LUNAR THERMAL RADIO EMISSION IN THE CENTIMETER BAND AND SOME CHARACTERISTICS OF THE SURFACE LAYER

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Findings from investigations of lunar radiofrequency emission at several wavelengths in the centimeter band, carried out on the 22-meter radiotelescope of the P. N. Lebedev Physics Institute of the Academy of Sciences of the USSR, are discussed.

The phase-dependent, two-dimensional distribution of brightness temperature and the constant poleward "darkening" of the lunar disc were detected at 0.8, 2.0, and 3.2 cm wavelengths.

Values of effective permittivity for the emitting layer and the latitude distribution of heating of the lunar surface are estimated. The frequency variation of the ratio of depths of penetration of radiofrequency and thermal waves lends strength to the argument favoring a quasi-homogeneous surface layer, and lends added weight to the homogeneous model of the surface. The low effective permittivity and the relatively high value of $(k\rho c)^{-\frac{1}{2}}$ (indeed high, but lower than hitherto supposed), where k is the thermal conductivity, c is the specific heat, and ρ is the effective density of the layer, support the view that the density of the emitting layer is low and apparently decreases toward the surface.

New data obtained on thermal radio emission from the moon are, on the one hand, stimulating a critical review of previously available findings, and, on the other hand, shedding some light on the extent to which these data agree with existing concepts on the structure of the radioemitting layers in the lunar crust.

Known data on lunar radioemission are entered in Table 1, which lists findings published by various authors, as well as findings recently obtained at the P. N. Lebedev Physics Institute of the Academy of Sciences of the USSR.

Observations carried out recently on high-resolution radio telescopes, and benefitting from reliable absolute calibration, permit us to state that the results of several earlier observations [4, 10, 18] were inaccurate, while some results were apparently in error [15].

The constant component of the lunar brightness temperature is 220-240°K, according to recent data. The variable component undergoes a regular variation, varying inversely with wavelength, as was predicted by theory.

The relative amplitude of the first harmonic of the variable component of the brightness temperature drops from 20% at 0.8 cm wavelength to a value not exceeding 1.5-2% [13] at 10 cm. The phase lag of this harmonic systematically increases with respect to the optical phase from 30° at 0.8 cm wavelength to about 45° at 3.2 cm.

Some additional lunar radio emission data would be required to base any inferences on the characteristics of the lunar crust surface layer responsible for emission at radiofrequencies. Until recently, it was necessary to extract the results of radiometric measurements referring to the infrared region, on the one hand and, on the other hand, to entertain several assumptions as to the density and specific heat of the surface layers.

The use of pencil-beam radio telescopes has, to a certain extent, mitigated the arbitrary features attendant upon such assumptions. It is interesting in this context to review the results obtained at the Lebedev Institute on the 22-meter radio telescope [3,9, 12,13].

By taking advantage of the high resolving power of the telescope, it was possible to make a successful estimate, a still crude one to be sure, of some of the characteristics of the surface layer without having to rely wholly on optical data. N. L. Kaidanovskii and the present author made an earlier allusion to this possibility [20].

Observations were conducted at 9.6, 3.2, 2, and 0.8 cm wavelengths during 1959 and 1960. The receiving units used were modulation radiometers. Antenna temperatures were calibrated by comparison with the radiation from a cold matched load and atmospheric radiation. Conversion of antenna temperatures to brightness temperatures was carried out while taking into account scat-

