



SolarP



Solar Constant Experiment

Student User Guide 1.0

Contents

- 1 Introduction
- 2 Sunny Day Experiment
- 3 Cloudy Day Experiment
- 4 Advanced Experiment Options
5. Solar Luminosity
6. Energy Generation and Mass loss in the Sun
- 7 The Lifetime of the Sun
- 8 The Solar Cycle and Global Warming

© Copyright Elliott Instruments Limited

Neither the whole nor any part of the information in this User Guide may be adapted or reproduced in any material form without the written approval of Elliott Instruments Ltd.

All information in this User Guide, is given by Elliott Instruments Ltd, in good faith, for the reader to make use of the SolarP. However, it is acknowledged that there may be errors or omissions. Elliott Instruments Ltd shall not be liable for any loss or damage whatsoever arising from the use of any information contained in the User Guide or any errors or omissions in the User Guide.

Any comments or suggestions, or problems with the use of SolarP should be addressed to Dr K H Elliott at the address below.



1 Oak Tree Cottage, Lady Hole Lane, Yeldersley DE6 1LR
Telephone: 01335 300856 Email: khelliott@btinternet.com

1 Introduction

SolarP is an experiment which allows you to determine the Solar Power received at the Earth's surface. Some of the power from the Sun is absorbed in the Earth's atmosphere. If we correct for the absorption in the Earth's atmosphere we can determine the power per unit area above the Earth's atmosphere and this is known as the "Solar Constant".

This is defined as the power from the Sun in a 1 square metre area, above the Earth's atmosphere. The accepted value is about 1370 watts per square metre.

1.1 The Instrument

SolarP consists of a small aluminium plate 0.05m x 0.05m with one surface blackened to absorb all incident energy from the Sun. At the rear of the plate is a temperature sensor and a 50Ω heating element. The plate and it's insulated by polystyrene. When the SolarP instrument is pointed at the Sun, the absorbed energy from the Sun heats the metal plate.



If we plot a graph of the temperature rise as a function of time, we can deduce the power input to the plate, from the gradient of the graph. Clearly if there is any heat loss from the plate, then the gradient of the graph will be reduced. However if we arrange that the temperature of the plate to be lower than ambient at the start, then at the point when the temperature of the plate goes through the ambient temperature, there will be no heat loss or gain from the surroundings and the heat rise will only be due to that of the Sun.

2 Sunny Day Experiment

The ideal day would be completely clear with no clouds and no wind in Summer time so that the Sun reached a good elevation. If it is windy it would be a good idea to find a sheltered spot, like the porch of a building from which the Sun was visible. The experiment cannot be done through a glass window, although through an open window in a laboratory would be ideal.

2.1 Taking the measurements.

Measure the ambient temperature in the shade by placing the SolarP experiment in the shade and note both the OUT and IN readings.

Place the SolarP in a refrigerator with the temperature display outside and wait till the SolarP sensor has cooled to 5-8C below ambient.

Quickly mount the SolarP sensor on a clamp stand and point it directly at the Sun, so the sensor plate is completely illuminated by the Sun.

Now using a stop watch, record the temperature of the sensor (OUT) every 15s until the temperature rises to 5-8C above the ambient. Note the time the temperature of the sensor is the same as the ambient.

2.2 Looking at your data

Now using a spreadsheet plot the temperature as a function of time as an X-Y plot and you should have something like figure 1 below.

