Why we cannot observe a Lunar Eclipse with our Radio Telescopes

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Lunar Observations

Because the lunar surface is not solid rock which heats quickly under the solar radiation, but is of broken-up composition of dust, sand, and small pebbles, known as 'regolith', which has a slow thermal response to illumination by the Sun, one expects that the few hours of a lunar eclipse do not appreciably alter the lunar soil temperature, which is measured by the radio emission of the entire Moon. The observations at DL0SHF indeed failed to record any genuine drop of the radio emission on 1.3, 8, 10, and 24 GHz.

But how large is the drop in lunar radio noise during an eclipse? The emission is thermal radiation and hence is the result of the illumination of the soil by the Sun.

As early as 1869, the Earl of Rosse used a 90 cm diameter optical telescope at Birr Castle and thermocouples to measure the infrared radiation from the Moon. In 1930 Pettit and Nicholson measured the lunar surface temperatures in the 8-14µm atmospheric window, finding that it is about 400 K at local noon. During a lunar total eclipse the surface temperature drops quickly to about 150 K and recovers almost immediately at the end of the eclipse. Likewise, the temperature varies during a month (“lunation”), from 100 K at New Moon and 400 K at Full Moon.
Theoretical treatments show that the lunar soil consists of a material with an extremely low thermal conductivity. A sudden change of the surface temperature is propagated to the lower layers only weakly and slowly.
Radio observations at 24 GHz by Piddington and Minnett (1949) revealed that the temperature throughout a lunation varied only 104 K and its variation lags the solar illumination by about 4 days. This demonstrated that the lunar soil is partially transparent to this wavelength, so that radiation from beneath the surface is observed.
Much more work was done – especially around the years of unmanned and manned lunar landings – which lead to a thorough understanding of the physics of the lunar soil and to refined models, which can be used to compute the thermal radiation from the Moon.

Modeling the Lunar Surface

It is not the aim of this document to use a complete and detailed model, based on the latest studies. Let us rather take a simplified model which incorporates the essential physical processes, but which is accurate enough for computing the radio radiation from the Moon in a reliable way.
The model of Wesselink (1948) with some modifications serves well this purpose. It consists of these assumptions:

- The lunar soil at the middle of the lunar disk is modeled as a column of material whose physical properties do not change with depth below the surface:
- density: $\rho = 3.3$ g/cm^3 (mean value for the entire Moon)
- specific heat: $c = 200$ J/kg/K
- thermal conductivity: $k = 0.003$ W/m/K
- electric loss tangent: $\tan\delta = 0.0143$
- The surface is illuminated by the Sun, whose elevation varies during one month. The incident power (solar constant 1.3 kW/m^2) is transported to deeper layers due to thermal conduction.
- According to its temperature, each soil layer emits thermal radiation, part of which emerges from the surface due to the transparency of the material, specified by its loss tangent.
- The start of a lunation (of 29.5 days) is taken at the local sunrise. Hence, full moon is at phase 0.25 (or 4 days).
- During the eclipse, the solar illumination falls or rises linearly during the time in the penumbra, and is zero when the Moon is in the umbra.

Some Technical Details

The equation of thermal conduction is applied in one dimension, viz. the depth below the surface. With the physical properties of the material being constant, one has to solve this partial differential equation for the temperature T as a function of depth x

$$\partial T/\partial t = a \ \partial^2 T/\partial x^2$$

which describes how the temperature of one layer changes due to the change in the vertical temperature profile by the heat flow in the column. The parameter $a = k/(\rho * c)$ is the thermal diffusivity. The incident solar flux F(t) determines the surface temperature (Stefan's constant $\sigma = 5.6696\text{E-}8$ Wm^{-2} K^{-4}):

$$\sigma T_0^4 = F(t) + k\, \partial T/\partial x$$

These equations are solved numerically: the column is divided into 500 layers, whose temperatures are initially set to 220 K. Depending on the incident solar flux, the changes in time of these temperatures are computed from the discrete form of the thermal equation, with the surface illumination as boundary condition, and using the Crank-Nicholson method. A simulation is taken through several lunations, so that the temperature profile is allowed to settle into its equilibrium shape.

The radio brightness temperature T_B at frequency f is the sum of the contributions from all layers:

$$T_B(f) = \int T(x) * \exp(-x*\kappa(f)) * \kappa(f)\, dx$$

with the frequency (or wavelength λ) dependent absorption coefficient

$$\kappa(f) = 2\pi \sqrt{\varepsilon}\ \tan\delta / \lambda$$

with the relative dielectric constant $\varepsilon = 1.5$, as used here.

During One Month:

Figure 1 shows the evolution of the temperatures at several depths during one lunation. As the solar illumination increases after sunrise, the surface temperature follows this very closely. It rises to about 380 K when the Sun is overhead, which corresponds to full moon as seen from Earth. After sunset, the temperature falls quickly, but retains a certain memory. When the Moon is no longer illuminated, the temperature falls very slowly towards about 100 K.

