Imperial College London

Solar Radiation

F1

Head of Experiment: Dr Michael McCann

The following experiment guide is NOT intended to be a step-by-step manual for the experiment but rather provides an overall introduction to the experiment and outlines the important tasks that need to be performed in order to complete the experiment. Additional sources of documentation may need to be researched and consulted during the experiment as well as for the completion of the report. This additional documentation must be cited in the references of the report.

3rd Year Physics Laboratory
Scattering in the Earth's Atmosphere

General remarks

This 3rd Lab experiment is part of a group of "outdoor experiments". The execution of the required measurements is rather straightforward but requires careful consideration of the relevant weather conditions and sources of error. During the data analysis special emphasis must be placed on the evaluation of systematic uncertainties arising from imperfect weather conditions and any other potential source of systematic bias that could impact the measurements. It is therefore a prudent approach to perform several independent measurement campaigns, ideally under similar weather conditions, in order to gauge the quality and compatibility of each set of measurements. For this reason, it is important that a timely analysis of the collected data is performed while still being in possession of the equipment – i.e. DURING the time you are assigned to the experiment.

The following guide is NOT intended to be a step-by-step manual of the experiment but rather provides an overall introduction to the experiment and outlines the important tasks that need to be performed in order to complete the experiment. It is expected that additional sources of documentation will be researched and consulted during the experiment as well as for the completion of the report. This additional documentation must be cited in the references of the report.

Philosophy of the experiment. Many lab-based experiments allow you to carefully develop and refine your measurements under well controlled and near constant conditions. Environment observations are typically very different and require you to deal with whatever conditions Nature throws at you. As a result, your data will be inherently noisy and you will probably benefit less from careful lab-based characterisation of your equipment, and rather more from a rapid move to outside observations and building up data sets. Long range planning, e.g. by looking at whether forecasts and targeting interesting observing days will be important, and you can sign out equipment if you want to work over a weekend or non-lab day.

Experiment Guide: Table of Contents.

Introduction

Incoming solar radiation is diverted or scattered from its direction of propagation when it encounters particles or inhomogeneities, such as air molecules, aerosols, and clouds. The scattering occurs as the refractive index of the particles differs from that of the homogeneous medium in which they are embedded. Although the frequency of the scattered radiation remains unchanged after scattering, its phase and polarisation may change substantially.

This experiment will examine the effect of two types of scattering upon the incident solar radiation. For scatterers with diameters that are "small" compared with the wavelength of the incident radiation, Rayleigh developed a theory that demonstrates that the amount of scattering is inversely proportional to the fourth power of wavelength ($\sim\lambda^{-4}$). Shorter wavelength radiation is also scattered by particles (dust, smoke, and ions). When the dimensions of the particle become similar to the incident radiation wavelength, the Rayleigh scattering law ceases to be valid and Mie scattering theory should be used.

Theoretical Background

Beer-Bouger-Lambert Law

In clear sky, consider a parallel beam of incident radiation with intensity I_λ passing through a non-scattering, absorbing medium. The intensity of radiation after traversing a layer of thickness ds in the direction of propagation is $I_\lambda + dI_\lambda$ and,

$$dI_\lambda = -\sigma_{\lambda a} I_\lambda n\, ds$$

where n is the number density of the medium and $\sigma_{\lambda a}$ is the absorption cross-section of a single particle for radiation of wavelength λ. Integrating this equation between $s = 0$ and $s = s_1$ yields the emergent intensity $I_\lambda(s_1)$ so that

$$I_\lambda(s_1) = I_\lambda(0) \exp\left[-\int_0^{s_1} \sigma_{\lambda a}\, n\, ds\right] \tag{1}$$

where $I_\lambda(0)$ is the intensity at $s = 0$. When the medium is homogeneous, all parameters are independent of s and the equation then expresses the Beer-Bouger-Lambert absorption law.

A similar law is valid for a non-absorbing, scattering of a parallel beam passing through the atmosphere. In this case, the scattering cross section $\sigma_{\lambda s}$ should be used. When absorption and scattering occur simultaneously, we may write $\sigma_\lambda = \sigma_{\lambda a} + \sigma_{\lambda s}$.

If the zenith angle of the sun is Z, ds = dz sec(Z), the transmissivity τ_λ of the slant path of the atmosphere at a given wavelength is then given by

$$\tau_\lambda = \frac{I_\lambda}{I_{\lambda_0}} = e^{-u \sec Z} \tag{2}$$

where u is the optical depth of the vertical column and is given by

$$u = \int_0^\infty \sigma_\lambda \, n \, dz \tag{3}$$

Assuming that there is no absorption, the transmissivity and the albedo, A, are related by

$$\tau + A = 1 \tag{4}$$

Rayleigh Scattering

The simplest approximate treatment of scattering describes the interaction of sunlight with molecules and is called Rayleigh scattering (Rayleigh 1871), which applies to particles much smaller than the wavelength of radiation.