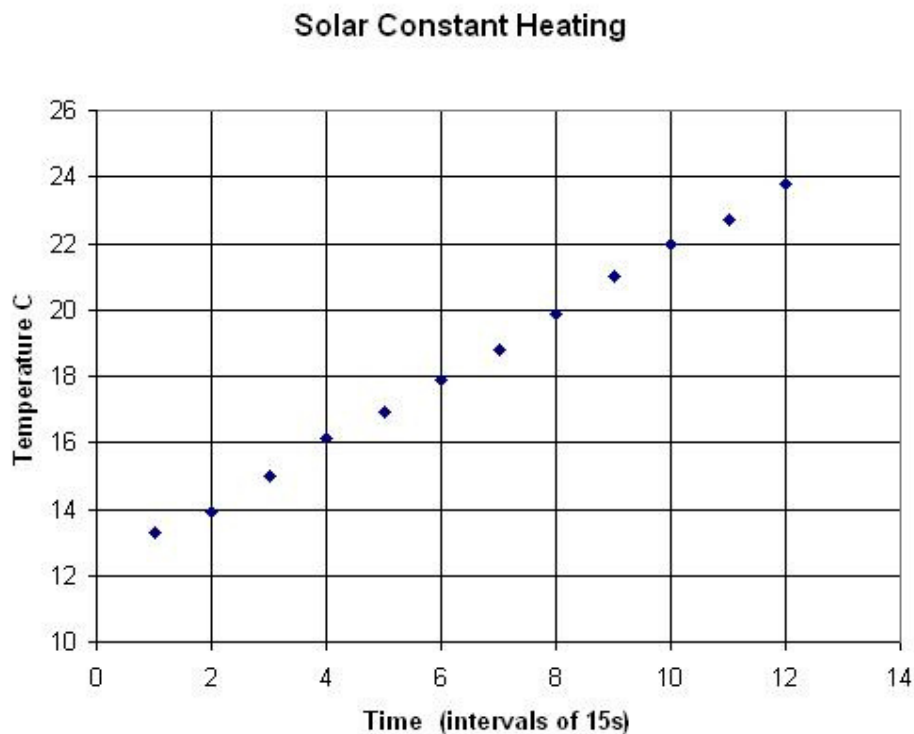


Figure1

Now add a trend line to determine the slope of the graph, making sure there are an equal number of data points above and below the ambient temperature.

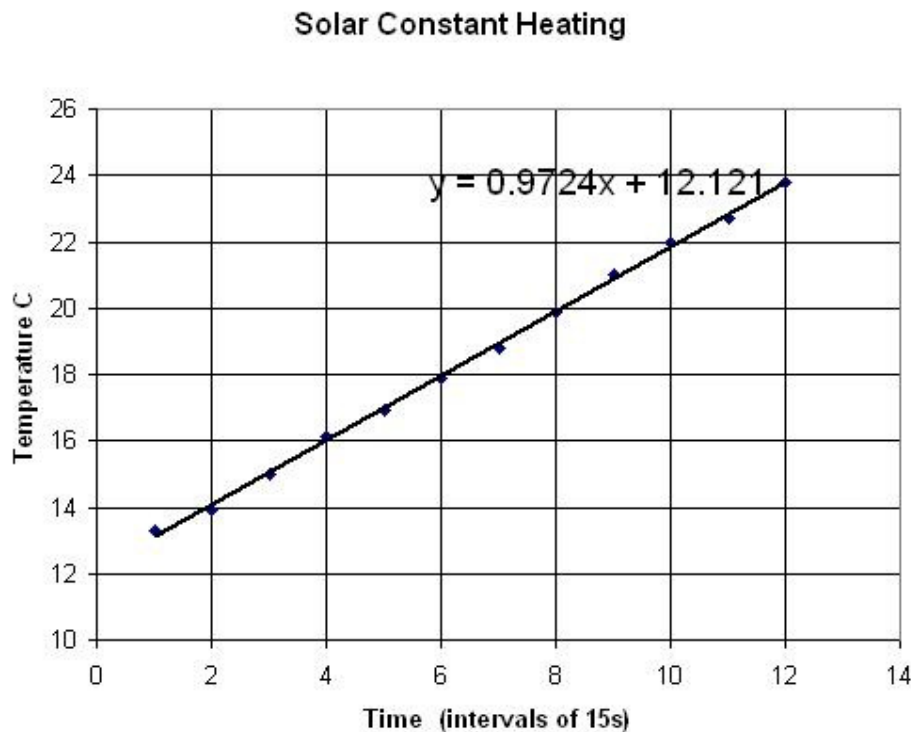


Figure 2

2.3 Data Analysis

If you can't use a spreadsheet then just plot the results and calculate the gradient from Gradient = (Temp max-Temp min) / (15 * number of data points). Make sure you have equal number of data points above and below the ambient temperature.

The rate of temperature rise is given by $\Delta T/t$ where ΔT is the temperature rise in degrees Celsius and t is the time in seconds depends on the power input W (watts) and the Thermal mass C_{th} , also called heat capacity which is measured in units of JK^{-1} . So we have

$$\Delta T/t = W / C_{th}, \text{ so the power received by the plate is thus } W = \Delta T/t * C_{th},$$

Remember the Solar Constant is the power per square metre so we need to take into account the small size of the plate and correct for this ie $1.0 / (0.05 * 0.05) = 400$

So we get that Solar Power at the Earth's surface is

$$W = 400 * \Delta T/t * C_{th}$$

The nominal value for the Thermal Mass C_{th} is $32 JK^{-1}$

You can determine this value yourself if you have time with a separate experiment in the Advanced Experiment Options.

