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Some Problems and Instrumental Features of Submillimetre Astronomy

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IV. TECHNIQUES

Some problems and instrumental features of submillimetre astronomy

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[Plate 12]

1. Introduction

Modern astronomy includes optical, ultraviolet, infrared and, in recent years, also radio astronomy, γ-ray and X-ray astronomy. Such a classification is justified to a certain degree. In fact, a difference in wavelength ranges necessitates a distinction in methods and techniques of receiving radiation. Also, specific problems need, for their solution, observations in different wavelength regions.

In this respect it is possible to speak about a new astronomical branch—I mean the submillimetre branch. It is known that the submillimetre range is one intermediate between infrared and microwave regions, as it is shown in table 1. The boundaries of this range are not very definite. Some authors include in the submillimetre range wavelengths longer than 50 μm, while others move this border to 100 μm. The long-wave edge of the submillimetre range is also diffuse. Formally it is a wavelength of 1 mm. But in some cases the 2 mm or 4 mm wavelengths are also ascribed to submillimetre range. The measurements of submillimetre receiver performances are sometimes carried out at wavelengths up to 8 mm. The uncertainty of the range boundaries is very understandable: their shifting depend on the methods of generation, transmission and detection of radiation.

Table 1

λ (mm)	λ (μm)	ν (GHz)	ν (cm^{-1})	photon energy (eV)	spectral range
10	10000	30	1	0·0001	
8	8000	37	1·23	—	microwave
5	5000	60	2	—	(mm)
4	4000	75	2·5	—	
2	2000	150	5	—	
1	1000	300	10	0·001	far
0·5	500	600	20	—	i.r.
0·2	200	1500	50	—	or
0·1	100	3000	100	0·01	sub (mm)
0·05	50	6000	200	—	
0·01	10	30000	1000	0·1	i.r.
0·001	1	300000	10000	1·0	

In this paper following Martin's (1962, 1963) terminology wavelengths between 50 μm and 2 mm will be attributed to submillimetre range.

The specific position of submillimetre astronomy depends on three features. The first two are closely connected with each other and concern methods. The last one is related to scientific problems, which need for their solution submillimetre observations.

It is known that the Earth's atmosphere is practically opaque for space submillimetre radiation. The absorption in atmospheric water vapour prevents any serious astronomical observation from sea level.

