telescopes can be used in two principal ways. One is to collect radiation and feed it to analysing apparatus, such as a spectrometer, photometer or polarimeter. The other is to image an extended region of the sky onto an image-detector such as a photographic plate. These functions are complementary, and the choice between them depends on the purpose of the observations, the kind of object under investigation, and the available intrumental resources.

In field imaging, the rate at which information can be collected is proportional to the product of the squares of the aperture and the field diameter of the telescope (Fellgett 1964).

The Schmidt configuration gives by far the largest field of any telescopic system which we now know how to design, construct and keep in adjustment. Other systems are known, for example Schmidt–Cassegrains, which can have higher theoretical performance, but the problem of maintaining their components in sufficiently good alinement during fabrication and use is as yet unsolved, though almost certainly soluble by further research.

An $f/3{\cdot}5$ Schmidt working over a field 5° across gives an aberration spread not exceeding 0·4 sec arc in diameter, and this spread is symmetrical. The next best field-imager is the Ritchey–Chrétien which is usually quoted as giving a field of 20 to 30 min arc at only $f/8$, and up to 60 min arc by the use of field-widening lenses (Greenstein 1966). Even the latter figure represents only 4 % of the field area of an $f/3{\cdot}5$ Schmidt, so that on this basis a Schmidt of 30 in. aperture is just as powerful a tool for field-imaging observations as a 150 in. Ritchey–Chrétien. Even this is not the whole story, because the quoted Ritchey–Chrétien fields correspond to a lower standard of imaging than is achieved by the Schmidt (Paul 1935; Linfoot 1955; Schulte 1963), and the performance of systems using corrector lenses is usually still lower (Wynne 1949; Linfoot 1955; Baker 1961). It is probably fair to suggest that a 15 in. Schmidt is at least as powerful as a 150 in. Ritchey–Chrétien.

The old-fashioned parabolic or Cassegrain telescope is even more hopeless as a field imager. For either configuration, the total coma spread C at angle θ from the axis (C and θ being measured in the same angular units) is

$$C = 3\theta/16F^2, \tag{1·1}$$

where F is the system focal ratio. Thus for a telescope of 100 in. aperture working at $f/3$, the field within which the coma is less than 1 sec arc has a radius of only about 1 min arc = 0·072 in. The wave error due to coma exceeds one wave at only 11 sec arc from the axis, and equals the traditional figuring tolerance of $\frac{1}{10}$ wave at little more than 1 sec arc from the axis! Such designs fall far short of modern standards of systems engineering.

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A currently topical example of the need for powerful field-imagers is the study of quasars. Individually these are 'point'-objects, the traditional fodder of the paraxially-stigmatic telescope, but the system of quasars is of course very extended. The 48 in. Palomar Schmidt is now making an important (even, one may feel, belated) contribution to their study by the use of colour-filter methods. A powerful field-imager with objective dispersion would be almost ideally suited to this study.

On any extended object or system, the 'small' field-imager of the comparison given above secures essentially the same information, to the same faint limit, in the same total observing time, and on the same volume of photographic emulsion, as the 'large' telescope having the same field-aperture product (Fellgett 1964). In quantitative work, the small field-imager, as well as being much cheaper, gives approximately equal protection against emulsion shifts, and much better protection against variations in emulsion sensitivity. It has the special advantage of possessing very wide isoplanatism regions; consequently the reduction of the observations requires far fewer internal standards of position or brightness than would otherwise be needed.

The principal large telescopes of the world have hitherto been essentially of the paraxial-stigmatic type having primary coma. This probably reflects their derivation from visual telescopes of the last century. The human eye has a field of about 40° over which it can resolve 1 min arc. A magnification of 120 is needed to exploit the resolution of even a small telescope, and magnifications of up to 600 have been successfully used. The field of view is then only 4 to 20 min arc on the sky, and moreover observers tend to be tolerant of peripheral unsharpness provided they can explore the object with the sharp central region of the field using the slow motions of the telescope. There was therefore little incentive towards good field-imaging. The attitudes thus engendered were taken over and eventually fossilized in the famous 100 and 200 in. designs. The undoubted preference of many observational astronomers for paraxial rather than field-imaging methods may well be less of a free choice than a habit imposed by the technical limitations of these telescopes.

The attempt to obtain some sort of field-imaging performance out of basically paraxially-stigmatic configurations greatly increases the cost of a large telescope (this is discussed below), and produces an unsatisfactory compromise which is indeed understandable historically but which cannot be justified today. The Schmidt, as we have seen, is so much better than currently competitive field-imagers that the conclusion seems inescapable that the functional distinction between field imaging and flux collection must be reflected in a division of labour between separate telescopes of quite different structure.