TABLE 1

λ, cm	T_0, °K	T~ per °K	$T_{\sim}/T_0$, %	Phase shift ξ°	Observers	Date publ.	Remarks
0.43	230	–	–	–	Coates [1]	1959	Three measurements (φ_A = 6'.7)
0.8	197	32	16	40	Salomonovich [2]	1958	Central part of disc (φ_A = 18')
0.8	211	40	19	30	Salomonovich and Losovskii [3]	1962	At center of disc (φ_A = 2')
0.85	150	–	–	–	Hagen [4]	1949	Only measurements accurate to ±40%
0.86	225	45	20	40	Gibson [5]	1958	Central part of disc (φ_A = 12'), corrected by [16]
1.25	292	–	–	–	Dicke and Beringer [6]	1946	Only one measurement
1.25	215	34	17	45	Piddington and Minnett [7]	1949	Centered on disc
1.63	224	36	16	34	Zelinskaya, Troitskii, and Fedosev [8]	1959	Centered on disc
2.0	190	20	10	40	Salomonovich and Koshchenko [9]	1961	At center of disc (φ_A ~ 4')
3.2	133	< 7	< 8	–	Kaidanovskii, Turusbekov, and Khaikin [10]	1956	Centered on disc; error in calibration
3.2	183	< 13	< 7	–	Koshchenko, Losovskii, and Salomonovich [11]	1956	Centered on disc
3.2	223	17	7.5	15	Troitskii and Zelinskaya [12]	1960	At center of disc (φ_A = 6'.3)
9.6	230	< 5	< 2	–	Koshchenko, Kuz'min, and Salomonovich [13]	1961	Central part of disc (φ_A = 19')
10	130	< 10	< 8		Kaidanovskii et al. [10]	1956	Centered on disc
10	215	–	–		Piddington and Minnett [14]	1951	Only one measurement
10	315	75	24		Arkabane [15]	1955	Centered on disc
20.5	250	–	< 2		Mezger and Strassl [16]	1959	Centered on disc
22	232	–	–		Westerhout [17]	1958	Centered on disc
25	212	–	—				Corrected by [16]
33	220	–	–		Piddington and Minnett [14]	1951	Only one measurement
75	205	–	–		Dennise and Le Roux [18]		Centered on disc
					Seeger et al. [19]	1957	Centered on disc, Corrected by [16]

tering effects in the side lobes and back lobes of the antenna beam, estimated at 15-20%. The systematic error in the determination of absolute brightness temperature values was in the neighborhood of ±15%, the relative error remained within ±5%, and within ±2% at 9.6 cm wavelength. During the course of the observations, sweeps were made in azimuth through the lunar disc with the axis of the radio telescope placed relative to the angle of elevation of the center of the disc at an angle roughly equal to the halfwidth of the antenna beam. At 9.6 cm wavelength, only the brightness temperature of the central portion of the disc was measured, and this portion was found to have a constant temperature of 230°K, within the limits of error.

Records of sweeps made at wavelengths 3.2, 2, and 0.8 cm were later corrected over the disc for smoothing of the distribution of the antenna beam, after which two-dimensional distributions of brightness temperature over the lunar disc were plotted.

Examples of distributions obtained for 3.2 and 0.8 cm wavelengths are shown in the diagrams. At all three wavelengths, a systematic shift of the region of maximum radio brightness, along the lunar equator and dependent upon phase, was detected. Furthermore, an effect of constant falloff in brightness poleward from the center of the disc was found, and attributed to the decrease of average brightness temperature with increase in latitude ψ over a full lunar cycle. In addition, a constant falloff in