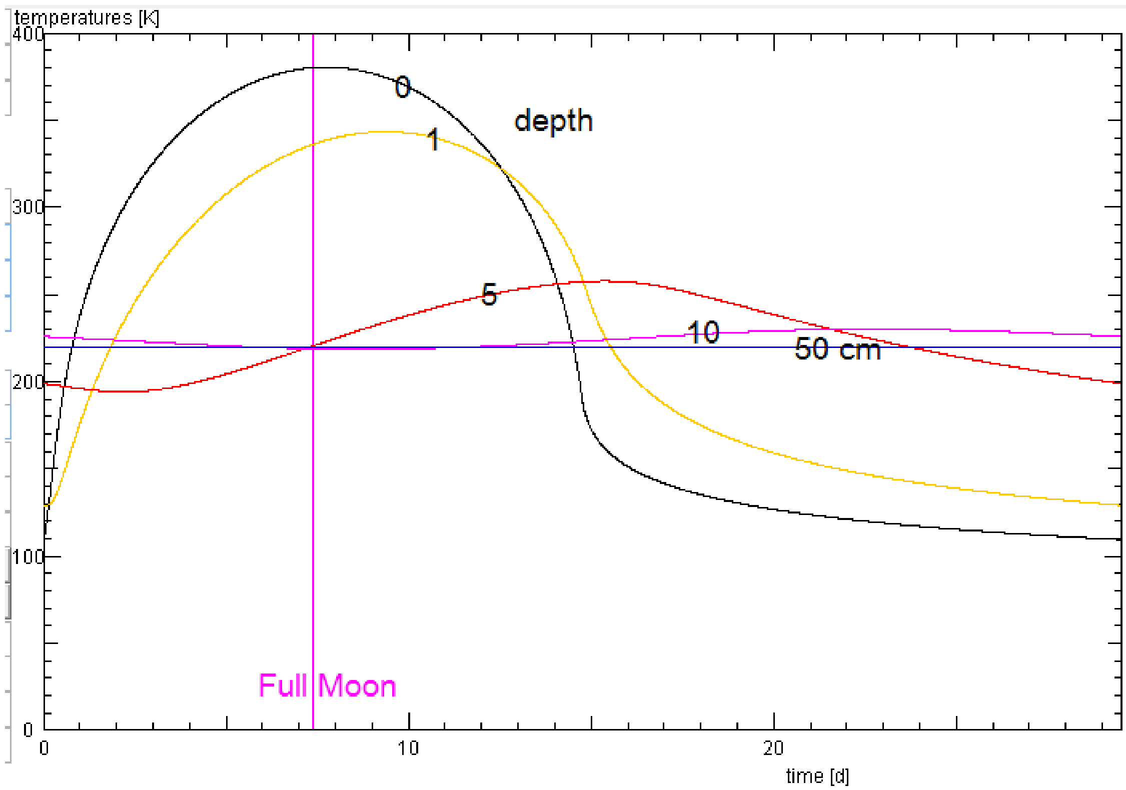

Fig. 1 *The variation of the temperature at the surface and at various depths during one lunation: Zero time is at sun rise, when solar illumination starts. It stops at sunset on day 14.25.*

The layers below the surface also follow the solar heating, but with a certain delay: at a depth of 1 cm the temperature reaches its maximum value – of only 340 K – only 3½ days after full moon. At 5 cm depth the delay is already a week, and the temperature varies quasi-sinusoidally throughout the month with a small amplitude of 25 K. The layers deeper than about 10 cm below the surface do not feel the monthly variation: the temperature remains constant at 220 K.

The temperature profile (Fig. 2) shows a large variation at the surface layer, which diminishes with increasing depth. Below about 10 to 15 cm the temperature remains constant. Thus the monthly change of solar heating occurs too quickly for the heat flow to penetrate into these deeper layers.