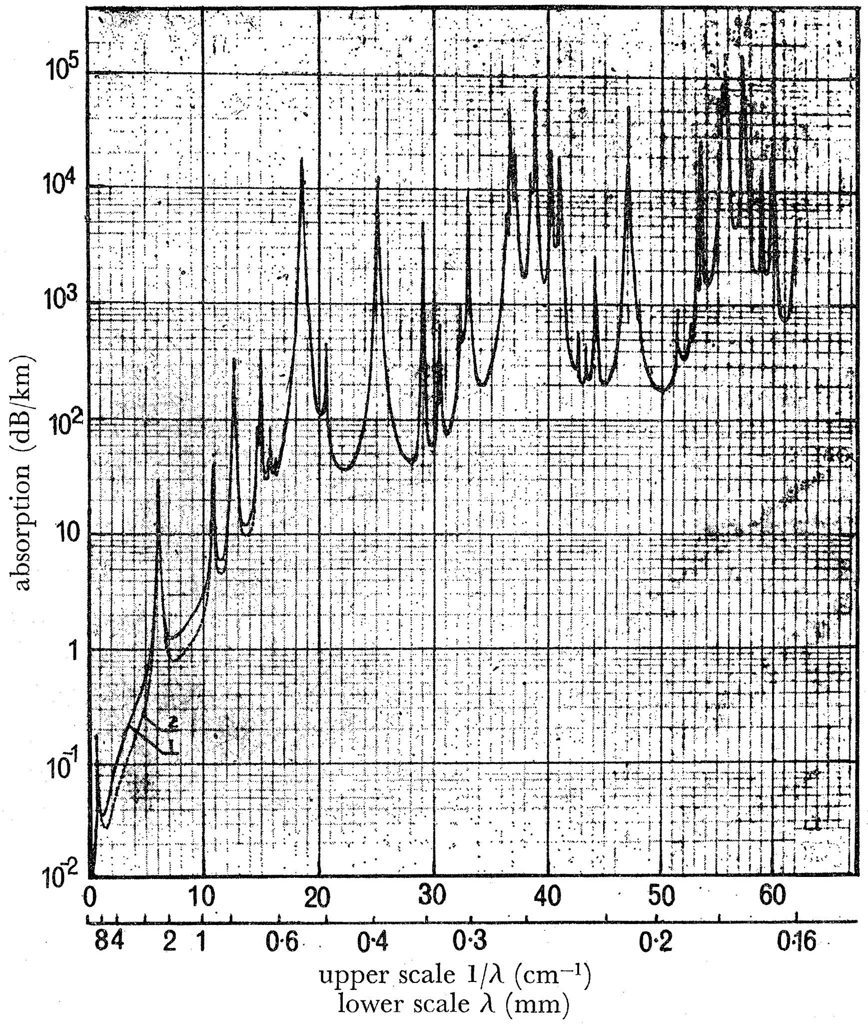

FIGURE 1. The absorption in atmospheric water vapour (dB/km) calculated by Gevakin & Naumov (1963), $T = 293$ °K, $P = 760$ mmHg, $\rho = 7{\cdot}5$ g/m^3.

Figure 1 shows the results of new calculations of the absorption in atmospheric water vapour which have been performed by Gevakin & Naumov (1963). In these calculations they have taken into account all the H_2O rotation lines (up to quantum number $Z = 12$) for which the matrix elements of directional cosines of asymmetrical spin are more than 10^{-6}. Even in the windows of relative transparency for wavelengths shorter than 2 mm the absorption coefficient turned out to be more than 1 dB/km. The results of these calculations are in satisfactory agreement with observational results, at millimetre and submillimetre wavelengths (see Salomonovich 1964; Wort 1962; Drjagin *et al.* 1966) as well as in the infrared region.

Such a high absorption has prevented us up to recent years from attempts to use submillimetre wavelengths for practical purposes (for communication, for instance). This circumstance could not help hindering the solution of difficult problems of elaborate techniques for generating and detecting submillimetre radiation. The absence of reliable oscillators and sensitive detectors together with difficulties of guidance and transformation of submillimetre radiation formed the second feature of this range.

The development of submillimetre astronomy has become possible only in the recent years and, it is due to two reasons: (1) to the success in semiconductor physics and quantum electronics; (2) to the extremely rapid development of space astronomy techniques which allow us to eliminate completely, or for the most part, the influence of absorbing terrestrial atmosphere. But the development of submillimetre astronomy would not be explicable if it were not for the third feature, which is probably the most important. I mean those specific and important problems, which need for their solution observations just in the range under consideration.

Without pretending to give a comprehensive account I would like to refer briefly to some actual problems of submillimetre astronomy, returning to its techniques later.

2. Some problems of submillimetre astronomy

The submillimetre window into space has been strictly curtained. This is the reason why, in connexion with submillimetre astronomy, it is possible to repeat the words which were once said of radio astronomy: 'In this field one can expect extremely unusual discoveries.' The first attempts at submillimetre observation confirm such a statement. At the same time, before the wide program of observation began to develop, astrophysicists tried to formulate some problems which required submillimetre astronomical activity.

(*a*) *The investigation of the characteristics of prestellar matter*

The expanded universe theory by A. A. Fridman predicted the possibility of the existence of an isotropic electromagnetic thermal radiation with a blackbody temperature of several degrees Kelvin. In accordance with the hot model of the universe, developed in the framework of this theory by several authors (see, for example, Zeldovich 1966), matter in the prestellar state is specified by high level of entropy. In thermal equilibrium the density of strong radiation in compressed hot plasma at an early phase is many times greater than the matter density. In the process of expansion the number of quanta remains constant, but their energy diminishes with the increase of wavelength. The density of this radiation at the present time turned out to be many orders greater than that of other sources of radiation (radio galaxies, radio stars) at the wavelength of maximum radiation. Figure 2 shows the predicted spectrum calculated by Novikov & Doroshkevich (1964) for $T = 1$ °K.

For thermal radiation of several degrees Kelvin this maximum occurs at submillimetre wavelengths. Figure 3 shows the recent published results. The measurements carried out by Penzias & Wilson (1965) at the wavelength $\lambda = 7{\cdot}3$ cm and also observations conducted by Roll & Wilkinson (1966) and V. S. Stankevich (private communication) at $\lambda = 3{\cdot}2$ cm suggest apparently the existence of such radiation with blackbody temperature