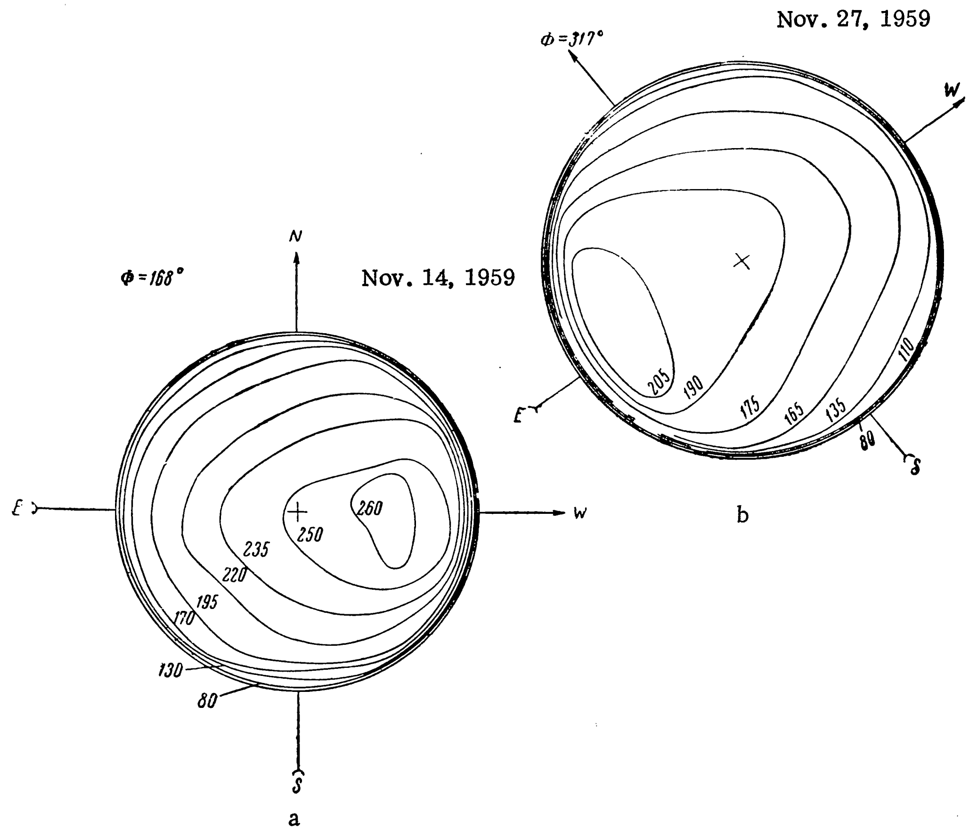

Fig. 1. Examples of two-dimensional brightness temperature distributions, obtained at λ = 0.8 cm; Φ is optical phase (Φ = 0 corresponds to the half-moon phase): a) Φ = 168°; b) Φ = 317°.

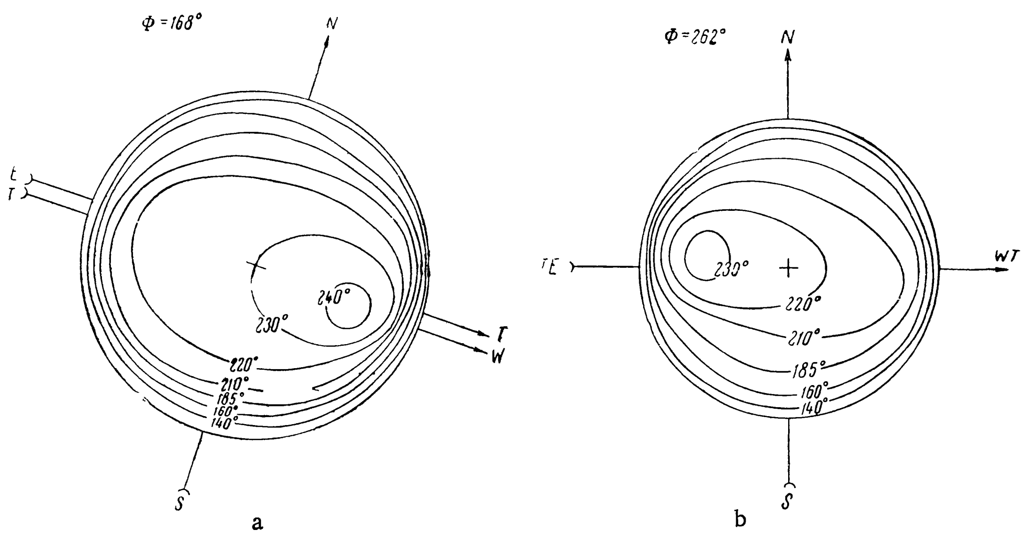

Fig. 2. The same as Fig. 1, but at λ= 3.2 cm: a) Φ = 168°; b) Φ = 262°.

brightness temperature due to a decrease in the emissivity of the moon was observed, the latter being subject to the extent to which rays emergent from the lunar surface emerge at grazing angles in the directions from the center of the disc to the moon's limb.