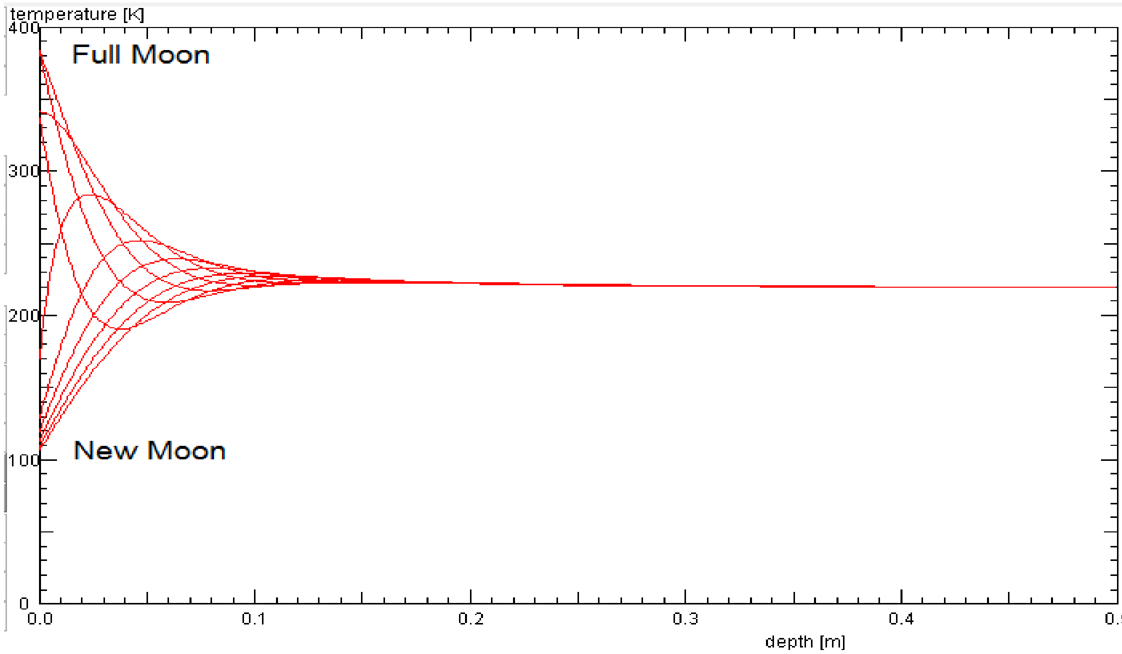

Fig. 2 *The variation of the temperature profile during one lunation, for a time interval of 3 days between individual curves.*

The radio emission does not peak at full moon, but only several days later. This delay and the variation of the intensity depends strongly on frequency: above 300 GHz – i.e. for sub-mm and infrared waves – the intensity follows very closely the curve of the surface temperature. In the SHF region the peak lags by 4 to 6 days, and there still is an appreciable variation. Below about 3 GHz – in the UHF region – the variation becomes progressively smaller.

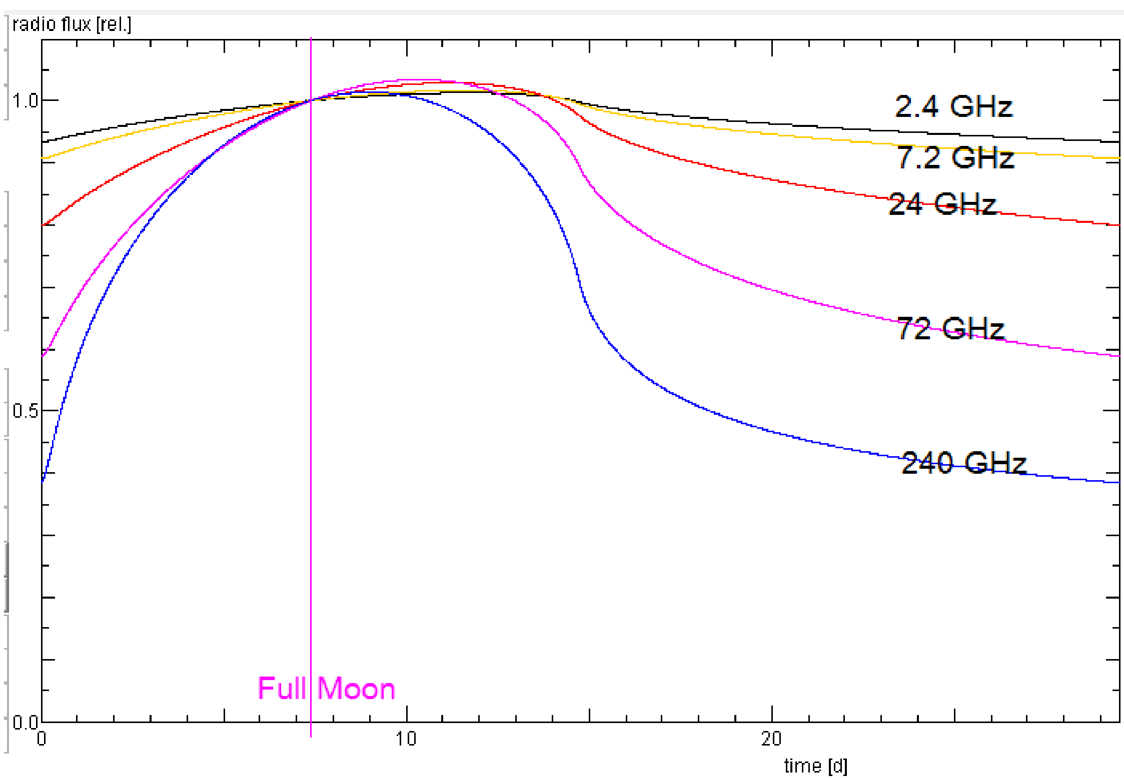

Fig. 3 *The monthly variation of the radio flux at 2.4 to 240 GHz.*

The reason for this behaviour lies with the interplay between the temperature profile and the depths from which radiation at a frequency comes from. Figure 4 depicts the contribution by each depth to the total radio flux at the time of local noon (or full moon). Since the lunar soil is more transparent at longer wavelengths, the radiation at 2.4 GHz comes from the hot surface layers, but mostly from the layers below about 15 cm, where the temperature remains constant. This is quite different from short-wavelength radiation at 240 GHz which comes only from the hot top soil.