Using the values from the above graph as an example

$\Delta T/t$ is gradient of graph divided by 15 to correct for the 15 second time intervals

$$\Delta T/t = 0.9724 / 15 = 0.0648 \text{ K s}^{-1}$$

$$W = 400 * C_{th} * \Delta T/t = 400 * 32 * 0.0648 = 829 \text{ W m}^{-2}$$

So we have a measurement of the Solar Power at the Earth's surface of 829 W m^{-2}

Use your data and the method shown to find your own measurement of the Solar Power at the Earth's surface.

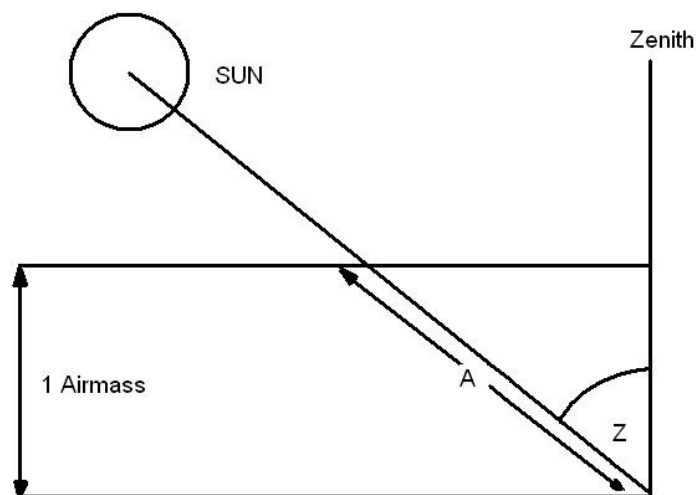
2.4 Correcting for the absorption in the Earth's atmosphere

When the Sun is overhead we have the minimum of atmosphere between the Sun and the observer. As the Sun sinks towards the horizon, the light from the Sun goes through a longer and longer path. If the length of the path at the zenith (overhead) is 1.0 units or 1.0 airmass A, then the length of the actual path A (Airmass) depends on

$A = 1 / \cos(Z)$ where Z is the zenith angle eg

Z	Zenith Angle	Airmass
0	overhead	1.0
30		1.15
40		1.30
50		1.55
60		2.0
70		2.9

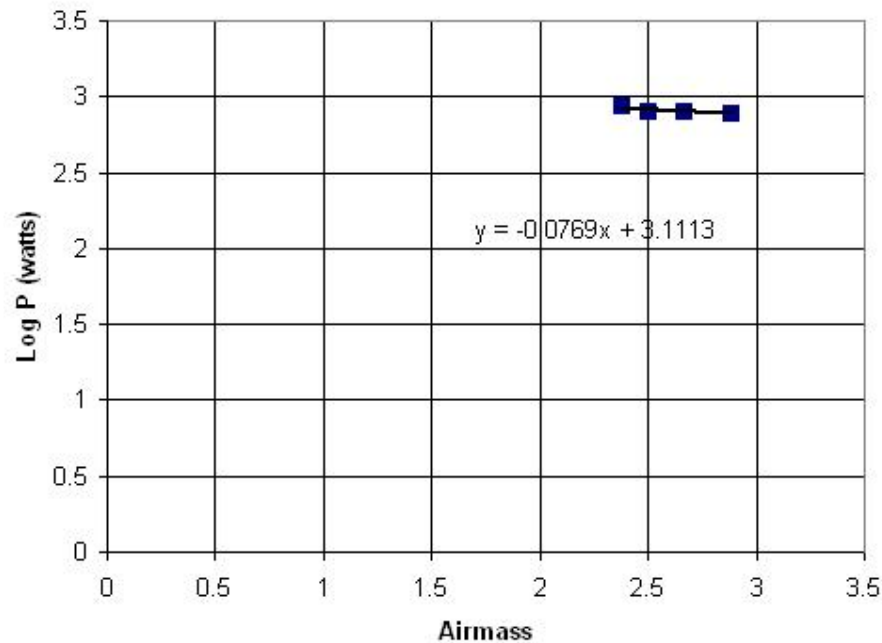
So you can see that there is almost 3 times as much absorption, when the Sun is at a Zenith angle of 70 degrees compared with overhead, see figure3 below.



It is possible to correct for the absorption in the Earth's atmosphere by making power measurements at different Zenith angles. Clearly from the table above you would expect

only half of the power from the Sun when it was 60 degrees from the zenith than when it was overhead.

