# Moon disc temperature as a function of phase at 1700 MHz

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**Abstract.** The aim of this work was measuring the moon's temperature at 1700 MHz (17.65 cm) and investigate whether there was a difference between full and new moon, as had been found earlier at different frequencies. The measurements were made at the APRAXOS radio telescope in the city of Zurich. Despite the difficulties, the background radiation and man made noise caused, a variation could indeed be found.

**Key words.** moon, temperature, phase, 1700 MHz

## 1. Introduction

In 1946, Dicke and Beringer descovered the thermal radiation of the moon. In 1949, Piddington and Minnet observed the moon at wavelength 1.25 cm and discovered, that the temperature varied with lunar phase. They found also, that the microwave temperatures exhibited a phase lag of about 3.5 days. The temperature variation gets smaller with longer wavelengths. Seeger, Westerhout an Conway reported a variation of maximum 10 percent at 75 cm wavelength [Kraus]. Christian Monstein from ETHZ made observations at 2.7 cm wavelength with a conventional satellite receiver and found a maximal temperature 5 days after full moon. Measurements at 1700 MHz or 17.6 cm have not yet been made.

## 2. Radio Emission from the moon

At optical wavelengths, the moon is mainly seen in reflected light from the sun. At radio wavelengths, the situation is different. Compared to the black body emission, the reflected radiation from the sun is very small. The microwave radiation has its origin at some depth below the surface of the moon. Therefore, from the phase lag of the thermal radiation, one can also get information about surface properties of the moon.

## 3. Observing the moon in Zurich

### 3.1. APRAXOS

The observations were made at APRAXOS, the 5 Meter antenna of the Institute of Astronomy, ETHZ, situated in the midst of town. The antenna was built in 1970. From 1972 until 1974, it was used to observe radio bursts from the sun. After that, it wasn't in use for 20 years. Since 1991, it is used by students for practical courses. In 1999 it was equipped by a new receiver which is connected to a PC. This makes full remote control via Internet possible.

The fact that the antenna is situated in the middle of town causes problems with background radiation. There is a lot of man made noise such as radiation from cellular phone antennas. Further there are buildings and trees with strong thermal radiation. Therefore, the conditions for a moon measurement were sometimes quite bad for the moon's radiation at 1700 MHz is weak. Assuming that the radiation of the cold sky has an antenna temperature of about 10 K. The moon on the other hand, has an antenna temperature of about 6 K. In addition, there is the man made noise and thermal radiation, as mentioned above. For these reasons, observations below an elevation of about 20° over the horizon don't make much sense. A good illustration of the proportions gives Fig. (1). It shows

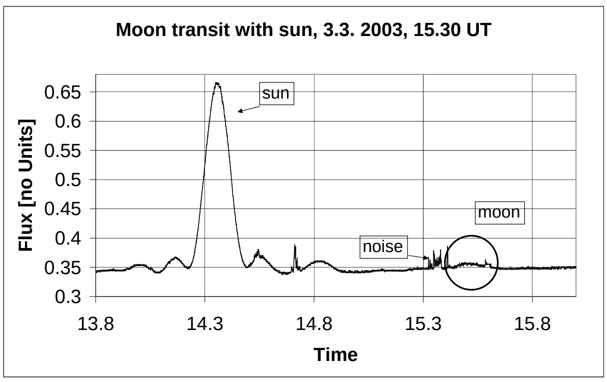


**Fig. 1.** Moon transit on 4.3.2003

a moon transit on 4.03.2003, at 15.30 UT. For it was the day after new moon, the sun was at about the same path and passed the antenna some time before the moon. There is also a lot of noise, which is sometimes several factors stronger than the moon's radiation.

## 4. Calculations

Three main calculations had to be made.