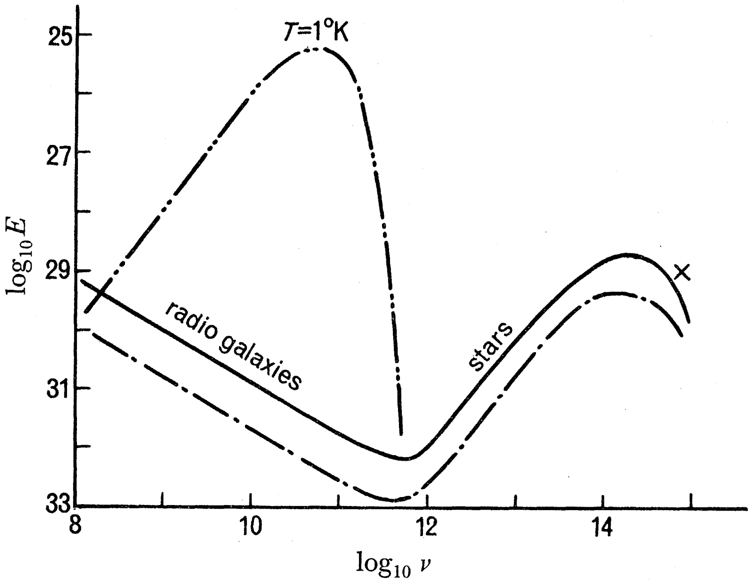

FIGURE 2. Spectrum of stellar and radio source radiation together with background spectrum ($T = 1$ °K) corresponding to the hot model calculated by Doroshkevich & Novikov—*Dokl. Akad. Nauk, U.S.S.R.* **154**, 745 (1964).

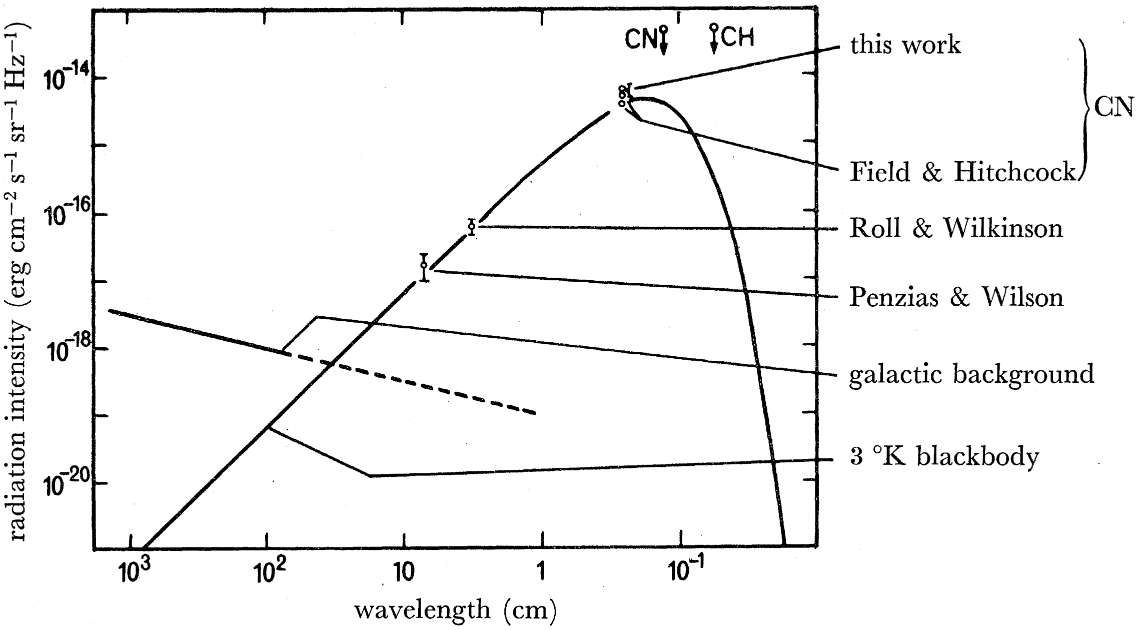

FIGURE 3. Plank radiation for $T = 3$ °K and the recent results of background measurements in centimetre and millimetre regions (see Thaddeus & Clauser 1966).

of *ca.* 3 °K. The same conclusion is supported by the analysis of the relative intensity measurements of interstellar CN lines ($\lambda = 3879{\cdot}60$ Å and $\lambda = 3874{\cdot}61$ Å), giving the temperature of background radiation at a wavelength of 2·53 mm, undertaken by Field & Hitchcock (1966) and Thaddeus & Clauser (1966).

The maximum of the background radiation falls at wavelengths ~ 1 mm. As a result of the discovery of this radiation it is very important to make measurements with high accuracy at wavelengths shorter than 1 mm. These measurements will allow us to conclude whether the spectrum of the background radiation is a Planck spectrum. Probable features of this spectrum may give some unique information about different stages of the evolution of the Universe (Galaxy condensation, etc.).