If we make observations of the power received at the surface of the Earth at various zenith angles and therefore airmasses, we get the following result.



A graph of log P against airmass is a straight line, and the line can be extrapolated to zero airmass, which means this is the power outside the Earth's atmosphere, or the Solar Constant. The slope of the graph can be used to correct for the Earth's absorption for your measurement, or you can make your own measurement of the absorption in the Earth's atmosphere using the method in Advanced Experiment Options.

2.5 Correcting your own measurements for the absorption in the Earth's atmosphere

If you want to correct your measurements of the power received at the Earth's surface so that you can find the Solar Constant you need to find the Zenith angle of the Sun when you made your measurements.

You can either do this with a plumb line and a protractor while you are taking the temperature measurements or you can use the Stellarium program provided (Appendix I). For this you need to know the longitude and latitude of your location on Earth and the time of your observation and the program will tell you the elevation angle of the Sun and hence you can determine the zenith angle which is (90-elevation),

$$\log_{10} (\text{Solar Constant}) = \log_{10} (W) + (A * 0.0769)$$

Insert your value for the Observed Power (W) and your value for the Airmass into the above equation to calculate the value for the Solar Constant.

Your value should be somewhere near the accepted value of 1370 Wm^{-2}

3 Cloudy Day Experiment

3.1 Analysis of provided data.

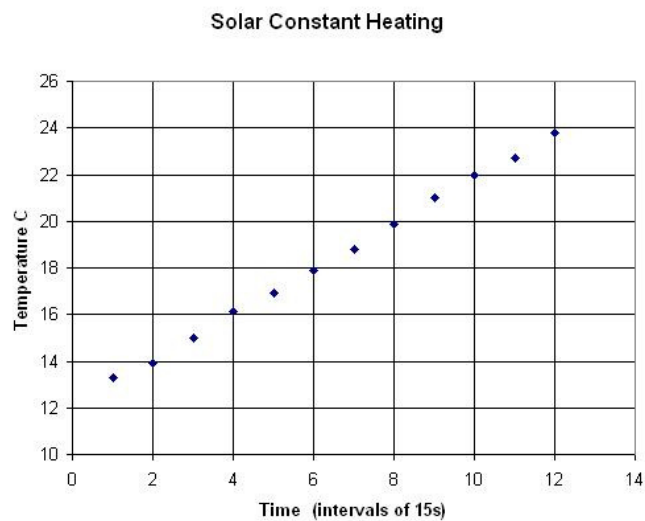
If the weather is cloudy, you can use a set of measurements which is provided.

Date of measurement	October 5 th 2008
Time of measurement	15h 44m 15s
Location of measurement	Birmingham, UK
Ambient temperature	10.3 Celsius
Time between measurements	15s

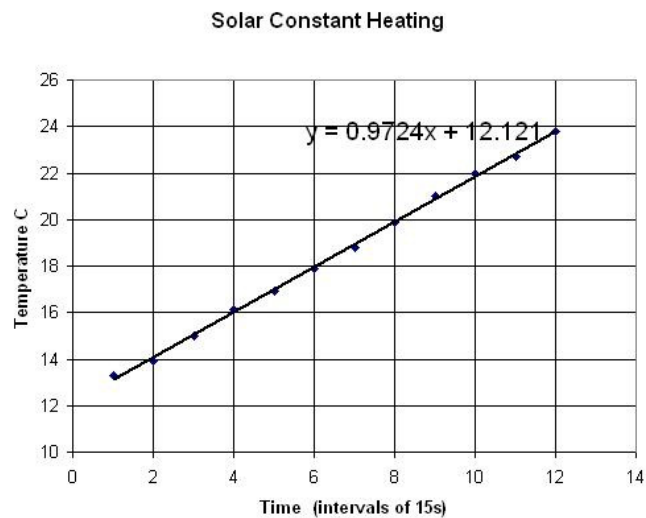
Temperature Data (Celsius)

5.2 5.8 6.7 7.3 8.3 9.2 10.3 10.9 12.0 12.9 13.6 14.7 15.5 16.3 17.2 18.3

Now using a spreadsheet plot the temperature as a function of time as an X-Y plot and you should have something like figure 1 below.(This is NOT the above data)



Add a trend line to determine the slope of the graph, making sure there are an equal number of data points above and below the ambient temperature.



Find the gradient of the Solar heating graph. (NB the graph above is just an example and isn't the data you have been given.