For Rayleigh scattering, the scattering cross-section of an individual molecule is

$$\sigma_s = \alpha^2 \frac{128\, \pi^5}{3\, \lambda^4} \tag{5}$$

where α is the polarisability of the scatterer and λ is the wavelength of the incident radiation.

We can then consider the atmospheric optical depth due to Rayleigh single scattering as

$$u = \sigma_s(\lambda) \int_0^\infty n(z) \; dz \tag{6}$$

where $n(z)$ is the air number density at height z.

Mie Scattering

Scattering from spherical particles of arbitrary dimension was first examined by Mie (1908). Mie scattering applies to the interaction between sunlight with aerosols and cloud droplets where the size of the object is similar to that of the optical wavelength.

Under Mie scattering conditions, the optical depth of a cloud can be approximated in terms of the column abundance of liquid water, called the liquid water path, $\Sigma_l = \rho\Delta z$, where Δz is the thickness of the cloud and ρ is the liquid water content per unit volume. The optical depth is then (see e.g. Salby 1996, Chapter 9) given by

$$u = \frac{3\Sigma_l}{2\rho_w a_e} \tag{7}$$

where ρ_w is the density of liquid water and a_e is the scattering-equivalent mean drop radius.

A more detailed account of both scattering processes can be found in Salby (1996).

The Beer Lambert Law does not work for cloudy conditions so more detailed radiative transfer models which include multiple scattering to infer cloud optical depths are needed. One such model, SBDART (Santa Barbara DISORT Atmospheric Radiative Transfer), is available in the form of a web or MatLab tool.

Cloud Radiative Forcing

A quantitative description of how clouds figure in the global energy budget can be achieved by comparing radiative fluxes at the top of the atmosphere (TOA) under cloudy conditions versus clear-sky conditions. Over a given region, the column-integrated radiative heating, dQ/dt, must equal the difference between the energy flux absorbed and that emitted

$$Q = \int_0^\infty \rho_{\text{air}}\, q\, dz$$

$$\dot{Q} = (1 - A)F_S - F_{LW} \tag{8}$$

where A is the albedo of the region and F_S and F_{LW} denote the downward shortwave (*SW*) and upward longwave (*LW*) fluxes at the TOA, respectively.

The cloud radiative forcing, C, is the difference between the heating rates under cloudy and clear-sky conditions and represents the net radiative influence of clouds on the column energy budget of the region. This can be written as

$$C = (A^{CS} - A)F_S + (F_{LW}^{CS} - F_{LW}) \tag{9}$$

where the superscript *CS* denotes clear-sky conditions and A is the albedo of the cloud.

Preparation

Before collecting data, have a look at the Met Office web site at http://www.metoffice.gov.uk and write a synoptic description of the day's expected weather conditions using the cloud and surface pressure charts and satellite images provided. A synoptic description is that of the meteorological conditions and weather elements over a wide area at a given time, the study of which is termed synoptic meteorology. This is an excellent way of familiarising yourselves with the charts and notations used by the synoptic meteorologists and forecasters, while also providing a record of the prevailing weather conditions when your measurements were made.

Two portable instruments will be used: a lightmeter (a photodiode based optical sensor) and a solarimeter (a thermopile, a broad band surface absorbing detector). There are a range of settings on the lightmeter for different light sources, to amplify the signal by a factor of 10 or 100. To promote consistency, the same setting should be used for each set of measurements.

The lightmeter detector has a wavelength dependent response function between 0.4 and 0.7 μm maximising at 0.55 μm. The solarimeter has a blackbody response between 0.3 and 2 μm. It is necessary to ensure that there are no obstacles within the field of view of the instruments when you are taking your measurements as they will affect the measurements, (a 5-metre radius is a good guide to the clearance needed). If some obstacles are present, quantify their effect.

To better understand your instruments, you can benchmark them against each other, or against an absolute scale in the laboratory. A precision light source and optical filter set (Thorlabs SLS201L/M Stabilized Tungsten lamp, 360 - 2600 nm) and a broad band surface absorbing energy meter (Thorlabs S425CThermal Power Sensor Head, 0.19 - 20 μm) are available. Take care to eliminate any uncontrolled external sources of light pollution while you work.

You should aim to schedule calibration measurements on days when observing conditions are particularly bad and prioritise "real world" external observations for the majority of your lab time.