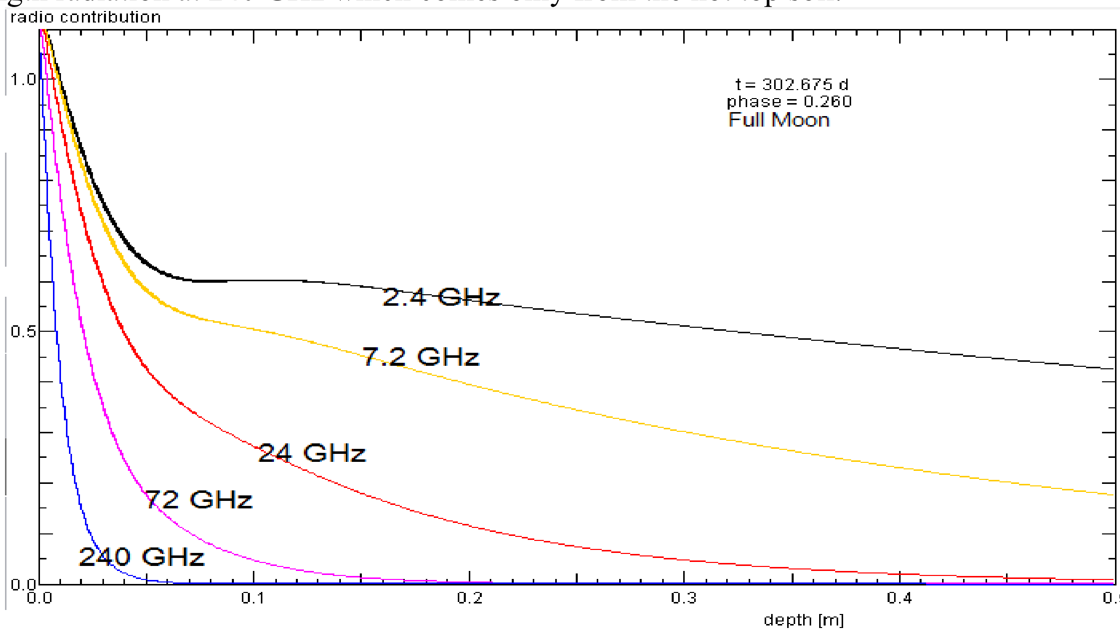

Fig. 4 *The contributions of each depth to the radio emission at Full Moon.*

Near new moon, when the soil is not illuminated and cools off, the contributions (Fig. 5) to the radio emission for longer waves still come from the deeper layers of constant temperature, and thus the emission at low frequencies remains almost unchanged. In contrast, the radio flux at 240 GHz is low because the surface temperature had dropped to about 100 K.