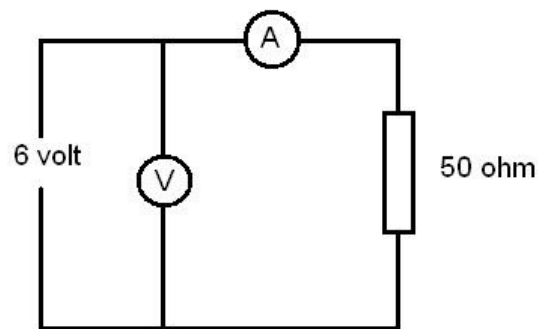
Remember that the data points are at 15s intervals so for the gradient $\Delta T/t$ to be in degrees Celsius per second you need to divide the value by 15.

You have determined the gradient $\Delta T/t$ and you now need to measure the Thermal Mass C_{th} of the sensor

3.2 Measurement of Thermal Mass

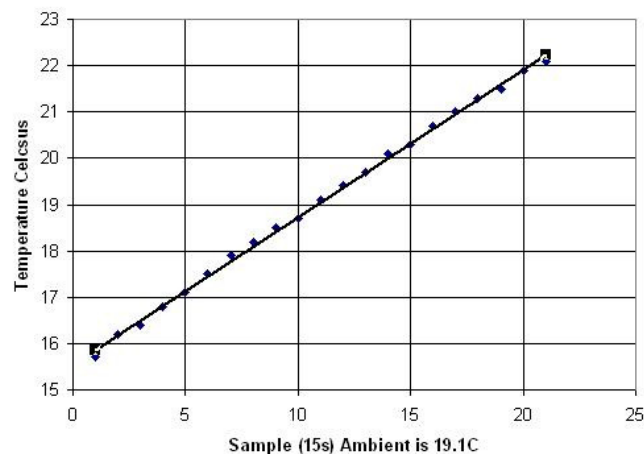
The Thermal Mass is the amount of energy (in Joules) needed to raise the temperature of the mass by 1 Kelvin so it has the units of JK^{-1} The thermal mass of the sensor can be determined by heating the sensor electrically and observing the rate of temperature rise. For this purpose there is a 50Ω heating element attached to the back of the aluminium plate.

Measure the ambient temperature in the laboratory by noting both the OUT and IN readings. Place the SolarP in a refrigerator with the temperature display outside and wait till the SolarP sensor has cooled to 5-8C below ambient. Quickly connect the terminals on the sensor to a 6V DC supply which is fitted with both current and voltage meters or set up external ammeters and voltmeters as shown in the circuit below.



Now using a stop watch, record the temperature of the sensor (OUT) every 15 seconds until the temperature rises to 5-8C above the ambient. Note the current and voltage when temperature of the sensor is the same as the ambient. Plot a graph of the temperature rise against time as below.

Determination of Thermal Mass



Determine the gradient $\Delta T/t$ in units of Ks^{-1} and also the electrical power input in Watts from the current I in amps and the Voltage (V).

So that $W = I * V$

The thermal mass can be calculated from the electrical power input W and the gradient of the graph

$$C_{th} = W / (\Delta T/t)$$

Note the units are Js^{-1} / Ks^{-1} so are JK^{-1} (Your value should be in the range 25-35 JK^{-1})

3.3 Calculating Solar Power (W) at the Earth's surface

Now use the gradient of your graph $\Delta T/t$ and Thermal Mass of the sensor C_{th} that you have measured to determine the Solar Power at the Earth's surface

$$W = 400 * C_{th} * \Delta T/t$$

So you now have a value for the Solar Power at the Earth's surface as measured at Birmingham on October 5th 2008. The value you calculate should be in the region of 700-800 Wm^{-2}

3.4 Correction for Absorption in the Earth's Atmosphere

The value you have measured is the power at the Earth's surface after passing through the Earth's atmosphere which can and does absorb a lot of the power causing the atmosphere to heat and generate our weather. If we wish to correct for this absorption and find the Solar Constant, which is the power above the atmosphere we need to know the angle of the Sun above the horizon and hence the zenith angle.

The US Naval Observatory provides a website

<http://aa.usno.navy.mil/data/docs/AltAz.php>

which allows you to find the elevation of the Sun at the time of the measurement.