(*b*) *The investigations of the state and chemical composition of interstellar and intergalactic matter*

Submillimetre wavelengths are the best range for investigation of very cold parts of the Galaxy. Measurements of the intensity distribution in this range will allow us to detect the regions where, maybe, at present gravitational condensation continues. It is very important for stellar and planetary cosmogonies. In particular it seems that detailed spectral investigation in mm and submm ranges will allow us to detect the existence of some molecules and dust in the Galaxy. At wavelengths close to 200 μm it is possible to expect the maximum of self radiation of interstellar dust (assuming that the dust temperature is close to 20 °K).

Further it is known, that several resonance lines of hydrogen, water, oxygen and some other molecules occur in the mm and submm ranges. The investigation of these lines will allow us to study the coldest and most condensed parts of Galaxy—their temperature, density and chemical composition.

By the way, it is known that in the mm range many lines exist which are caused by excited atomic hydrogen and other elements, these lines correspond to transitions between energy levels with large quantum numbers.

This effect has been predicted in U.S.S.R. by Kardashev (1959), and discovered also in this country by Sorochenko *et al.* (1964). Excited hydrogen lines are a very effective tool for investigation of the distribution and motions of regions with strongly ionized interstellar gas. Although the line brightness temperatures in the submillimetre range are smaller than in the mm range, the spectral density must be considerably greater than the thermal radiation density of the galactic continuum. For the brightest nebulae the expected hydrogen line flux densities in the 10 to 0·05 mm range (quantum number $n = 50$ to 10) are 3×10^{-18} to 3×10^{-12} W/m^2 (for $\Delta f/f = 10^{-4}$).

(*c*) *The investigation of 'infrared stars' and quasars*

In recent years new sources of electromagnetic radiation were discovered. I speak about 'Infrared stars', all the spectrum of which falls in the range between 3 and 20 μm, corresponding to a blackbody temperature of only 700 °K. It is very probable that such sources may be detected in the longer i.e. submillimetre range. Radio astronomical and optical observations show that the maxima of intensity of the strongest sources—the most intense superstars and remnants of super novas must lie in the submillimetre or infrared ranges. It seems, this radiation possesses a large diversity of characteristics. In particular, the intensity of radiation in this range is variable, it is strongly polarized, has an unusual spectrum, etc.

Investigations at submillimetre and infrared wavelengths may be of decisive importance in revealing the nature of these objects and also for resolving related problems (formation and evolution of galaxies, investigation of Universe models with the help of the most distant sources, mechanism of acceleration of cosmic rays, discovery if extraterrestial civilizations). The expected flux densities from the brightest sources in the wavelength range close to 1 mm must be about 10^{-14} to 10^{-25} W m^{-2} Hz^{-1}, which at $\Delta f/f = 30\,\%$ gives 10^{-12} to 10^{-13} W/m^2.

(*d*) *Investigations of planetary atmospheres*

Spectral observations in millimetre and submillimetre ranges are extremely important for revealing the chemical composition, pressure and temperature distributions in planetary atmospheres. The composition and conditions in planetary atmospheres are practically unknown. It is known that in the millimetre and submillimetre ranges there are strong resonance lines and bands of such molecules, as may be expected in planetary atmospheres: H_2O (13·5 mm, etc.), O_2 (5 and 2·53 mm), CO (2·61 and 1·3 mm), NO (1·99 mm and 1·2 mm), etc.

The investigations of spectral features of planetary radiation will allow us to detect the existence of such molecules in the atmosphere. Measurements of form and intensity of spectral lines will help us to decide about the distribution of atmospheric pressure and temperature. In the submillimetre range it can be expected that flux densities may be equal to 10^{-20} to 10^{-22} W m^{-2} Hz^{-1} or 10^{-9} to 10^{-11} W m^{-2} in the relative waveband $\Delta f/f = 30\,\%$.

(*e*) *Investigations of solar radiation*

The submillimetre solar radiation is the source of information about the deepest layers of the chromosphere. In particular, the measurements of intensity, polarization and time dependence of radiation from active regions on the solar disk, connected with flocculae and spots, allow us to obtain reliable data about magnetic fields and electron densities above spots. These measurements will help to make clear the nature of bursts connected with chromospheric flares, which play a significant role in geophysical phenomena.

A rather high resolving power of instruments (exceeding 30 sec arc) is necessary for these observations.

3. INSTRUMENTAL TECHNIQUES

The state of submillimetre astronomy technique is characterized by its intermediate position and specific difficulties in mastering this range.

The review by Putley (1963) makes it unnecessary to relate all the methods of submillimetre radiation detection.