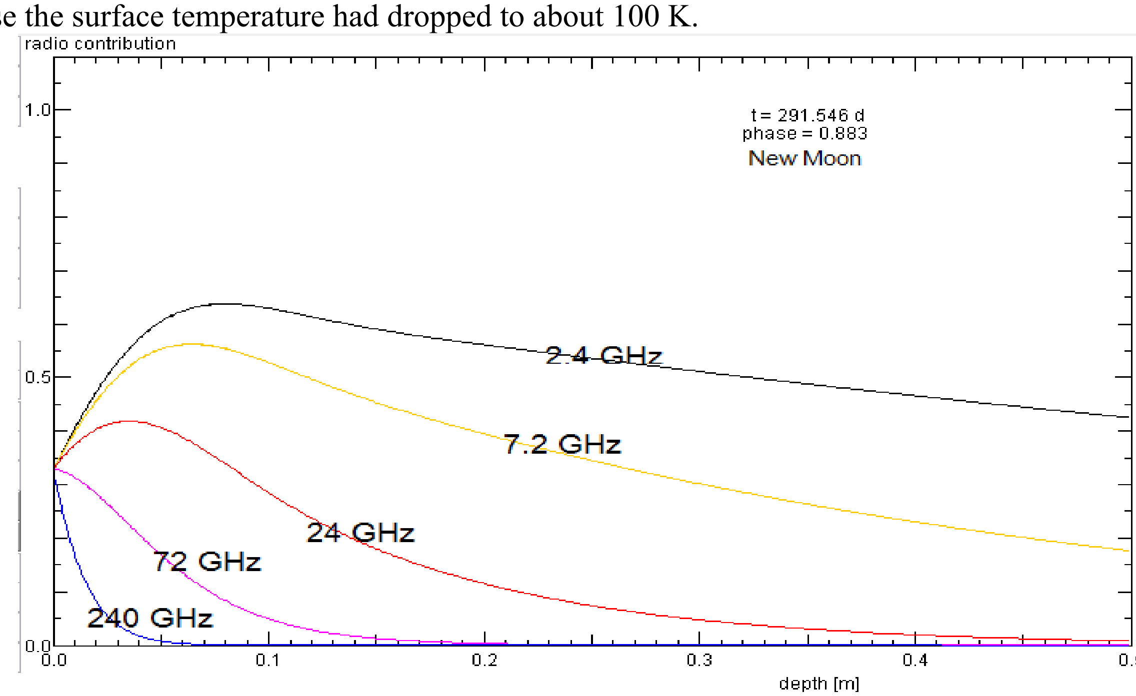

Fig. 5 *The contributions of each depth to the radio emission at New Moon.*

During a Total Lunar Eclipse:

When the Moon enters the penumbra of the Earth, the solar illumination is reduced. It reaches zero when the Moon is in the umbra. As a consequence, the surface temperature falls (Fig.6), and reaches about 200 K at the end of the umbra interval. Then the temperature rises again in the penumbra. After the end of the eclipse, it still takes 1 or 2 hours to reach the pre-eclipse value.

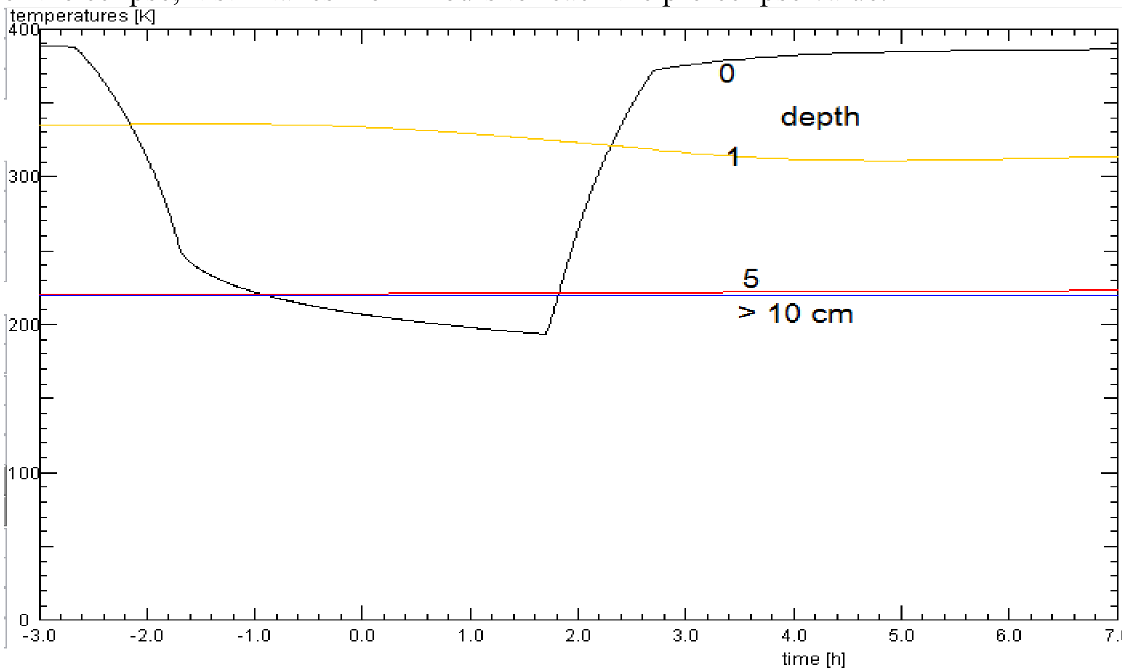

Fig. 6 *The variation of temperature at various depths during a total lunar eclipse. Maximum eclipse is at time = 0.*

The layers below the surface show little or no reaction: at 1 cm depth the temperature falls slowly by about 20 K and takes a long time after the eclipse to recover. At depths below 5 cm the temperature does not change at all. This is also shown in the temperature profiles (Fig.7) taken at several instants during the eclipse.