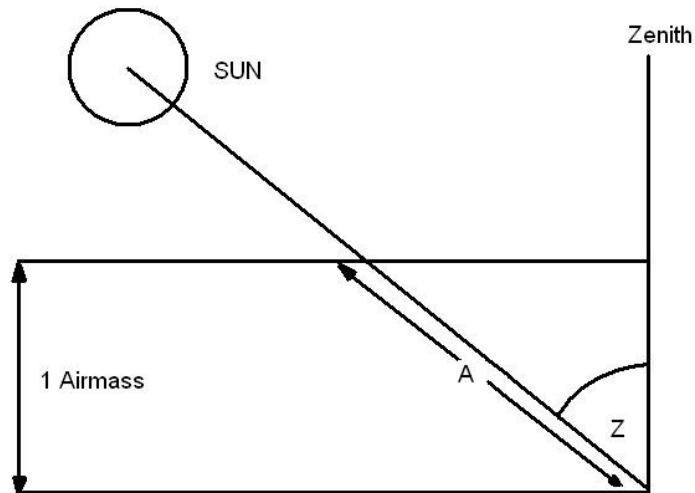
Date : October 5th 2008 Time : 15h 44m Location Birmingham, UK

When the Sun is overhead we have the minimum of atmosphere between the Sun and the observer. As the Sun sinks towards the horizon, the light from the Sun goes through a longer and longer path. If the length of the path at the zenith (overhead) is 1.0 units or 1.0 airmass A , then the length of the actual path A (Airmass) depends on

$A = 1 / \cos(Z)$ where Z is the zenith angle eg

Z	Zenith Angle	Airmass
0	overhead	1.0
30		1.15
40		1.30
50		1.55
60		2.0
70		2.9

So you can see that there is almost 3 times as much absorption, when the Sun is at a Zenith angle of 70 degrees compared with overhead, see figure3 below.



The USNO website will give you the elevation of the Sun above the horizon.

Clearly the Zenith angle $Z = (90 - \text{elevation})$ so calculate Z for the Sun.

Now calculate the amount of atmosphere in the line of sight which is the Airmass A

$A = 1 / \cos(Z)$ where Z is the zenith angle

You can now correct for the absorption in the Earth's atmosphere to get the Solar Constant from the equation below.

(Full details of how this equation is obtained can be found in section 2.4)

$$\log_{10}(\text{Solar Constant}) = \log_{10}(W) + (A * 0.0769)$$

Insert your value for the Observed Power (W) and your value for the Airmass into the above equation to calculate the value for the Solar Constant.

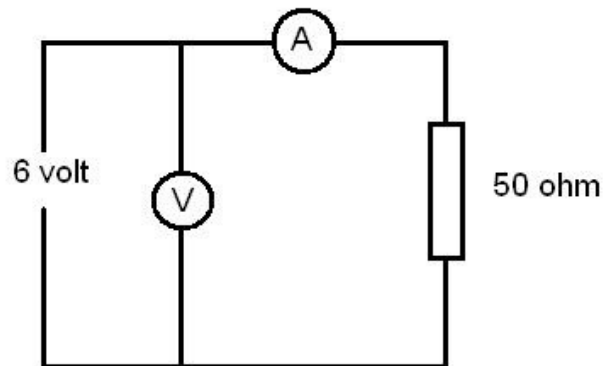
Your value should be somewhere near the accepted value of 1370 Wm^{-2}

4 Advanced Experiment Options

4.1 Measurement of Thermal Mass C_{th} of Sensor

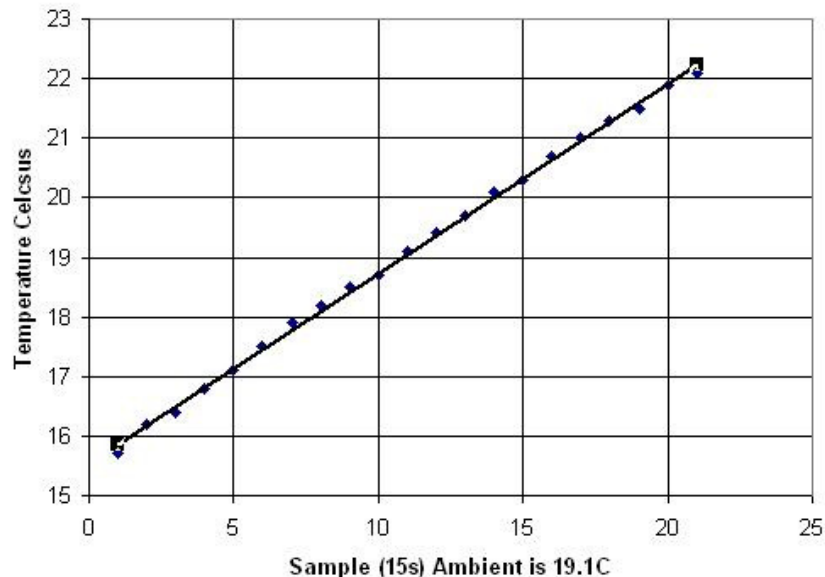
The thermal mass of the sensor can be determined by heating the sensor electrically and observing the rate of temperature rise. For this purpose there is a 50Ω heating element attached to the back of the aluminium plate.