Curves $\frac{1-R(\varphi)}{1-R(0)}$ giving the variation in the relative emissivity of the moon as a function of longitude φ along the equator were successfully plotted from the two-dimensional distributions obtained at wavelengths 2 and 0.8 cm. To achieve this, distributions corresponding to phases close to lunar quadratures (with phase lag taken into account) were taken in the daytime. A correction was made for inaccurate matching to quadratures, and also for the presence of the second harmonic of the variable component [3]. The result was the plotting of curves of the function $\frac{1-R(\varphi)}{1-R(0)}$, where $R(\varphi)$ is the reflection coefficient. This curve sloped downward toward the edge of the disc, with the clear implication that the lunar surface is not as rough in the centimeter wavelength band as it appears in visible light. Direct application of the $1-R(\varphi)$ law to find the latitude distribution of the surface temperature is possible when the slope of $1-R(\varphi)$ coincides with the slope of $1-R(\psi)$, which is valid only for polarization of the intercepted radiation subtending an angle ±45° from the lunar equator. At measurements on 2 cm, this was indeed the case. Curves of $1-R_V$ for a range of values of permittivity ϵ were plotted to aid in processing results obtained at 8 cm, where the measurements were carried out with a horizontal polarization (corresponding to the vertical component of the electric field vector at the lunar equator).

A comparison with the observational curve demonstrated that values of ϵ lie within the range $1 < \epsilon < 2$. For the value $\epsilon = 1.5$, curves of the latitude distribution of the constant component of brightness temperature were plotted, and these curves, as well as $1-R_h(\psi)$, were plotted as a function of the distribution of the lunar surface temperature (lunar heating) under insulation [21] and governed by the function $\eta(\psi)$*:

$$\frac{T(\psi)}{T(0)} = \frac{1-R_h(\psi)}{1-R_h(0)} \times \frac{T_n + \frac{a_0}{2} D\eta(\psi)}{T_n + \frac{a_0}{2} D}.$$

A comparison of curves plotted for various $\eta(\psi)$ and the observational curve made it possible to choose a function $\eta(\psi)$.

A falloff in surface temperature poleward from the center of the disc was confidently detected and established. The pattern followed by the decreasing readings at 2 cm was close to $\cos^{\frac{1}{2}}\psi$. Measurements at 0.8 cm did not contradict this, however, and the accuracy of the measurements provides no justification for a definitive choice between $\cos\psi$ and $\cos^{\frac{1}{2}}\psi$. Using the parameters corresponding to the more probable law $\cos^{\frac{1}{2}}\psi$, which would bring us closer to the findings reported by Pettit and Nicholson on their measurements [22], we may convert from the relative amplitudes of the variable component of brightness temperature at the center of the disc $T_{\sim}/T_0$ to the physical parameters of the emitting layer. Accordingly, without recourse to optical data, we obtained the value $1 < \epsilon < 2$ and the distribution $\eta(\psi) \approx \cos^{\frac{1}{2}}\psi$. From values of $\epsilon \sim 1.5$, we learn that the emissivity is inordinately high [$(1-R) > 0.99$] in the centimeter wavelength band.

It must be duly noted that the value ϵ = 2-4 assigned here is apparently somewhat too high. Evidence for this may be found independently in a comparison of brightness temperatures in the radiofrequency band and the mean surface temperature at the center of the disc.

We thus assume $\eta(\psi) = \cos^{\frac{1}{2}}\psi$ as a working hypothesis, and the values $T_S = 407°$ and $T_n = 125°$ (more will be said later on the choice of those values). Taking the following expression as a point of departure [21]:

$$\frac{T_{\sim}}{T_0} = \frac{a_1 D}{\sqrt{1+2\delta+2\delta^2}\left(T_n + \frac{a_0}{2} D\right)},$$

we arrive at values of δ equal to the ratio of the depths of penetration of radio waves and the first harmonic of a thermal wave in the course of a lunar cycle.