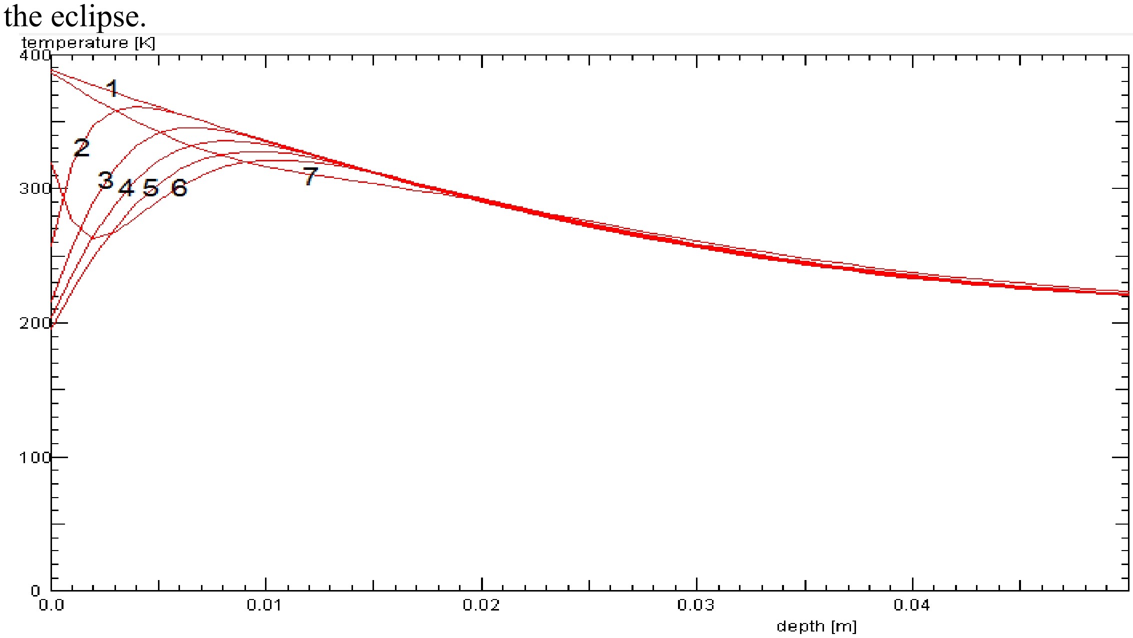

Fig. *7 The variation of temperature during a total lunar eclipse. The numbers mark a sequence of times from the start of the eclipse to sometime before the end.*

Consequently, the radio emission does not change very much during the eclipse (Fig. 8). While at 240 GHz the radio flux drops by as much as 20 percent, the drop at 24 GHz is only 3 percent, and 0.2 percent at 2.4 GHz.

On the 24 GHz antenna at DL0SHF, the Moon is about Y = 10 * log((Moon+Noise)/Noise) = 2 dB above the noise, i.e. its signal is 0.58 times the noise level. A drop by 2 percent in the lunar signal means that the Moon at eclipse is only 0.58 * 0.98 = 0.57, hence Y = 1.97 dB or 0.03 dB below the level of the unobscured Moon. In the observations, the noise due to short-term random fluctuations of the measured level and to the tracking updates is about 0.01 dB, which indicates that a detection of the lunar eclipse on 24 GHz could just have been possible, if it had not been for the gradual increase and drop of instrumental noise near maximum eclipse. The situation is much less favourable at lower frequencies.

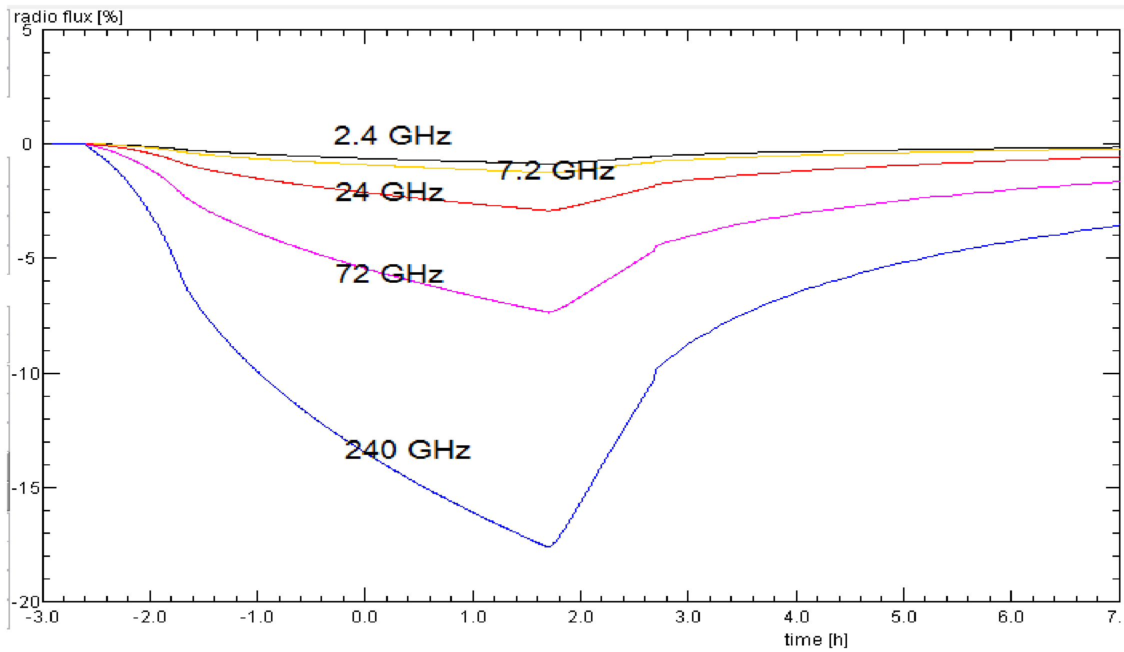

Fig. 8 *A total lunar eclipse as seen at radio frequencies from 2.4 to 240 GHz.*

The contributions of the layers to the radio flux, at maximum eclipse (Fig. 9) show how little the emission is perturbed by the cooling of the surface layer.