Measure the ambient temperature in the laboratory by noting both the OUT and IN readings. Place the SolarP in a refrigerator with the temperature display outside and wait till the SolarP sensor has cooled to $5-8^{\circ}\text{C}$ below ambient. Quickly connect the terminals on the sensor to a 6V DC supply which is fitted with both current and voltage meters or set up external ammeters and voltmeters as shown in the circuit below.



Now using a stop watch, record the temperature of the sensor (OUT) every 15 seconds until the temperature rises to $5-8^{\circ}\text{C}$ above the ambient. Note the current and voltage when temperature of the sensor is the same as the ambient. Plot a graph of the temperature rise against time as below.

Determination of Thermal Mass



Determine the gradient $\Delta T/t$ in units of K s^{-1} and also the electrical power input in Watts from the current I in amps and the Voltage (V).

So that $W = I * V$

The thermal mass can be calculated from the electrical power input W and the gradient of the graph

$$C_{th} = W / (\Delta T/t)$$

Note the units are $\text{Js}^{-1} / \text{Ks}^{-1}$ so are JK^{-1}

Your value should be in the range $25\text{-}35 \text{ JK}^{-1}$

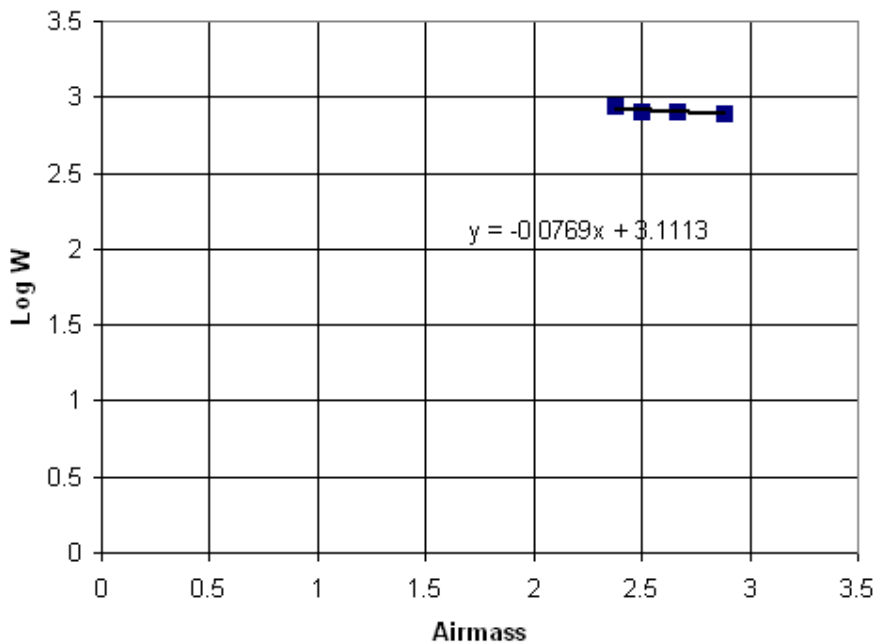
4.2 Measurement of the Absorption in the Earth's Atmosphere

The absorption in the Earth's atmosphere depends on the presence aerosols and dust and varies from day to day. If we want to make an accurate measurement of the Solar Constant we need to measure the extinction in the Earth's atmosphere at the same time as we measure the Solar Power at the Earth's surface.

To do this we need to make many measurements at different zenith angles (Z) and therefore different airmasses (A). So the experiment needs to be repeated.

The experiment is best done on a very clear day with measurements taken from early morning when the Sun is low in the sky with a large airmass, until local noon, when the Sun has the minimum zenith angle Z .

If we have a set of measurements of observed power W and airmass A we can plot a graph of $\log_{10}(W)$ against Z and we get a straight line graph like that below.