At present superheterodyne, very wide band receivers with crystal-mixers on the input are used in the long-wave part of submillimetre range (Cohn, Wentworth & Wiltse 1963). Optical methods are represented by Golay cells, bolometers of different kinds (including superconducting type and germanium, cooled to liquid helium temperature). Evidently the most promising in the submillimetre range are photoconductive detectors and cooled bolometers with semiconducting sensitive elements (In-Sb and Ge). Radiometers with such receivers are used for ground-based astronomical observation in the U.K., U.S.S.R., U.S.A. and France (Low 1961; Putley 1965; Rollin 1961; Popov 1965; Karlova & Karlov

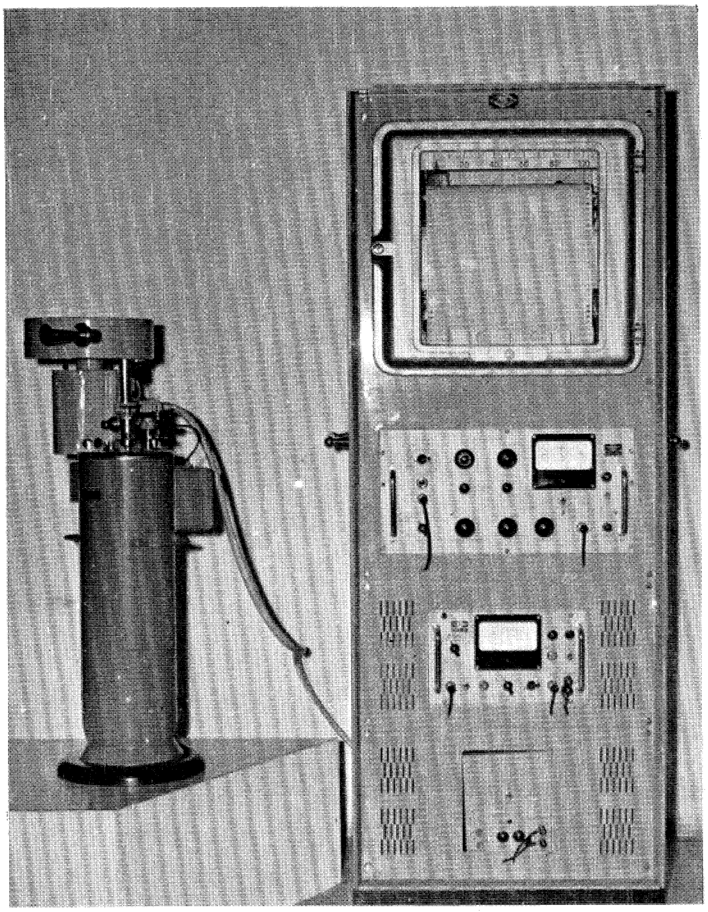

FIGURE 4. The submillimetre radiometer with In-Sb sensitive element used in the Institute of Radiotechnics and Electronics (Moscow) by A. N. Vystavkin and E. J. Popov.