The resultant economies can be very great. A pure flux-collector does not need the multiplicity of traditional observing positions (prime and Cassegrain foci, etc.), or the customary kind of fine guiding controls. Not even a skeleton 'tube' is needed; the engineering structure can be largely confined to the support of the main mirror, and secondary mirrors can be carried on comparatively light booms which may be given active stiffness. It will often be appropriate to degrade the imaging standards well below those of field imagers; this is discussed in § 2. Design studies show that a large pure flux-collector and a medium-sized Schmidt can together easily out-perform a traditional compromise 'telescope' of equal total cost both in flux collection and field imaging.

It is no longer appropriate to decide to build an 'X-inch telescope' (where $X = 100$, 150, 200, etc.) and then ask what structure it ought to have. The purpose of the construction must be specified in terms of observational requirements, and the overall telescopic system (which may consist of more than one separate instrument) then optimized in terms of cost and performance.

2. Diameter–resolution relations

Figure 1 summarizes compilations of data and relations due to Connes & Ring (1967). The points show the reported or expected angular resolution of some of the world's large telescopes plotted against diameter of aperture on logarithmic scales. Lines superposed on the diagram represent a number of significant relations.

A line of slope -3 is seen to represent the empirical limit to resolution set by flexure (which scales as the cube of the linear size of a structure). Only two points lie significantly on the high-resolution side of this line; the ground-supported Arecibo fixed mirror, and the projected Sugar Grove servo-stabilized instrument. It is interesting that the 200 in. Palomar telescope lies close to the line defined by the radio telescopes.

Lines of slope $+1$ show the wavelength at which the diffraction limited resolution is attained. Small optical telescopes attain this limit at their working wave-number. Atmospheric seeing sets an earlier limit for the larger optical telescopes, and flexure does so for the larger radio instruments.

Further lines of slope $+1$ show (for illustrative assumptions; see the figure description) when the optical luminosity (area × solid-angle product, sometimes called through-put) of the telescope matches that of a spectrometer of given spectral resolving power. The theory is outlined in the appendix. There are two families of parallel lines, one for grating spectrometers and the other for interferometers.

The diagram shows that there would have been little point in building a flux collector significantly larger than the 200 in. so long as reliance had to be placed on grating spectrometers; the spectrometer would not have accepted enough of the light from the telescope at the spectral resolutions which are now of interest. This limitation has been greatly pushed back by the advent of interferometric spectrometers with their much more favourable luminosity characteristics (equation (A4)).

The capital cost per photon remains constant if the cost of a flux collector increases as the square of its linear dimensions. The tendency, however, is for the cost of a structure to increase as the cube of its size; engineers often speak of 'cost per ton' for a given type of work. In fact optical telescopes have so far achieved an index (log cost)/(log diameter) of not much more than 2, and radio telescopes an index of 2·5 to 3.

When the index exceeds 2, large instruments may still be justified on the grounds of making possible observations which would otherwise be impracticable to organize or would take too long to complete, of the cost of the many analysing instruments that would be needed for a multiplicity of smaller telescopes, and related advantages. However the effective light-collecting power of a telescope feeding a grating of inadequate luminosity may be no more than simply proportional to the diameter of the telescope, and this is economically unjustified. Accordingly, the possibility of now building large flux gatherers and using them efficiently depends strongly on the advances that have been made in high-luminosity interferometric spectrometers.

A striking feature of figure 1 is the relative dearth of telescopes represented by points near to the flexure line in the gap between the clusters of optical and radio telescopes. The characteristics of such telescopes would be particularly well suited to infrared studies, as is suggested by the intersection of the flexure line with the wave-number-resolution lines in this gap. This topic is discussed further in the following section.