The equation of the line fitted $y=mx+c$ gives m , which is the slope of the line (-0.0769) is a measure of the extinction and c is the intercept of the line where the airmass is zero and is hence the $\log_{10}(\text{Solar Constant}) = 3.1113$, which gives a value of 1297 Wm^{-2}

5 Solar Luminosity

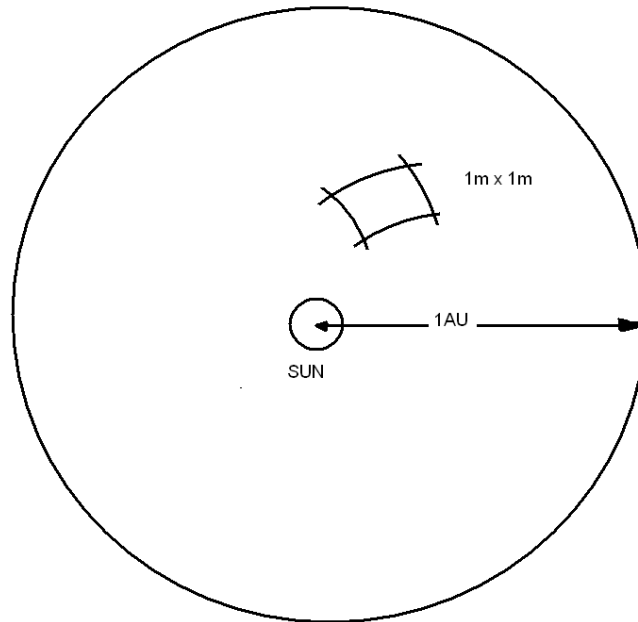


Diagram not to scale

The Solar Constant is the power in an area of 1 m x 1 m above the Earth's atmosphere. The Earth is at a distance of one Astronomical Unit (AU) 1.49×10^{11} m from the Sun. So every square metre of the surface of a sphere of radius of 1 AU receives the Solar Constant power. If we multiply the Solar Constant power by the surface area A of that sphere then we can calculate the total power from the Sun. This is called the Solar Luminosity L .

For a sphere the surface area $A = 4 \pi R^2$

So the Solar Luminosity in Watts

$$L = 4 \pi R^2 * \text{Solar Constant} \quad \text{where } R = 1.49 \times 10^{11} \text{ m}$$

Use your value of Solar Constant to calculate the Solar Luminosity in Watts.

6. Energy Generation and Mass loss in the Sun

6.1 Mass converted into Energy

The Luminosity of the Sun L is measured in Watts and of course a Watt is a Joule per second

We all know that the conversion of mass to energy is determined by Einstein's equation

$$E = mc^2 \quad E \text{ is the energy in Joules, } m \text{ is the Mass in kg and } c \text{ is the velocity of light in } \text{ms}^{-1}$$

The mass converted per second $m/t = (E/t) / c^2$ but E/t is L if t is 1s

$$\text{So mass converted per second } m/t = L / c^2$$

Use your value of L to calculate the rate of mass conversion to energy. (kg s^{-1})

6.2 Fusion of Hydrogen to Helium

The total mass of four Hydrogen nuclei is 6.693×10^{-27} kilograms. The mass of a Helium nucleus is 6.645×10^{-27} kilograms. Thus, there is a loss of 0.048×10^{-27} kilograms every time a Helium nucleus is formed by fusion.

You can see from the above numbers that the fusion of 6.693×10^{-27} kilograms of hydrogen, only converts 0.048×10^{-27} kilograms of mass into energy so we have

$6.693 \times 10^{-27} / 0.048 \times 10^{-27} = 139.4$ times as much Hydrogen converted to Helium than the amount of mass converted to energy.

So to calculate the rate of conversion of Hydrogen to Helium we need to multiply the rate of mass conversion by 139.4

So what is the rate of conversion of Hydrogen to Helium? (kg s⁻¹)

7 The Lifetime of the Sun

The Sun has a mass of 1.98×10^{30} kilograms and it is believed that most of the life of the Sun will be spent in a phase of Hydrogen burning, fusing Hydrogen to Helium. Only about 0.25 of the mass of the Sun can be consumed, before Hydrogen fusion stops and the Sun becomes unstable, so we can estimate the lifetime of the Sun as a stable star, by calculating how long it will take for 0.25 of the mass of the Sun to be consumed, at the present rate of conversion of Hydrogen to Helium.

Use your calculations of rate of conversion of Hydrogen to Helium and a knowledge of the mass of the Sun to estimate its lifetime and express your answer in years.