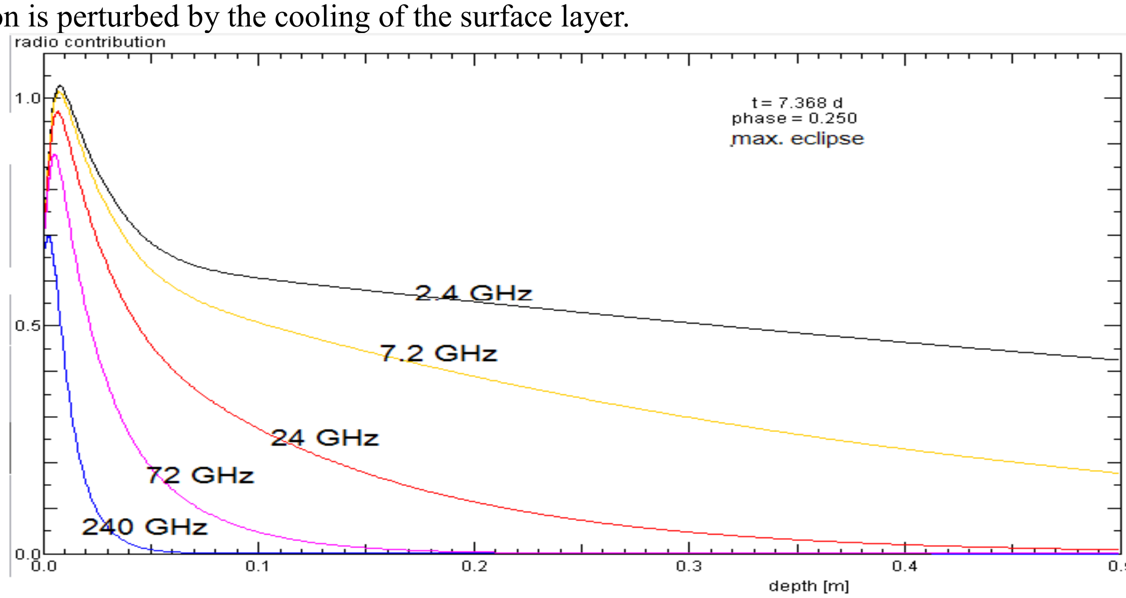

Fig. 9 *The contributions to the radio flux at frequencies from 2.4 to 240 GHz at the time of maximum eclipse.*

A More Realistic Model

The model of the lunar soil can be made more realistic (Jones et al. 1975, Ulich et al. 1974) by taking into account that the soil density varies with depth, as well as the temperature-dependence of the specific heat – as measured with samples from the Apollo 11 mission – and that the thermal conductance depends on temperature and density, as measured from basalt rocks in vacuum. The depth variations of these three quantities are depicted in Fig. 10.