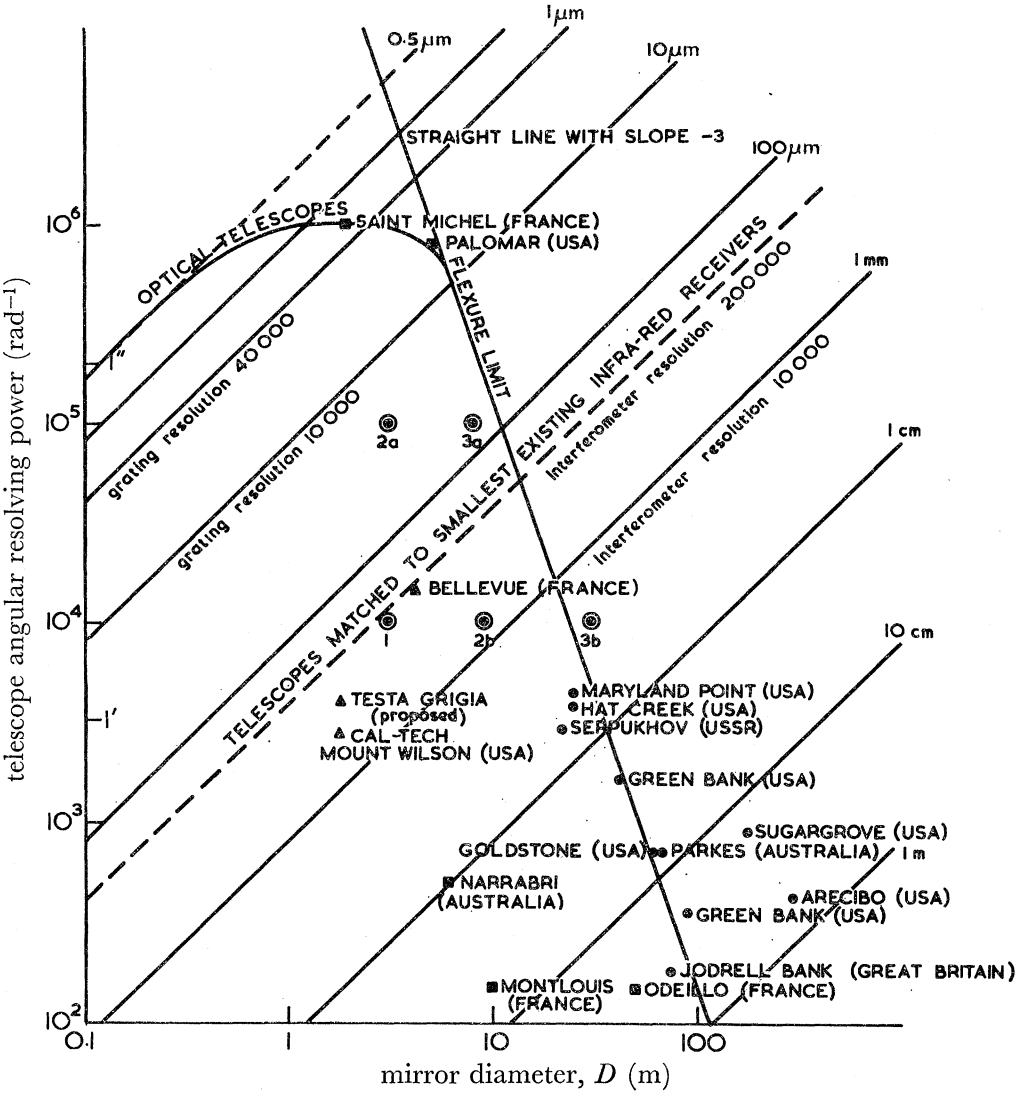

Figure 1. Connes–Ring diagram showing the angular resolution of large telescopes as a function of diameter of aperture. The line of slope -3 is the empirical flexure limit. Lines of slope $+1$ show the wavelength at which the angular resolution becomes diffraction limited, and the approximate spectral resolution attainable with grating and with interferometric spectrometers matching the luminosity of the telescope. The spectral resolution lines are drawn for grating delay $b = 25$ cm and $k = 2{\cdot}4$, and for interferometer aperture $a = 10$ cm and $k^2/8k' = 1$ in the notation of the Appendix. *Key.* ■, Optical telescopes including solar furnace and intensity interferometer; ●, radio dishes; ▲, infrared flux-collectors; ⊙, present proposals: phase 1 120 in.; 2*a*, accurate 120 in.; 2*b*, 360 in.; 3*a*, accurate 360 in.; 3*b*, 1000 in.

3. Infrared telescopes

It is almost a commonplace that when a new region of the electromagnetic spectrum is explored astronomically, not only is new information gained about familiar objects but in addition totally unexpected sources are discovered. This has happened throughout the development of radio astronomy, currently culminating in the discovery of quasars. The opening up of the ultraviolet region by rocket and satellite vehicles has led to similar advances of both kinds.

In the infrared region, the Leighton–Neugebauer objects (1965) and the Orion object described at the present meeting were quite unexpected, and a wealth of new information about the atmosphere, Moon, planets and stars has been presented. An outstanding example of new knowledge about objects that have been studied for centuries has been the planetary infrared spectrometry of the Connes (1966, 1967).