Table 2 gives values for this quantity referring to wavelengths 0.8, 2.0, 3.2, and 9.6 cm, obtained by the author, and wavelengths 1.25, 1.63, and 20.5 cm, obtained by other authors [7,8,16]. Values of ξ, the lag in "radiophase" with respect to optical phase, are also tabulated.

We see from the table that the value of the ratio δ/λ is close to two for $\lambda > 1$. Values obtained at 1.63 cm do not entirely fit in. At 0.8 cm, the ratio $\delta/\lambda = 2.5$, which is slightly above average value.

We compared the curves of the phase variation with Jaeger's calculations [23]. The average brightness temperature values obtained at 0.8, 2.0, and 3.2 cm were converted to the more reliable measured value $T_0 = 230$°K at 9.6 cm wavelength, to facilitate the comparison. We note that agreement between T_0 at 0.8 and 3.2 cm and $T_0 = 230°$ obtained at 9.6 cm is found as the antenna scattering coefficient β varies from 0.15 to 0.20 in the side lobes and back lobes, which is within the limits of error prevailing when these antenna parameters were determined and in agreement with data of other authors [24].

To compare results with Jaeger's calculations it is convenient to convert from the parameter δ figuring in Troitskii's calculations [21] to the parameter C in Jaeger's work. It is readily appreciated that $C = \sqrt{\pi}/\delta$. Thus, for $\lambda = 0.8$ cm, parameter $C = 0.85$; for $\lambda = 2.0$ cm, parameter $C = 0.4$; and for $\lambda = 3.2$ cm, parameter $C = 0.29$.

Jaeger's curves were extrapolated to apply to the corresponding C values and were compared with the phase variation found at the three wavelengths. It was found that neither the single-layer model nor the Jaeger two-layer model satisfied the observational evidence. The explanation apparently resides in the following.

Jaeger's curves were designed to fit the data of Pettit and Nicholson [22], where $T_S = 374°$ and $T_n = 120° \pm 15$°K. But, as stated earlier [20], the actual

*Here, according to [21], $D = T_S - T_n$, where T_S is the surface temperature of the subsolar point; T_n is the nighttime lunar surface temperature; $a_0 = \frac{1}{\pi}\int_{-\pi/2}^{+\pi/2} \eta(x)dx$.

TABLE 2

λ, cm	$T_{\smile}/T_0$	δ	δ/λ	$\tan\xi=\frac{\delta}{1+\delta}$	ξ_{theor}	ξ_{obs}
0.8	0.19	2.0	2.5	0.67	34	30°±5°
1.25	0.17	2.4	1.9	0.71	35	45
1.63	0.16	2.3	1.4	0.69	35	34
2.0	0.10	4.4	2.2	0.82	39	40°±5°
3.2	0.075	6.1	1.9	0.86	41	45°±5°
9.6	$\lesssim$0.02	$\gtrsim$24	$\gtrsim$2.4	0.97	44	—
20.5	$\lesssim$0.02	$\gtrsim$25	$\gtrsim$1.20	—	—	—