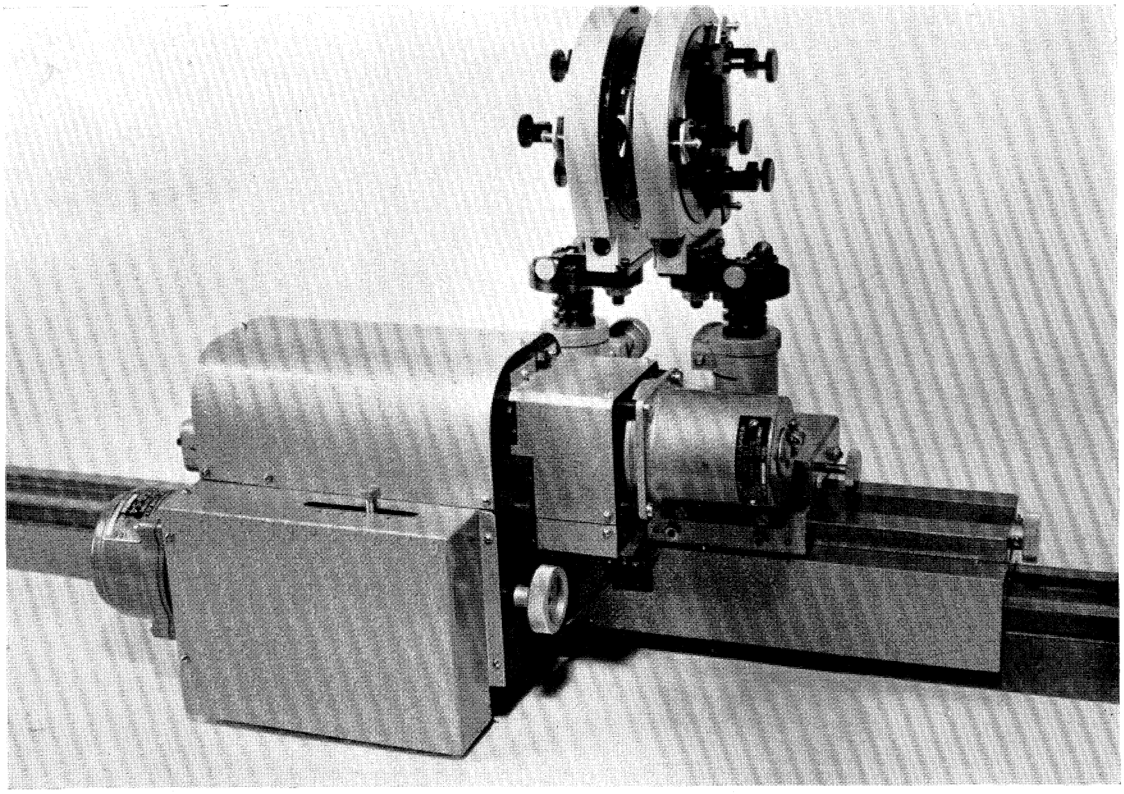

FIGURE 5. The submillimetre Fabry–Pérot interferometer with wire-grid elements constructed in the Moscow P. N. Lebedev Physical Institute by N. A. Irisova, E. Dianov and E. Vinogradov.

1966; Arams *et al.* 1966; Besson *et al.* 1965). Figure 4, plate 12, shows as an example, the submillimetre radiometer with In-Sb sensitive element developed in the Moscow Institute of Radiotechnics and Electronics by Dr Vystavkin and Dr Popov. Great progress has been made in the field of submillimetre guidance, filtering and techniques of measurement, in particular, polarization and interference techniques (see review by Colleman 1963; also Vinogradov, Dianov & Irisova 1965). Figure 5, plate 12, shows a submillimetre Fabry–Pérot interferometer using wire-grid elements, developed in the Moscow Lebedev Physical Institute (in the Laboratoty led by Academician A. Prochorov) by Dr Natalie A. Irisova and her collaborators E. Dianov and E. Vinogradov.

It is known, that in submillimetre radiometers multimode detectors are used instead of the single-mode ones, developed for the microwave range. In these detectors the linear dimensions are larger than the mean wavelength, and each element of the detector transforms the radiation incident on it independently of the others. This circumstance, as is known, causes some modifications in expressions of antennae directivity and noise threshold sensitivity of radiometers. These problems are investigated in a number of papers by Williams & Chang (1963), Karlov & Prochorov (1964), Popov (1965) and others.

In some calculations of sensitivity it turned out to be necessary to use Plank's representation instead of the Rayleigh–Jeans. But this is only when energy of one quantum $h\nu$ is of the same order or more than kT. When we consider a high temperature submillimetre radiation it is possible to keep a Rayleigh–Jeans representation. These problems are investigated in detail by Karlov & Chichachev (1959) from Lebedev Institute and by other authors.

The main difficulties in the development of submillimetre astronomy technique arise from the necessity of taking the receiving apparatus out of the Earth's atmosphere, or at least by partially excluding its influence.

Naturally, the first method consists in installing radiometers at high altitude, where humidity is less than 1 g/m^3 during the most part of the year. Such attempts were undertaken by several groups among which is the group from the Queen Mary College, London (Bastin *et al.* 1964; Baldock *et al.* 1965), which conducted observations at the altitude of about 2000 m at wavelengths of 1–4 mm. The group from Gorki Radiophysical Institute (U.S.S.R.) has worked on Elbrus and Aragaz (Caucasus), and also on East Pamyr (Gorohov, Drjagin & Fedoseev 1962; Kisliakov & Plechkov 1964; Fedoseev *et al.* 1967).

During these observations atmospheric attenuation and also Sun and Moon submillimetre radiation have been mainly investigated. All these observations allowed to obtain very interesting data concerning Sun and especially Moon radiation in the long-wave part of the submillimetre range. At the same time it is urgently necessary to carry out observations at the highest altitudes, especially for wavelengths shorter than 1 mm.

In particular, the results of measurements by Fedoseev indicate that the observed attenuation caused by a non-resonant absorption in oxygen may, in winter time, considerably exceed that of water vapour. For this reason the calculated attenuation for 1–1·5 mm wavelength turned to be somewhat underestimated.

From what is said above it evidently follows, that for submillimetre astronomy the most promising methods are space astronomy ones.

One of the relatively simple methods consists in the use of stratoplanes and balloons. The first published results of using of such a technique for far infrared observations (Bater *et al.* 1964; Woolf *et al.*, this volume p. 267) are very interesting.