Suggested Location

For clear sky and cloud cover measurements, the roof at the eighth floor of the Blackett laboratory is a suitable location. For surface albedo measurements you should use Kensington Gardens/Hyde Park, as a range of different surfaces can be found close to each other. When working outside College, make sure you have a short, snappy description of who you are and what you are doing ready to go for interested members of the public or the police, who have been known to query students.

Note that it is not necessary to make the clear sky observations first. Make sure you read through all the tasks before doing any of them, and understand what meteorological conditions are required for each, so that when the opportunity arises, you can take all the necessary readings.

Specific Tasks

1. Under clear sky conditions, for a good range of solar zenith angles (SZA), measure the direct flux using the lightmeter and the thermopile. It is not necessary to take all the measurements on the same day or for the clear sky to be totally consistent throughout the day. The direct flux is obtained by subtracting the diffusive flux from the total flux. The diffusive flux can be measured by carefully shading the detector using a disc of card or paper, ensuring that the sensor is just covered. The zenith angle can be obtained by using an online solar angle calculator use the location of London at 51.3N and –0.07E and the local time (GMT) of your measurement.

   Determine the vertical column optical depth of the clear sky using a plot of your measurements for both instruments.

2. For a range of different surfaces, i.e. water, grass, concrete and sand, determine their albedo.

3. From readings of local pressure and temperature [see Appendix 1], use the ideal gas law to determine the ground level number density of air molecules, n_0. The number density varies with height as

$$n_z = n_0\, e^{-\frac{z}{H}} \tag{10}$$

   where z is the height, n_z is the number density at that height and H is the appropriate scale height. Assuming a scale height of 7 km, calculate the clear sky scattering cross section from your optical depth, for both instruments.

   Did you calculate a different scattering cross section between the two instruments? From your measurements of the cross section, deduce the ratio of effective wavelengths for the two devices. What wavelength region do you think accounts for most of the solar energy? (Use your observations and the spectral properties of the different sensors).

   Typical values lead to an approximate value for the Rayleigh scattering cross section of $3\times10^{-27}\text{cm}^2$. Is your clear sky scattering cross section consistent with Rayleigh scattering alone being important? What other scatterers have we ignored, what is their relative significance? Check the consistency of your results by deriving the value of the polarizability α (c.f. equation 5), and explain what α represents.

4. For several different cloud types (be able to provide appropriate technical descriptions and nomenclature), measure the total flux using the instruments provided. In the paper by Fitzpatrick et al (2004) you will find a model of cloud transmittance as a function of cloud optical depth, SZA and surface albedo. Use your measurements to derive cloud optical depth. Cloud transmittance is the ratio of the flux measured under cloudy conditions to the equivalent measured clear sky flux at the same SZA. You will need to use data from Task 1 here. Keep a record of the cloud types you encounter.

   How sensitive are your calculations to the uncertainties in your surface albedo?

   How do the assumptions, instrumentation, meteorological and physical environment used in defining the model affect the validity of your application of the model?

   What does the behaviour of the model when $u \gg 1$ say about the scattering processes in the cloud?

5. At regular intervals throughout both a clear-sky day and another with a persistent cloud type (practically, it is not essential that it is on the same day), calculate the transmissivity (and hence the albedo) for a range of zenith angles. How do they differ and why? How does the surface albedo compare to that of the cloud?

6. By taking a reading every minute for around an hour during a consistently cloudy period, obtain a probability distribution of cloud optical depths. Are the optical depths normally distributed? What does that mean?

7. Determine the cloud base height, and estimate the thickness of the cloud. [Appendix 2] Using your inferred cloud optical depth, estimate the liquid water path and hence the liquid water content (mixing ratio of liquid water to air).

   Use local weather data [Appendix 1] to obtain the relative humidity at the time of your cloud observations. Using the definition of the relative humidity as the ratio of the surface water vapour pressure over the saturation water vapour pressure, determine the surface water vapour mixing ratio (equivalent to a mass of water per unit of volume). The saturation water vapour pressure will be calculated using the following empirical equation (derived from the Clausius-Clapeyron equation):

$$P_{sat} = 10^{a-\frac{b}{T}} \times T - c \qquad (11)$$

   with a = 23.5518, b = 2937.4 and c = 4.9283, and P_{sat} given in hPa, and T the temperature in Kelvin. Compare the value obtained for the surface water vapour mixing ratio to that of the cloud liquid water mixing ratio, comment on the result.

8. Using your observed values for the surface albedo, and the surface temperature from the weather station, estimate the cloud radiative forcing [use the Stefan-Boltzmann law to determine the long wave outgoing flux. Use the moist adiabatic lapse rate 6 K/m in cloud to determine the cloud top temperature].

   What is the radiative role of low cloud cover in the climate system?