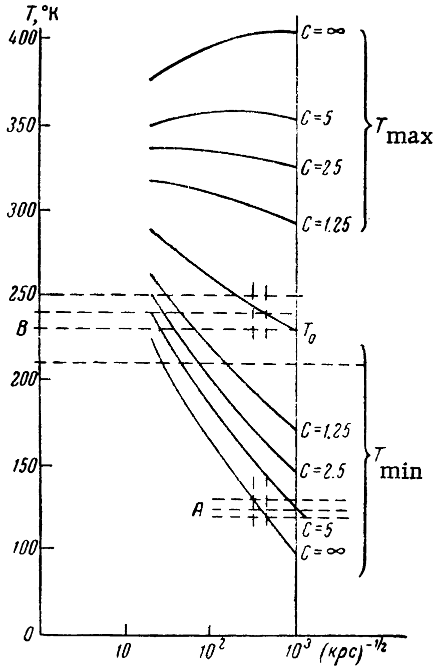

Fig. 3. T_0, T_{max}, and T_{min} plotted against $(k\rho c)^{-\frac{1}{2}}$ for a range of values $C = \sqrt{\pi}/\delta$ (Jaeger [23] with 9.5% corrective factor). Broken lines: A) value $T_n = 125 \pm 5$°K (Sinton [25]); B) average radio temperature $T_0 = 230° \pm 10\%$, and the corresponding $(k\rho c)^{-\frac{1}{2}}$ values.

measurement by Pettit and Nicholson gives $T_S = 407$°K, and the value 374°K was obtained theoretically, using the well-known value of the solar constant at that time. Further, according to Sinton's latest data [25], the nighttime temperature of the moon $T_n = 125° \pm 5$°K.

Consequently, Jaeger's curves must be revised. Since the equations which Jaeger utilized were nonlinear equations, they were solved by numerical integration, and the task of replotting the curves proved to be quite intricate. We made the correction only by increasing all the ordinates of the curve by 9.5%, which came out close to the ratios 374/407 and 120/215. According to the corrected curves (Fig. 3), the results of Pettit and Nicholson (variation of surface temperature during a lunation from T_S to T_n) can be accounted for by assuming a highly porous layer in which $(k\rho c)^{-\frac{1}{2}} = 300$-$450$ [pumice stone has $(k\rho c)^{-\frac{1}{2}} = 250$].† We obtained the values $T_0 = 230° \pm 10\%$, corresponding to the values $(k\rho c)^{-\frac{1}{2}} = 300$-$1000$. For the two values $(k\rho c)^{-\frac{1}{2}} = 380$ and $(k\rho c)^{-\frac{1}{2}} = 10^3$, curves for the phase variation were plotted after extrapolation to the corresponding values C = 0.85, C = 0.4, and C = 0.29. As is clear from Fig. 4, a comparison with observational data indicates satisfactory agreement. However, the insufficient accuracy in the measurements removed any groups for a definitive choice of either $(k\rho c)^{-\frac{1}{2}}$ value in the range of interest. The approximately constant value of the δ/λ ratio could be accepted with greater confidence than earlier, however, from which we can infer that the homogeneous single-layer model is correct, and, further, that dust is not necessarily present as an emitting layer. $(k\rho c)^{-\frac{1}{2}}$ below 1000 suggests some highly porous and low-density material like slag or pumice. The comparatively low permittivity value also implies that the material is highly porous.

To estimate the order of magnitude of the depth to which the thermal wave penetrates, we may assign some intermediate value $(k\rho c)^{-\frac{1}{2}} = 600$. If we assume that the low value $1 < \epsilon < 2$ is due to porosity, such that $\epsilon \approx (1-\rho_{eff})/(\rho_M + \epsilon_M)(\rho_{eff}/\rho_M)$, then, at density $\rho_M = 2$ g/cm³ and $\epsilon_M = 3$, the effective density of the layer $\rho_{eff} = 0.5$ g/cm³. Under these assumptions, $k = 3.5 \cdot 10^{-5}$ and the depth of penetration of the first harmonic of the thermal wave $1/\beta \approx 20$ cm.

By using to good advantage the value $\delta = 2\lambda$, which is in any case valid for wavelengths longward of 1 cm, we find the depth of penetration of an electromagnetic wave [21], $1/\chi = \delta/\beta = 40\lambda$. For the wavelength 2 cm, for example, this depth is found to be 80 cm. The loss angle of the material is then

$$\Delta = \operatorname{arc\,tg}\frac{\lambda\chi}{2\pi\sqrt{\varepsilon}} = \operatorname{arc\,tg}\frac{1}{80\pi\cdot 1{,}2} = 10'.$$

†As T_S increases from 370 to 407°K, $(k\rho c)^{-\frac{1}{2}}$ must drop from 1000 to 750 in order for the theoretically predicted [23] and empirically observed [22] lunar eclipse curves to coincide.