The three principal characteristics of the Connes method are that it is *multiplex*, *interferometric* and *Fourier*. Multiplexing (Fellgett 1951, 1958) avoids the scanning loss, and by multiplexing over 60000 resolved points covering the whole lead sulphide region the Connes are able to secure in one night observations which would need over 150 years with an otherwise comparable non-multiplex spectrometer; with predictable improvements the number of resolved elements will be increased to 300000–500000 giving a multiplex advantage of over a millennium to one night. The interferometric attribute gives the high luminosity discussed in §2 (Jacquinot 1954). The Fourier attribute enables a wide spectral range to be covered, in contrast for example to the Fabry–Pérot interferometer (Jacquinot 1954), and has permitted the Connes to obtain better control of resolution function than has ever been attained with gratings.

As a result of these combined advantages, the spectral resolution on the nearby planets has been increased by some 100 times over the best previous observations. A resolution of 0·08 $\mathrm{cm^{-1}}$ has been reached with signal/noise ratio *ca.* 100:1 both on Mars and on Venus.

The detailed interpretation of these new spectra will give much new information concerning the physical condition and chemical composition of the planetary atmospheres. Such information, particularly about the presence of biologically significant trace constituents, is urgently needed at the present time in order to optimize the design of life-detection experiments proposed for Mars and Venus landers.

It would be desirable to extend the observations by improving still further the spectral resolution and intensity accuracy, by introducing disk-resolution and permitting observations away from the most favourable presentation of the planet so that the study of seasonal and Doppler variations can be extended, and by extending the observations to the 10 μm window.

The basic energy relations for multiplex interferometric spectrometry are

$$\frac{S/N}{\Delta\nu} = \frac{\pi^2}{16\sqrt{2}}\beta B\lambda^2 h^2 D t^{\frac{1}{2}} \tag{3·1}$$

or

$$\frac{S/N}{\Delta\nu} = \frac{\pi^{\frac{3}{2}}\beta B\lambda h D^* t^{\frac{1}{2}}}{8\sqrt{(2)}\,F}, \tag{3·2}$$

where B is the brightness of planet ($\mathrm{W\,m^{-2}\,rad^{-1}\,cm^{-1}}$), β is the optical efficiency of system,

λ is the angular diameter used (radians), h is the diameter of telescope aperture (metres), D is the detectivity of radiation receiver (watt^{-1}), D^* is the detectivity normalized to 1 cm^2 area of receiver, t is the time of observation, F is the focal ratio of condenser feeding the detector, S/N is the spectral signal/noise ratio, and $\Delta\nu$ is the spectral discrimination.

Equation (3·1) applies always, (3·2) is applicable when the size of detector is made equal to that of the final image.

Detailed application of these relations shows that increasing the size of flux collector will permit the scope of the present observations to be extended progressively, without any particular threshold, up to a diameter of at least 1000 in. The next section explores some of the ways in which large flux-collectors might be constructed.

4. MATERIALS AND METHODS OF CONSTRUCTION

The flexure line in the Connes–Ring diagram (figure 1), suggests that it is feasible in principle to build flux collectors of appropriate resolution considerably larger than the present world leaders, the Palomar 200 in. and the Soviet 240 in. It seems safe to assume that reflecting optics would be used in any very large instrument. The principal design requirements for the main mirror are that it should possess adequate rigidity, stability and reflectivity. The supporting structure is required to provide means of directing the mirror in a suitably controlled way.

In fulfilling these requirements, many technical resources are available that were denied the designers of the pioneer 200 in. It seems appropriate to review these briefly, without going into detail which would be unsuited to the present discussion.

Computer and servo techniques have reached the state of development at which the problems of control of a telescope can be solved systematically; the Jodrell Bank mk II radio telescope illustrates this. In order to obtain equatorial motions it is no longer necessary to have equatorial bearings, or indeed any fixed bearings at all, and there may be advantages in supporting the mirror on servo-controlled hydraulic legs in the manner shown in figures 2 and 3, plate 14.

Recent advances in structures have included renewed research into Michell-optimized structures (Michell 1904) and developments in geodetic and space-frame structures. The availability of honeycomb sandwich and related bonded configurations has pushed back limitations formerly set by elastic instability. The over-all consequence has been that structures can now be built economically which have appreciably better weight/stiffness ratios than was possible by traditional methods.

Perhaps the greatest advances have been in materials. The choice is open of either seeking a mirror material which combines all the requirements listed above, or of using a composite structure in which there is division of labour between different materials. An early example of such division of labour was the change from speculum metal to glass mirrors in which the provision of high reflectivity was relegated to a silvered coating applied to the supporting glass substrate. In very large sizes, it appears necessary to provide the glass layer in its turn with rigid structural support. Several ways of doing this are currently being investigated.