9. If possible, using the polariser placed over the lightmeter during a completely clear sky, measure the polarisation of direct sunlight and diffuse light at right angles to the direct beam. Comment on your findings.

10. Finally, perform your own experiment as an extension to the tasks above.

References

Note: This is a partial list of references relevant for this experiment. You are expected to research additional documentation. Please make sure that this material is properly cited in your report.

Rayleigh, 1871. J.W. Strutt. *Phil Mag* XLI, 147

Salby M.L., 1996, *'Fundamentals of Atmospheric Physics'*, Academic Press.

Jose P.Peixoto and Abraham H. Oort, 1992, *'Physics of Climate'*, American Institute of Physics Press.

Fitzpatrick, M.F., et al. *'Transmission of Solar Radiation by Clouds over Snow and Ice Surfaces: A Parameterization in Terms of Optical Depth, Solar Zenith Angle and Surface Albedo.'* J. Climate. **17** 2 p266-275, 2004

Appendix 1 – Local Meteorological Measurements.

The London Grid for Learning website http://weather.lgfl.org.uk/ has data from a number of weather monitoring sites in London. Look to interpolate values for Imperial College from the surrounding data sources.

Appendix 2 – Cloud Base Height and Thickness.

In convective conditions, the lifted condensation level (LCL) can be used to calculate the height at which an air parcel, if lifted from the ground would condense; i.e. the cloud base height. A number of LCL calculators are available online, http://www.csgnetwork.com/lclcalc.html, for example. You will need the mean sea level temperature, dew point temperature and pressure, information available from local weather sources.

There are online tools (e.g. https://www.meteoblue.com/) that can provide real time weather maps and measurements of the cloud base height.

If you cannot determine the cloud base height by any other means, assume it to be 1km.

If the cloud is broken, a visual estimate of the cloud thickness is possible. For a uniform continuous cloud deck, images from https://ladsweb.modaps.eosdis.nasa.gov/ may be helpful. [You'll need level1&2, Collection 5.1 images centred on the UK.] If more accurate data is unavailable, use 500m if the location of the solar disk can be seen or 1km if not.

Imperial College London

RISK ASSESSMENT AND STANDARD OPERATING PROCEDURE

1. PERSON(S) CARRYING OUT THIS ASSESSMENT – This assessment has been carried out by the head of experiment.	
Name (Head of Experiment)	Michael McCann
Date	20/09/2024

2. PROJECT DETAILS.					
Project Name	***Solar Radiation***			Experiment Code	F1
Brief Description Of Project Outline	Measurement of solar radiation [outside experiment]				
Location	Campus	South Ken	Building		Room	

3. HAZARD SUMMARY – Think carefully about all aspects of the experiment and what the work could entail. Write down any potential hazards you can think of under each section – this will aid you in the next section. If a hazard does not apply then leave blank.			
Manual Handling	Use of tripods and carrying equipment	Electrical	Use of some electrical equipment
Mechanical		Hazardous Substances	
Lasers		Noise	
Extreme Temperature		Pressure/Steam	
Trip Hazards		Working At Height	
Falling Objects		Accessibility	Weather Conditions
Other	Outside Location		

4. CONTROLS – List the multiple procedures which may be carried out during the experiment along with the controls/ precautions that you will use to minimise any risks. Remember to take into consideration who may be harmed and how – other people such as students, support staff, cleaners etc will be walking past the experimental setup even when you aren't around.	
Brief description of the procedure and the associated hazards	**Controls to reduce the risk as much as possible**
Outside Location and Accessibility.	• Wear suitable clothing and footwear. • When working in the field you should inform your demonstrator/technician that you intend to do so and inform them upon your return. • Do not execute any field work (e.g. in Hyde Park or Princes Gardens) if there are wind or thunderstorm warnings. • Avoid placing equipment where there is a chance that it may fall to the ground. This is especially important if you are taking measurements at the terrace of level 8 - please stay clear of the balustrade. You can take the measurements on the ground. • Do not place equipment where it may obstruct others. • Return equipment to laboratory inside normal working hours unless you have signed it out for extended use out of hours. • Do not operate the equipment in wet conditions.
Manual Handling	• Be extremely careful with the quartz window of the measuring equipment. Make sure the tripod and mounts are stable before attaching fragile equipment. • Heavy and/or bulky equipment must be transported safely into the field of work (eg. the park). All equipment comes in hand held carry cases.

5. EMERGENCY ACTIONS – What to do in case of an emergency, for example, chemical spillages, pressure build up in a system, overheating in a system etc. Think ahead about what should be done in the worst case scenario.
No specific emergency actions. If the equipment appears damaged report to a demonstrator/technician immediately.