**System temperature**: The system noise temperature $T_{sys}$ determines the sensitivity of the radio - telescope receiver. It consists of the antenna temperature $T_{ant}$ and the noise temperature of the receiver, $T_{RT}$.

$$T_{sys} = T_{ant} + T_{RT} \quad (1)$$

It can be found through a measurement of a strong source, such as the sun. As a function of the temperature of the sun, the system temperature in Kelvin is given as

$$T_{sys} = \frac{T_{sun}}{Y-1} \quad (2)$$

where $T_{sun}$ is the temperature of the sun and Y the so called Y-Factor of the source. The sun temperature is given as

$$T_{sun} = \frac{SA_{eff}}{2k_B} \quad (3)$$

$S$ is the solar flux in $[W/m^2Hz]$, $A_{eff}$ is the effective aperture of the telescope. Using the geometric antenna aperture $A_{geo} = \pi D^2/4$, Eq. (3) can be written as

$$T_{sun} = \frac{SA_{geo}\eta}{2k_B} \quad (4)$$

D is the antenna diameter. For APRAXOS $D = 5\ m$. $\eta$ is the antenna efficiency factor. It has been measured as $\eta = 0.518$ [Dominique Buser]. Putting together Eq. (2) and Eq. (4), the system temperature can be written as

$$T_{syst} = \frac{S\pi D^2\eta}{8k_B(Y-1)} \quad (5)$$

For our purposes, the system temperature should be below 300 K to get a good measurement.

**Antenna temperature**: The moon's antenna temperature is given as

$$T_{ant} = \frac{\Phi moon \pi D^2\eta}{8k_B}10^{-22} \quad (6)$$

$\phi_{moon}$ is the moon flux in solar flux units $[sfu]$. $1sfu = 10^{-22}W/m^2Hz$ . To determine it, one has to make a calibration with the sun, which is described in the next section. Fig. (2) shows the antenna temperature of different sources depending on the frequency.

**Moon temperature**: From the antenna temperature, one can calculate the moon's temperature as

$$T_{moon} = T_{ant}\left(\frac{d_{HPBW}}{d_{moon}}\right)^2 \quad (7)$$

$d_{HPBW}$ is the half power beam with of the main lobe. $d_{moon}$ is the apparent diameter of the moon disc. It changes with lunar phase.

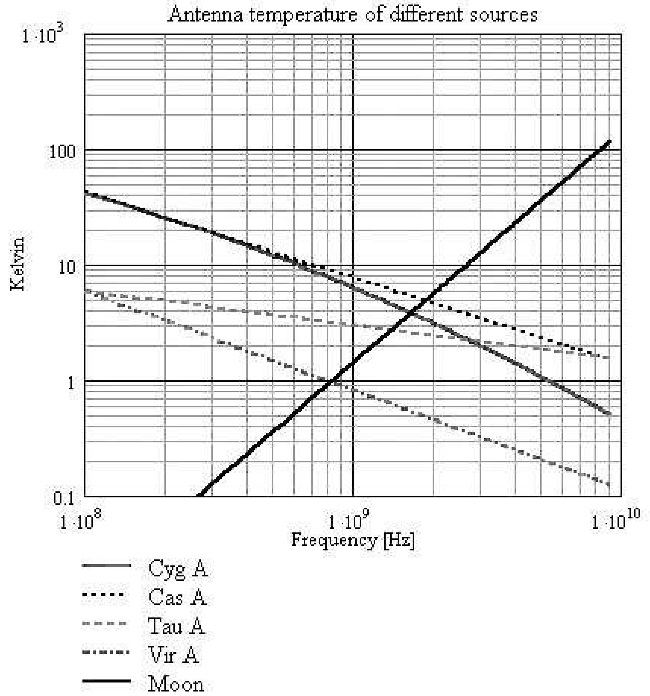


**Fig. 2.** Antenna temperature of different sources, simulated with APRAXOS

## 5. Antenna calibration using the sun

A calibration of the reveiver is necessary to provide an absolute scale of antenna temperature. The measured flux is given as a voltage in logarithmic scale. In order to transform it into a flux density, one has to compare it to a calibration source of known density. A suitable calibration source is the sun. The flux for a determined time and frequency can be found on the homepage of the Space Environment Center (*http://www.sel.noaa.gov/ftpmenu/lists/radio.html*) The calibration consists of the following points.

- Making an on/off-source measurement of the sun, including the cold sky.
- Attenuation in $[dB]$ of the sun. This means, increase the attenuation until the signal has reached the level of the cold sky.