Alternatively, it may be possible to find a structural material which can be fabricated in

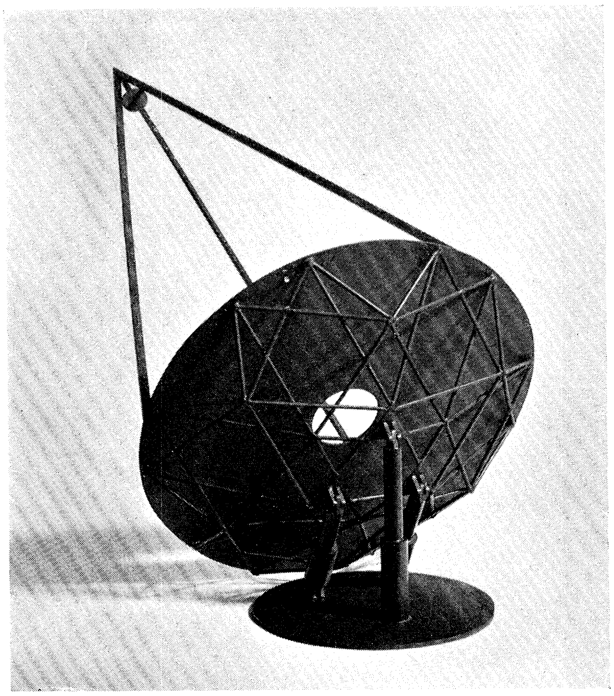

FIGURE 2. Model study for 120 in. flux-collector. The servo-controlled hydraulic legs enable the instrument to be directed to any part of the sky, but there is no fixed axis of rotation.

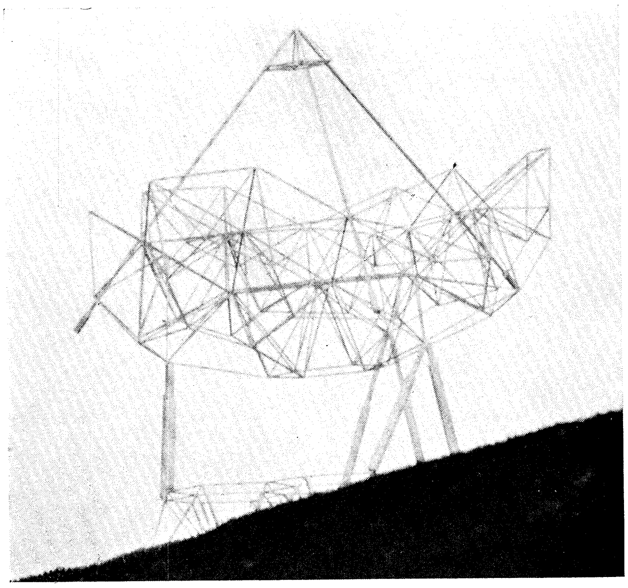

FIGURE 3. Model study for 1000 in. flux-collector. The six hydraulic legs permit a fixed centre of rotation to be maintained. The focal ratio in this model proved too extreme.

large sizes and will itself form a surface of optical quality. Some ceramic and glass-ceramic materials are promising candidates, glass-ceramic in particular having a low coefficient of expansion and taking an adequate polish. The difficulties of metallizing a very large mirror are sufficiently formidable to direct attention to the possibility of forming a mirror surface directly on suitable structural alloys of aluminium. New developments in electrochemical machining and polishing give some promise of making this practicable.

Finally, flexure can in principle be drastically reduced by using whisker-reinforced composite materials. Graphite has itself a stiffness/weight ratio 24 times better than aluminium, but is weak. Graphite-whisker reinforced epoxy is a strong material having a stiffness/weight ratio 16 times that of alluminium, but may not be secularly stable; graphite reinforced aluminium is over 10 times better than aluminium. These composites are not yet economically available for telescope construction, but there is some promise of developing less costly materials of the same general kind but with lower specifications and these would still give substantial advantages.

5. A PROGRAMME LEADING TO A 1000 IN. FLUX-COLLECTOR

There are many advantages in building a large flux-collector out of repeated smaller units. This can save design and development costs, converts a one-off job in some degree to a batch-production one, and can provide a working instrument at a comparatively early stage of the work. Above all, the programme can be modified as experience is gained, and the whole expenditure is not committed irrevocably from the beginning.

Convergent reasons suggest a unit of 120 in. diameter. This size gives a suitable diffraction-limited angular resolution in the 10 μm window. Strain computations indicate that the suggested accuracy of 10 to 20 sec arc can be obtained with comparatively crude structures of this size, and 2 sec arc with refined geodetic or composite structures. These calculations tend to confirm the validity of the empirical flexure line in the central portion of figure 1. A diameter of 120 in. is the largest size in which glass blanks (if used) are likely to be readily available, and is also about the largest convenient size for handling and transport.