The rigid requirements for radiometer sensitivity due to the weakness of measured intensities demand the development of cooled detectors suitable to stratoplane and balloon altitudes. Of course there are also difficulties with orientation technique. The above-mentioned difficulties considerably increase when using satellite technique for submillimetre observation.

Meanwhile submillimetre and millimetre astronomy are the main branches of space radio astronomy. Two problems must be resolved to ensure the future success of submillimetre astronomy: (*a*) development of high precision mirror antennae suitable for submillimetre wavelengths; (*b*) the use on satellites of cooled submillimetre detectors.

As to the first problem, it seems that here the difficulties may be somewhat smaller than for terrestrial radio astronomy. The absence of wind and weight loadings facilitates the engineering calculations. The main difficulty, probably, will be the problems of assembling and controlling highly directional submillimetre antennae.

The detector cooling problem under satellite conditions is a complicated one. The requirement of cooling to helium temperature (since there are not yet semiconductors or other sensitive elements operated at higher temperatures) necesssitates a volume filled by liquid helium. The storage of such liquid required some economical micro-cooler or cryostat capable of storing liquid helium during a sufficient time interval.

In this case a cryostat is required which can withstand vibration and stresses during the active part of a trajectory and able to store liquid helium during a relatively long period of observation in space conditions—absence of gravity, high vacuum and low-temperature environment. If these difficult technical problems are resolved we may hope that a new and promising branch of astronomy–submillimetre astronomy will arise and give us surprising results.

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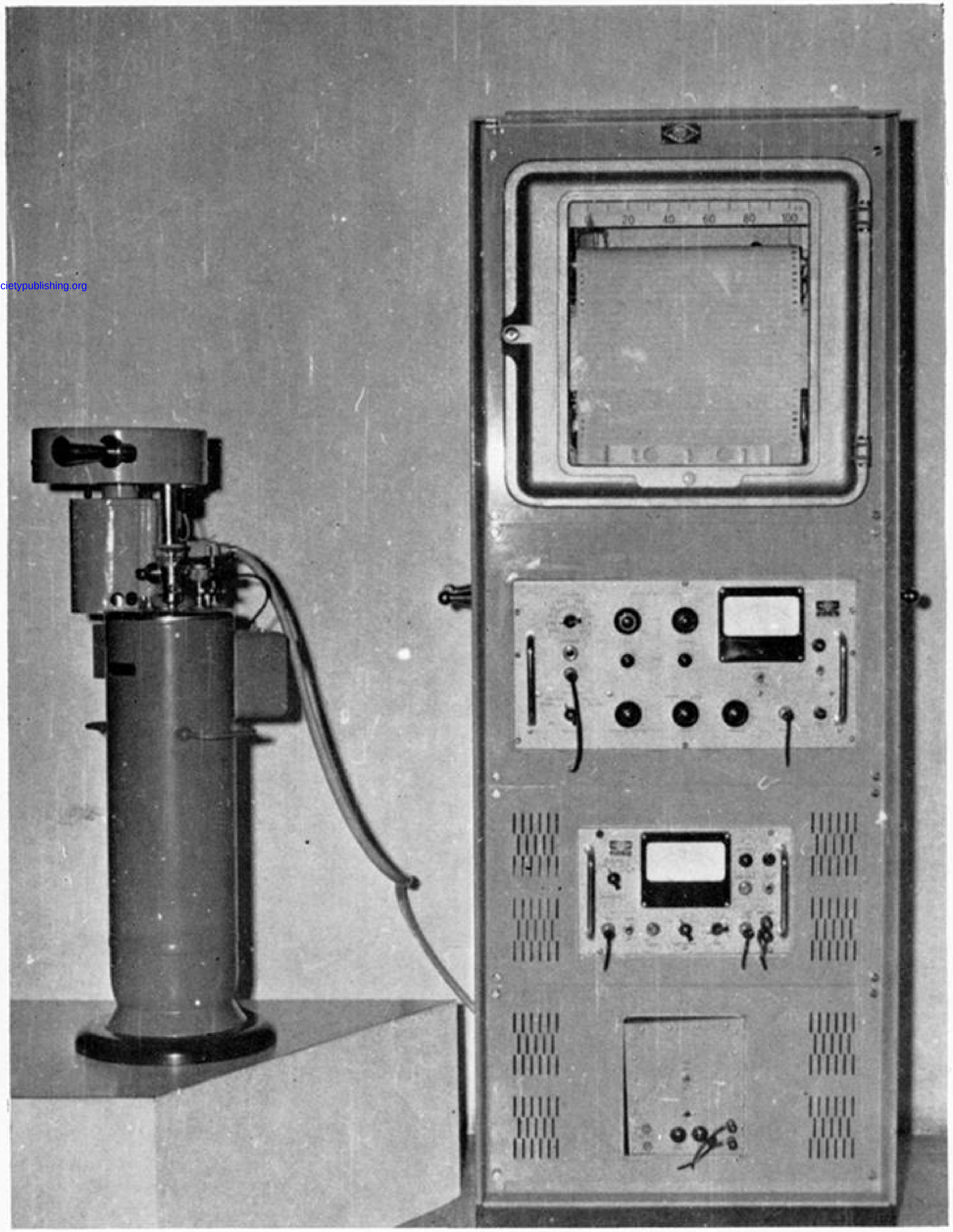