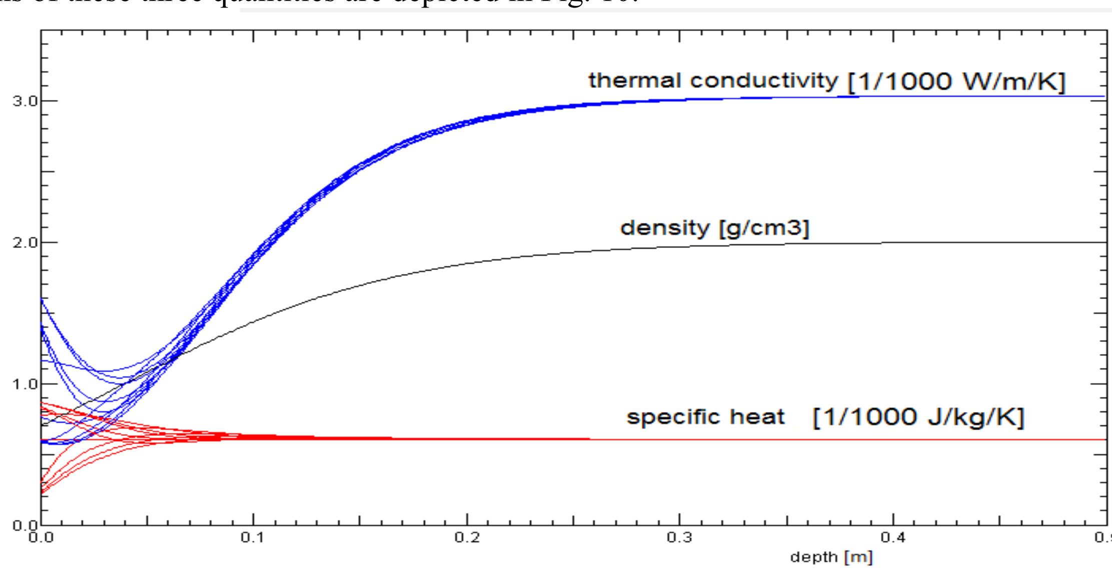

Fig. 10 *The depth dependence of the density, specific heat, and thermal conductivity of the lunar soil. The profiles of the latter two quantities are shown for several times during one entire lunar day.*

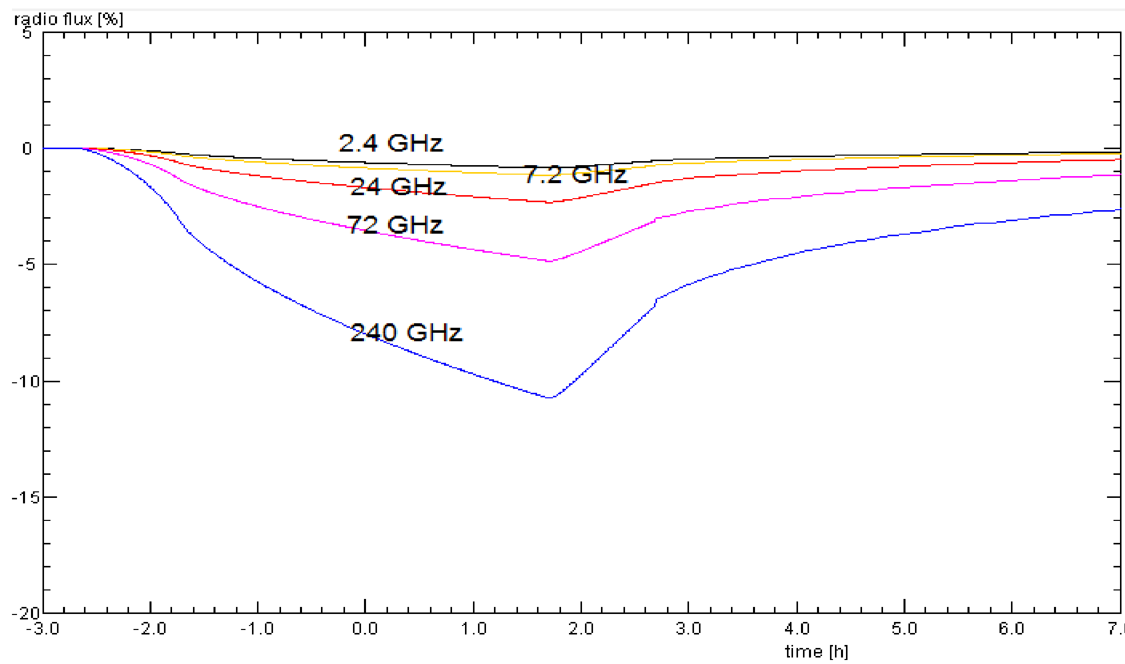

Fig. 11 *A total lunar eclipse as seen at radio frequencies from 2.4 to 240 GHz, computed from the more detailed model.*

The eclipse simulation (Fig. 11) reveals that the drops in radio flux are even less deep than predicted in the simplified model of Fig.8.

Conclusions

A demonstrative model for the heat transfer in the layers of the lunar soil by sunlight permits to compute the temperatures and the radio fluxes from the Moon during the periodic monthly illumination and during a total lunar eclipse. The results can be summarized as

- The maximum of the radio emission occurs several days after full moon. This amounts to about 5 days for 10 to 100 GHz, and less than 1 day for 300 GHz and higher
- The monthly variation is less than 10 percent for frequencies below 10 GHz, but is measurable at frequencies above 10 GHz
- The drop in radio flux from the Moon during a total lunar eclipse is very small: 0.2 percent at 2.4 GHz, 2..3 percent at 24 GHz, and 10..20 percent at 240 GHz
- The conclusions depend on the details of the model, i.e. the physical properties of the lunar soil. But already the simple model shows the basic features and is accurate enough to provide reliable predictions. A more realistic model based on measured soil properties from the Apollo lunar landings gives even less deep drops in radio flux.

Due to the lunar soil's thermal inertia and the penetration of radio waves into the lunar soil the drop in radio flux during a lunar total eclipse is very small, especially at lower frequencies. Thus a detection of a signal drop with ordinary amateur equipment is rather difficult. Additional measures would need to be taken to make the system more stable and to cut down noise, for example by continuous tracking.

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