Single 120 in. units would have significant flux-gain over the largest telescopes which have so far been used regularly in infrared studies. Two or three such instruments in Britain and Europe, at least one at a high altitude station, would enable much new knowledge to be gained, especially if they were available for setting up the necessary sophisticated analysing instruments and for long integration times without having to compete with non flux-gathering observations. It would be technically desirable to specify the lower accuracy of 10 to 20 sec arc in the first place, and to upgrade this towards 2 sec arc as experience was gained. The unit cost has been tentatively estimated at £20 000 to £30 000, and it will certainly be comparable with that of a quite modest telescope of the conventional kind. The lead time from inception to the first instrument becoming available could be less than a year.

In a second phase, 6 to 7 units could be combined, not necessarily in the form of a single dish, into a flux collector of 360 in. equivalent diameter (Horn-d'Arturo 1965; Wright 1966). It would again be desirable to aim at 10 to 20 sec arc resolution in the first place, and to upgrade this to 2 sec arc when tests had been made on the first unit; servo control may be the cheapest way of achieving this accuracy.

The final phase could be to assemble about 70 units into a collector of 1000 in. equivalent diameter having a resolution of 10 to 20 sec arc suited particularly to the 10 μm window (see figure 1). This size is similar to that of the very successful and economical 80 ft. radio dishes of which some dozen have been built. Cost estimates at this stage are little more than guesses, but £3 to 4 M is indicated, with a lead time of about 5 years. This is comparable to the cost and lead time of a traditional major telescope having only 1 to 2 % of the flux-gathering power.

Such an instrument would be of immense value in advancing man's ability to observe the Universe in which he lives. Its potentiality is too various to list in detail, and problems which it could provide means of elucidating will occur to each reader according to his interests. Basically it enables the radiation from distant bodies, whether galaxies, nebulae, stars or planets, to be collected in sufficient quantity that it may be analysed in far greater detail and with greater refinement than ever before. The spectacular continuing success of the Connes planetary infrared spectrometry makes the building of such an instrument timely. The space programme and the desire to seek life on our nearest planetary neighbours makes it urgent; it is a necessary part of the spacecraft work, and a complement to it. The cost is modest by comparison with that of rocket instrumentation.

Through international cooperation in this enterprise, the cost can be shared, the widest choice of observing site made available, and the instrument can be made available to all qualified investigators.

APPENDIX

(a) *Grating spectrometer*

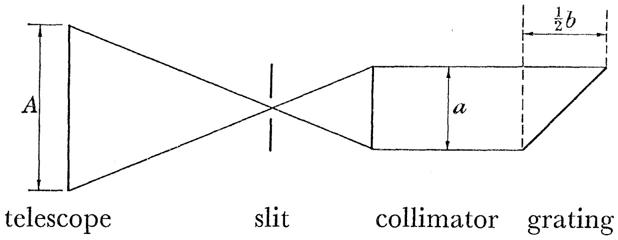

FIGURE 4. Grating spectrometer.

At wave-number ν cm^{-1}, there are νb waves in the grating delay b; if the grating is used in autocollimation, b is twice the axial distance between the first and last ruled line. The change in this number when the wave-number is changed by dν, and the angle of arrival by dθ is, since d$b = a\,\mathrm{d}\theta$,

$$\begin{aligned}\mathrm{d}(\nu b) &= \nu\,\mathrm{d}b + b\,\mathrm{d}\nu \\ &= \nu a\,\mathrm{d}\theta + b\,\mathrm{d}\nu.\end{aligned}$$

Comparing the two terms on the r.h.s., the angular dispersion is seen to be $\mathrm{d}\theta/\mathrm{d}\nu = b/\nu a$. If the width of the slit subtends angle θ at the collimator, this limits the resolution to $R = \nu/\Delta\nu = b/\theta a$. The angular subtense of the slit images into star-space with magnification a/A, and the slit is therefore able to accept a telescopic image with diameter not exceeding

$$\alpha = a\theta/A = (b/A)\,R^{-1}. \tag{A 1}$$

The diffraction-limited image spread becomes equal to α at wave-number

$$\nu = kR/b. \tag{A 2}$$

Here $k \sim 1$ is a constant depending on the precise definition of image-spread which is adopted; $k \sim 2{\cdot}4$ on the old-fashioned Rayleigh definition.

The diffraction-limited resolution of the grating is approached when the value of ν which satisfied equation (A 2) agrees with the wave-number of the radiation being analysed.