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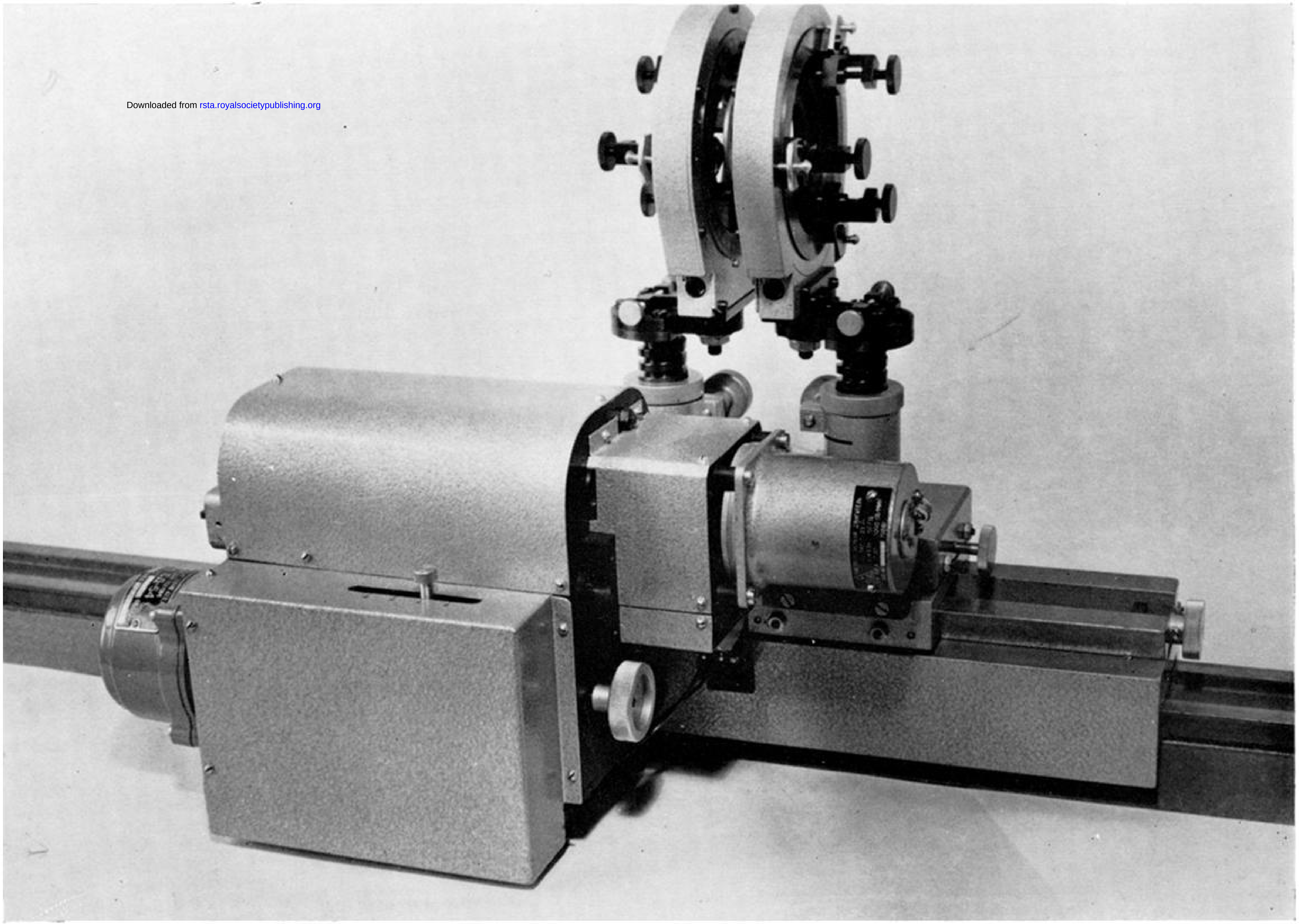

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