The attenuation can be varied in known steps. Taking the dB difference between the level of the sun and the level of the cold sky gives the above mentioned Y-Faktor in $[dB]$. To calculate the system temperature, it has to be transformed in a linear scale ($Y = 10^{Y_{dB}/10}$). The difference between sun level and background level in an anti-logarithmic scale is proportional to the solar flux. Comparing it to the value in the list on the web gives the measured flux in solar flux units. Fig. (3) shows an ex-

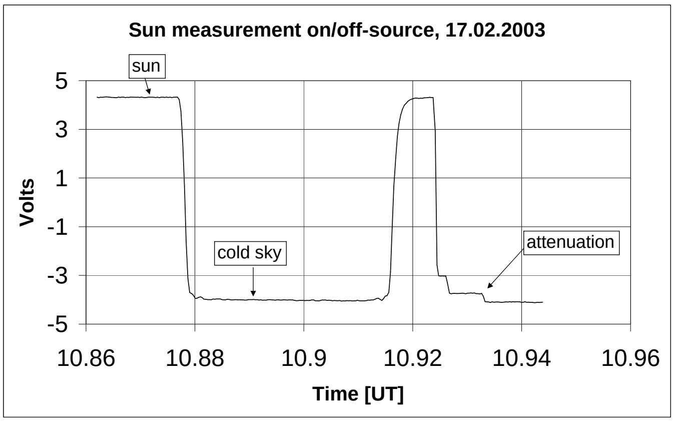


**Fig. 3.** Example of a calibration measurement

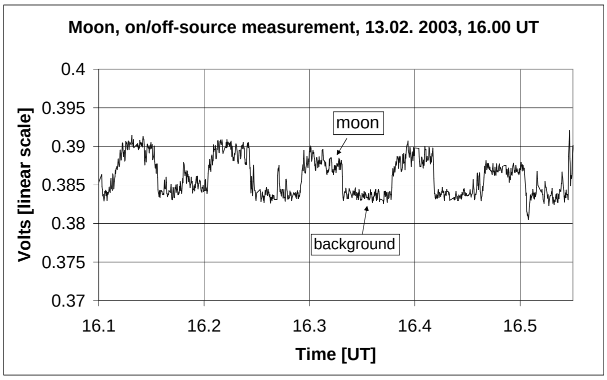


**Fig. 4.** Example of an on/off-source measurement

ample of such a measurement. The moon flux can now be calculated easily. Be $\phi_{moon}$ the measured flux in unknown units, $\phi_{sun}$ the measured solar flux and $F$ the published flux on the Web. The lunar flux in $sfu$ is then given as

$$\Phi_{moon} = \frac{F\phi_{moon}}{\phi_{sun}} \quad (8)$$

## 6. Measuring methods

For the moon observations, two different observation methods where used, depending on the elevation and observation time of the object.

### 6.1. on/off-source

The telescope points at the source for a fixed time, usually a few minutes. It moves then away and stays on the cold sky in the neighbourhood of the source for the same time and so on. The advantage of this method is, that one gets a lot of measurements over a few hours of observation time. On the other hand it's more difficult to decide, whether the background flux is only cold sky, or overlayed by interference. Fig. (4) is an example of such an on/off-source measurement, taken on 17.02.2003 at 16.00 UT. This method has been used for most measurements.

### 6.2. Transit

In a transit, the antenna points at specified coordinates and the source drifts by.

In detail: the telescope is pointed at coordinates, where the source is expected to be at a specified time. The measurement starts two hours before the transit and ends about 2 hours after. This guarantees, that enough background radiation is measured at that point. Because of the longer integration time, this method is more accurate. The disadvantage is, that one gets only one measurement in four hours. It happens, that at the time of the passage,

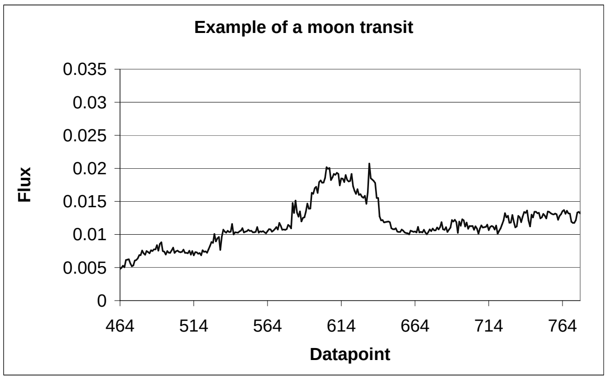


**Fig. 5.** Example of a moon transit

the man made noise is too strong and the measurement is falsified. Fig. (5) is an example of a transit measurement, taken on 4.03.2003 at 15.30 UT. This method has been used, in the week before new moon, when the elevation was low and the time, a measurement could actually be made was short.