(*b*) *Interferometer*

An interferometer with maximum axial delay b gives spectral discrimination $\Delta\nu = 1/k'b$, where k' is a constant depending on apodization. Because of the symmetry of the interferogram, k' can be as large as $k' = 2$.

The delay along a path making angle θ with the axis is $b \cos \theta$, and destructive interference will occur if this differs from b by more than one wavelength. The radius of image acceptable at the collimator is therefore given by

$$\left.\begin{aligned} b\nu(1-\cos\theta) &= 1, \\ \theta^2 \simeq 2/b\nu = 2k'\Delta\nu/\nu &= 2k'/R. \end{aligned}\right\} \tag{A 3}$$

As for the grating spectrometer, this angle images into star-space with magnification a/A (a being diameter of collimator, and A the diameter of telescope aperture) and therefore the interferometer can accept a telescopic image of diameter

$$\alpha = 2a\theta/A = (8k')^{\frac{1}{2}}(a/A)\,R^{-\frac{1}{2}}. \tag{A 4}$$

The wave-number ν at which the diffraction-limited resolution of the telescope corresponds to α is now

$$\nu = (R^{\frac{1}{2}}a)\,(k^2/8k')^{\frac{1}{2}}. \tag{A 5}$$

The acceptance angle of an interferometer can be further increased by a number of known 'field-widening' methods.

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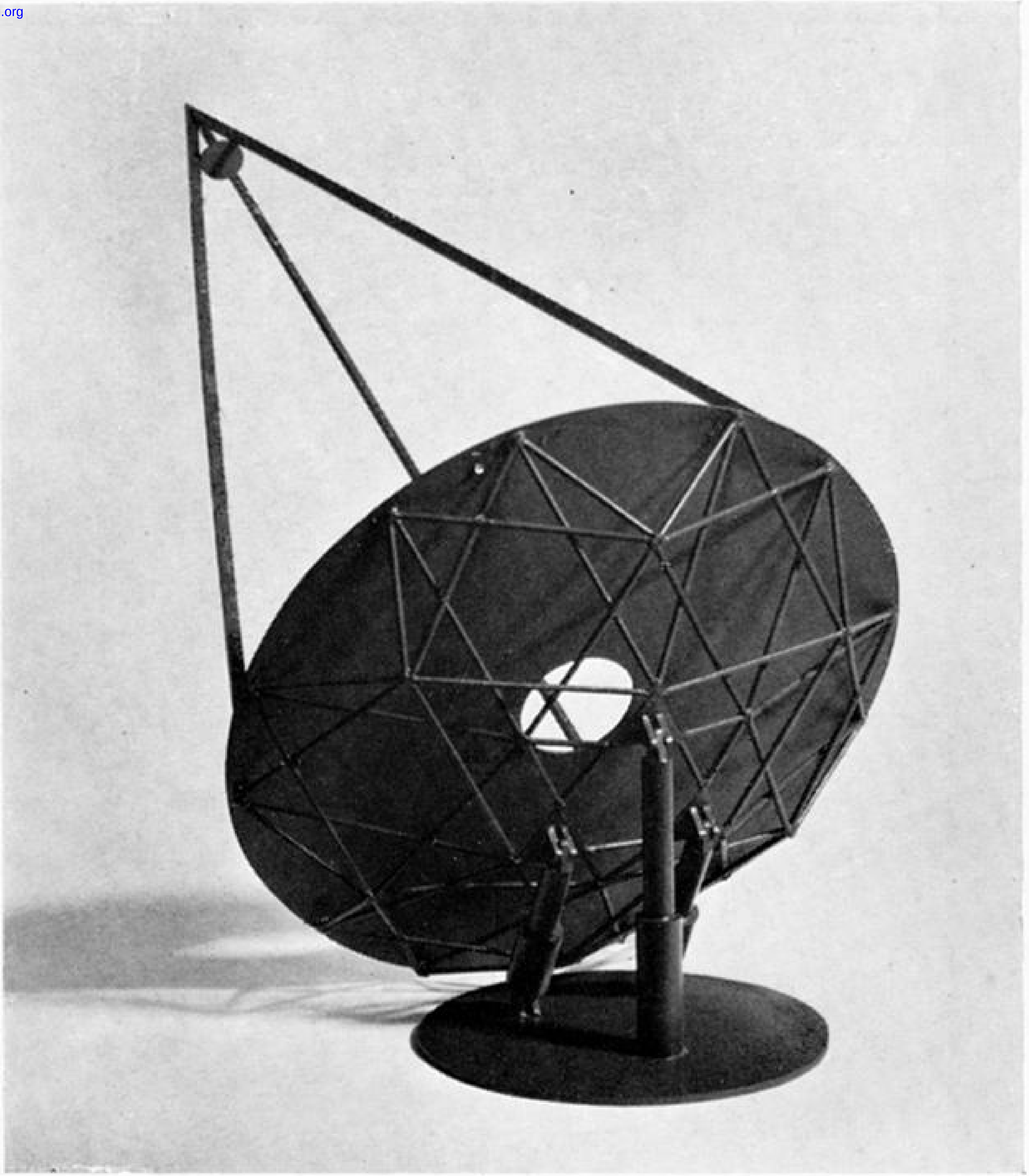