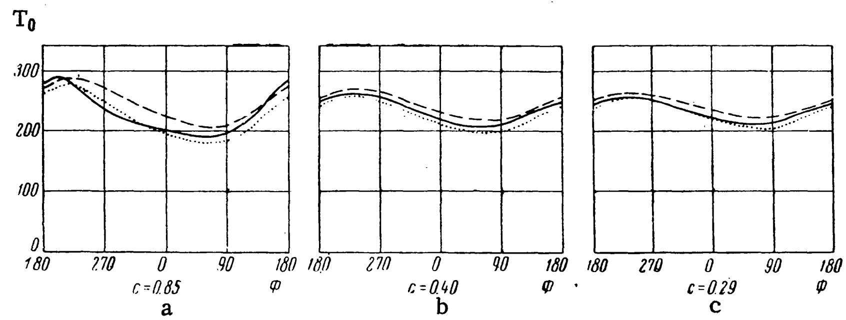

Fig. 4. Curves of phase variation of brightness temperature at center of disc for wavelengths: a) λ = 0.8 cm; b) λ = 2 cm; and, c) λ = 3.2 cm, obtained after processing the observational material (solid-line curve) and predicted values at $(k\rho c)^{-\frac{1}{2}}$ = 380 (dashes) and $(k\rho c)^{-\frac{1}{2}}$ = 1000 (dots).

The value of δ for the wavelength 0.8 cm attenuating in the near-surface layer is relatively higher. This is apparently evidence in support of the earlier advanced law [26] that dielectric losses are lower and thermal conductivity is lower in that layer; we are dealing, it appears, with some gradual decrease in these properties with increased depth.

The results of investigations carried out with the Lebedev Physics Institute radiotelescope bring us to the following conclusions:

1. Observations benefiting from increased resolution have confidently revealed the varying distribution in radiobrightness, predicted by theory, over the lunar disc at wavelengths 0.8-3.2 cm. In addition to the phase-dependent longitude distribution, there is a constant latitude distribution and a " darkening" of the limb of the moon's disc due to a falloff in emissivity at the limb.

2. Investigations of these distributions enabled an estimate to be made, based on radio data, of the value of the effective dielectric constant, viz., $1 < \epsilon_{eff} < 2$, as well as an estimate of the surface heating function $\eta(\psi)$, which was found to be close to $\cos^{\frac{1}{2}}\psi$. These data led to a determination of the emissivity, which was placed at the high value ~0.99.

3. Assuming more accurate surface temperature values T_S and T_n, it was demonstrated that the relation $\delta/\lambda = 2$ holds for wavelengths $\lambda > 1$ cm. At 0.8 cm wavelength, $\delta/\lambda = 2.5$, which probably attests to a lower thermal conductivity and lower ϵ_{eff} value in the layer adjacent to the surface.

4. Comparison with corrected Jaeger curves (first-approximation corrections) indicates that the single-layer homogeneous model of the lunar surface is the more plausible hypothesis, at $(k\rho c)^{-\frac{1}{2}} < 10^3$ in any case. Data obtained at infrared wavelengths, and requiring $(k\rho c)^{-\frac{1}{2}}$ = 300-750, do not contradict observed radio-temperature measurements at $T_0 = 230° \pm 10\%$. A comparison of the behavior of the curves of radio-temperature variation bear evidence that $(k\rho c)^{-\frac{1}{2}}$ is close to 600 to 700. But the inaccuracy of the measurements bars our arriving at a definitive value of which we can feel confident for the time being, however.

5. The low ϵ_{eff} value argues in support of a low density for the surface layer, with the density apparently decreasing toward the surface.

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