## 7. Measurements

The main parameters of the antenna adjustments were put in at the beginning of the measurement series and stayed the same for all measurements. The goal was, to attain a signal as strong as possible. The parameters are listed in table (2).

### 7.1. Sun measurements

For every moon measurement, there had a calibration measurement to be made. It consisted of an on/off-source measurement to determine the Y-Factor and the solar flux, and a passage, to find the HPBW of the main lobe.

| Parameter | adjustment |
|---|---|
| Frequency | 1700 MHz |
| Bandwith | 10 MHz |
| DC-Gain | 5.5 |
| DC-Offset | 5.2 |
| Integration time | 1 sec up to 20 sec |

**Table 1.** Main receiver parameters

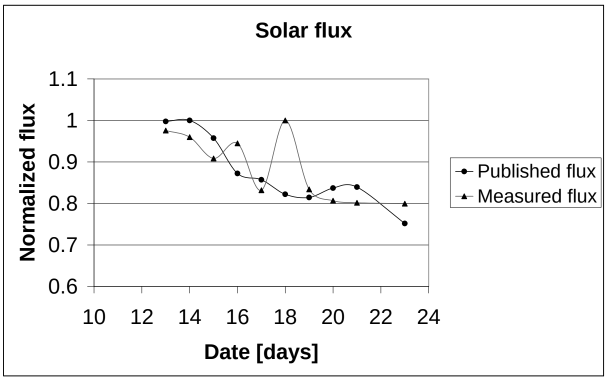


**Fig. 6.** Solar flux over 10 days, normalized by division through maximum

The on/off-source measurement was made with an angle of 7° and a time of 140 sec. The angle had to be big enough to ensure, that only cold sky was measured. On the other hand, the antenna had to be given enough time to move away and back on the source. Usually, the measurement was made at 11 UT, for the list on the web has a data at this time. The data on the web are for 610 MHz, 1415 MHz and 2695 MHz. Therefore, an interpolation had to be made to find the value at 1700 MHz.

On some days, no calibration measurement was made or could be made, so it was necessary to interpolate over the last few days to find a value. The solar activity changed and had to be watched carefully. If there had been an x-ray burst at the time of the measurement, the result must'nt have been used, for the radiation was too high. The change in solar activity and the interpolations caused unceraintties. Further, there hasn't always been correspondence between the measured solar flux and the published flux on the web. This is illustrated in Fig. (6). It shows the qualitative behavior of the measured and published solar flux from 13.2. until 23.2 2003. The data have been normalized by dividing through their maximum.

These facts lead to a big scatter in the values for the moon temperature. Therefore, the average solar flux was calculated and assumed to be constant. As the HPBW also changes with solar activity, the constant value of $d_{HPBW} = 2.8°$ has been used.

### 7.2. Moon measurements

The moon measurements have been made with the same basic adjustments as the sun measurements.

The on/off-source measurements were made with an angle of 8°, a time of 150 s and an integration time of 1 sec. For the transits, integration times of 1 and 10 seconds have been used.

**Problematic measurements**: As mentioned above, measurements below an elevation of about 20° above horizon are problematic because of the optical horizon, that means the buildings and trees. As mentioned before, the antenna temperature of the moon is around 6 K. A measurement of a building on 6.3. 2003 at 9.30 UT gave an antenna temperature of order 200 K. The value is of course only an estimate, but it shows, that the thermal radiation of the buildings is about a factor 20 higher, than the moon's radiation. On 26.2.2003, the moon culminated at an elevation of 15.7°. Considering the optical horizon, it climbed barely over the buildings. Two times, the moon was on the geostationary orbit. These measurements are also not reliable because of the noise of the geostationary satellites. On new moon, the radiation from of sun was too strong. For these reasons, values from the week before new moon are rare.

## 8. Results

As described before, calculating the moon's temperature needs a lot of variables (solar flux, HPBW of the antenna etc.), that means, a lot of uncertain factors. Therefore, the final calculations have been made using an average solar flux and an average HPBW. That doesn't change the basic results, but it gives a smaller scatter in the values for the temperature.

| Variable | average value |
|---|---|
| solar flux (measured) | $2.40 \pm 0.27$ |
| solar flux (published) | $(92.96 \pm 12.87) sfu$ |
| HPBW | $(2.8 \pm 0.1)°$ |

**Table 2.** Values for constant parameters. The value for the measured flux is the output of the receiver in anti logarithmic scale. It corresponds to 92.96 sfu

### 8.1. System temperature

As mentioned above, a low system temperature is important for a good measurement. The average system temperature has been

$$T_{sys} = (232.3 \pm 22.8)\ K \quad (9)$$

### 8.2. Lunar flux

The lunar flux varied clearly over one cycle. This is illustrated in Fig. (7). It shows the output of the receiver in linear scale as a function of phase.