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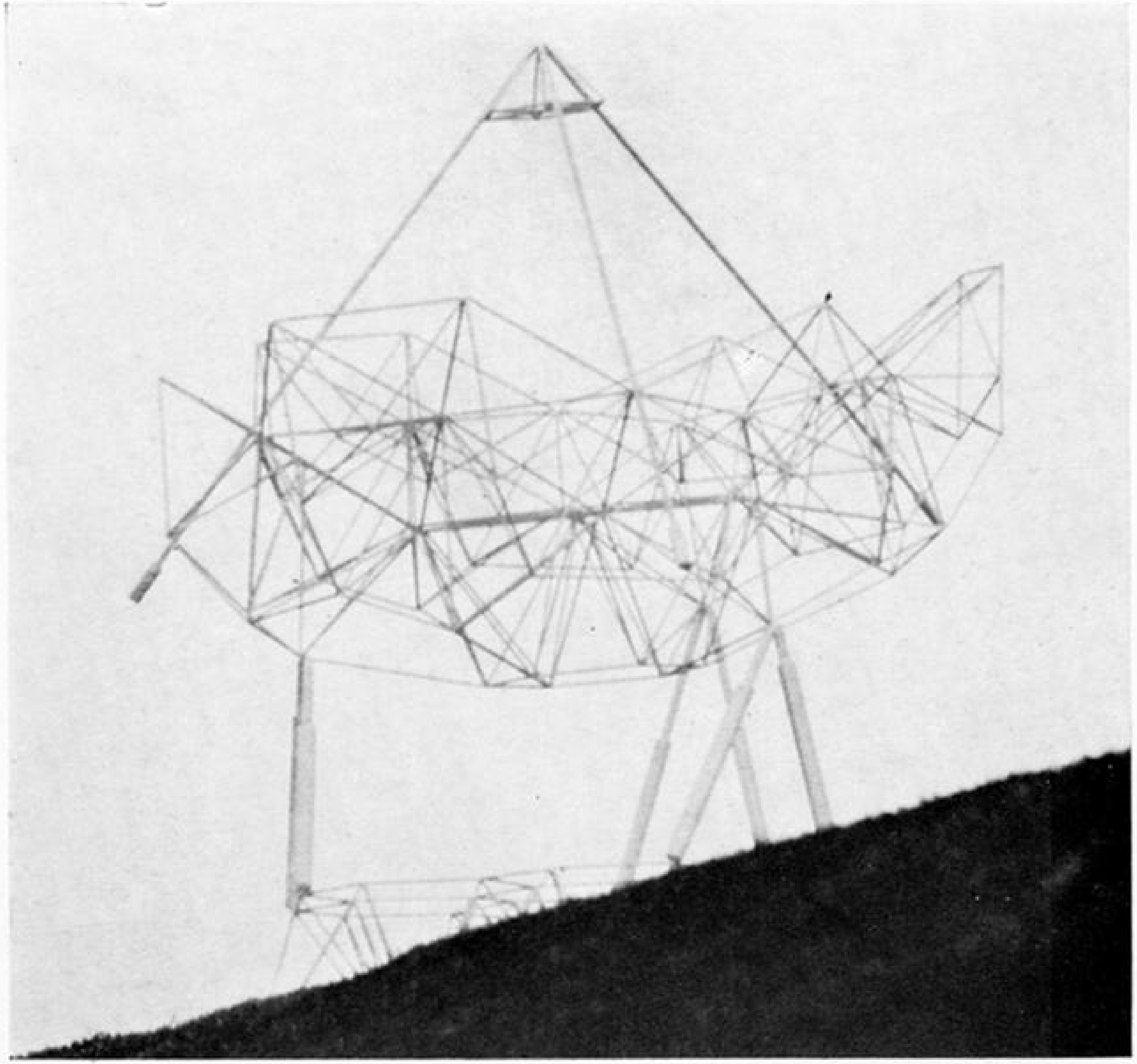

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