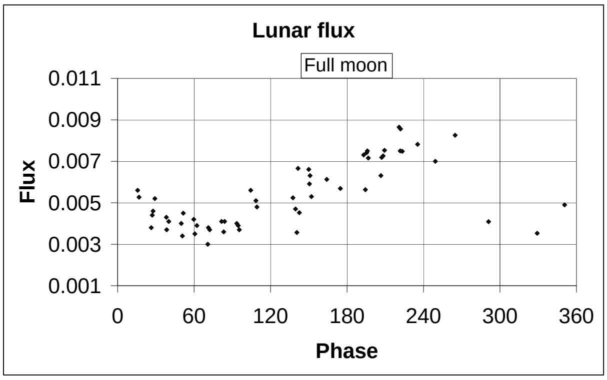


**Fig. 7.** Lunar flux as function of phase (output of the receiver in linear scale). Full moon is at 180°

### 8.3. Moon temperature

For the moon temperature, a variation of 20 % has been found. The average temperature was 234 Kelvin with a maximum of 288 Kelvin, 5.9 days after full moon. The minimal temperature was 180 Kelvin, 8.5 days before full moon. Fig. (8) shows the measured data.

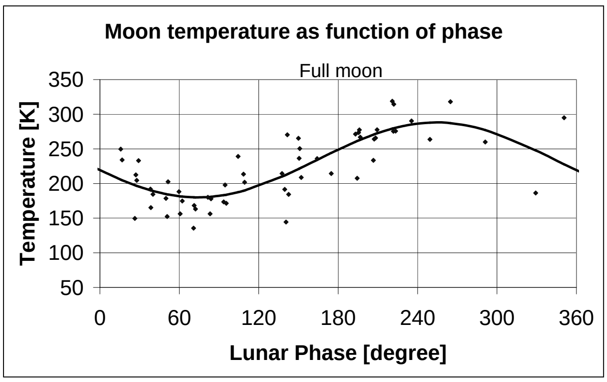


**Fig. 8.** Moon temperature measured over one cycle

As second version, from values of the same day, day average value has been calculated. Fig. (9) shows the temperature with one value a day.

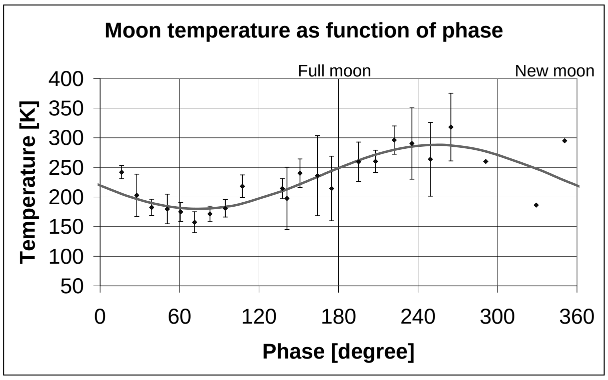


**Fig. 9.** Moon temperature measured over one cycle, average values of each day

There's no theory about the kind of curve the temperature should describe. A sin-curve provided the best fit. To find it, the following function has been taken to start

$$T_{moon} = T_{av} + A\sin(\phi_{moon} - \phi_0) \tag{10}$$

where $T_{av}$ is the average temperature, $A$ the amplitude of the temperature variation and $\phi_0$ the phase of the curve. These parameters have been determined, that the sum of the squared faults was minimal:

$$\sum (T_{moon} - T_{approx})^2 = minimal \tag{11}$$

The parameters have been found as listed in table (3)

| Parameter | value |
|---|---|
| $T_{av}$ | 234 K |
| A | 54 K |
| $\phi_0$ | $164° \doteq 13.2$ days |

**Table 3.** Parameters for moon temperature curve

## 9. Conclusion

Despite the difficulties caused by man made noise and background radiation, a temperature variation could be observed. It would be interesting continuing the measurements over several moon cycles. This would provide more values, maybe even around new moon and a better fit could be made.

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