Imperial College London

Wind Turbulence

F2

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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

Turbulence in the Fluid Boundary Layer of our Atmosphere

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 Content

Introduction 3

Theoretical Background 3

Preparation 5

Tasks 6

Appendix 8

References 12

Introduction

Turbulence in the atmosphere exerts a very important influence on our environment. It is central to questions concerning the transport of heat and water vapour essential for growing plants and to the dispersal of air pollutants both in the atmosphere and the ocean. This experiment is concerned with the interaction between the atmosphere and the Earth's surface and in particular the very lowest layers above ground which is characterised by intense and well developed turbulence.

The aim of this experiment is to introduce students to some of the basic ideas and terminology used in turbulence arising in the atmospheric boundary layer. Turbulence, being chaotic in nature, is unfortunately one of the few fields in physics where theory lags behind experiment, however, with a little patience; students will hopefully find many of the tasks below illuminating.

Theoretical Background

At heights in excess of 500m or so above the Earth's surface, airflow is generally smooth and turbulence free over short length scales. However, below 500m (the upper limit of the *planetary boundary layer*) turbulence is very much in evidence and the moving fluid experiences tangential or shearing forces through frictional drag exerted by the air's motion over the Earth's surface. Between 50m and the surface, a sub layer known as the *fluid boundary layer*, wind speed reduces rapidly towards zero, its character being determined largely by the physical nature of the underlying surface and by the corresponding vertical temperature gradient.

The apparently chaotic motion of fluid in the turbulent layer may be visualised as a smooth mean flow on which large numbers of eddies (at a range of length scales) are superimposed as in Fig.1 below.

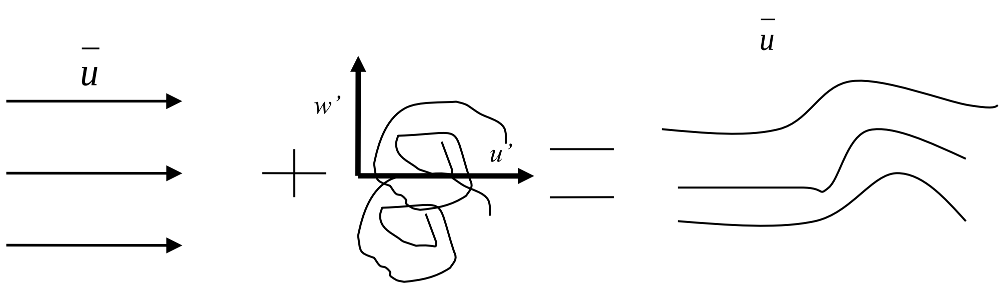


Fig.1. Turbulent flow can be thought of as horizontal and vertical velocity perturbations u' and w' superimposed onto a smooth mean wind, ū.

At a height above the ground, *z*, each eddy moves with the mean velocity *ū(z)*, to which its own internal motions, characterised by *u'* and I, the horizontal and vertical wind speed components, are added. The instantaneous wind speed component *u(z,t)* deviates from the average speed *ū(z)* by an amount,

$$u'(z,t)=u(z,t)-\bar{u}(z)$$

(1) (1)

The turbulent fluctuations u' are thus distributed equally above and below the mean value $\bar{u}(z)$. It is with the scale of these individual eddies that the characteristic *mixing length*, l, of the flow can be identified. Turbulent dispersion acts on all conserved properties (e.g. particle number) and is, at least qualitatively, analogous to molecular diffusion. In the laminar sub-layer nearest the surface, the diffusive motions of the fluid are entirely molecular in origin and character. However, in the turbulent zone above they are macroscopic with discrete *lumps* being displaced by turbulent action through a characteristic distance known as the mixing length, before merging with the surrounding fluid. The simplest possible deduction is that l is directly proportional to the distance above the surface so that

(2)

k is known as *von Karman's constant*, it has the value 0.4 and is found experimentally to be independent of the underlying surface.

The *shearing stress*, η, exerted on the surface by the fluid flow is generated within the lower boundary layer and transmitted downwards to the surface in the form of a momentum flux. The horizontal eddy shearing stress is formally defined through Newton's law of friction as,

$$\eta = \rho K_M(z)\frac{du}{dz} \tag{3}$$

where $K_M(z)$ is *the kinematic eddy viscosity* in m^2s^{-1} and ρ is the *mass density* of the air. Equation (3) is an example of how the molecular analogy is extended to turbulent flow. It relates the flux, η, to the gradient of *horizontal momentum* ($\rho\, du/dz$) and the ability of eddies to transfer momentum ($K_M(z)$). It has been found, therefore, that the shearing stress is proportional to the square of the wind velocity at some arbitrary reference height. This square law holds exactly when

$$\eta = \rho u^{*2} \tag{4}$$

where u^* reflects the turbulent shear stress near the ground and is known as the characteristic friction or *eddy velocity*.

Typical wind profiles over uniform and extensive surfaces are found to have a large vertical wind shear du/dz near the surface, decreasing gradually upwards. Plotting du/dz against z^{-1} invariably produces a linear relationship such that $du/dz = c/z$, where c is a proportionality constant. Show that this wind profile equation can be written as

$$\overline{u(z)} = \frac{u^*}{k}\ln(z) + A \tag{5}$$

where A is an integration constant and $u^* = u' = w'$. (Hint – consider the first order approximation of the velocity deviation u' with respect to l.) Equation (5) is the logarithmic law governing the shape of wind profiles in turbulent boundary layer flow down to the surface laminar sub layer. In fact, the equation can be rewritten as

$$\overline{u(z)} = \frac{u^*}{k}\ln\left(\frac{z}{z_0}\right) \tag{6}$$

where z_0 is the *roughness length* that characterises the underlying surface and takes on the role of *A*, the constant of integration, such that $u(z_0) = 0$.

The logarithmic behaviour predicted by equation (6), however, only accurately describes the form of the wind variation with height under conditions of *neutral stability*. The atmosphere is deemed to be neutrally stable if a parcel of air has no relative tendency to rise or sink in the absence of a displacing force. The air in the parcel and the surrounding environment at the same level are identical so that the parcel possesses no net buoyancy and remains static. The *gradient Richardson number*, *Ri*, relates to the relative importance of free convection (turbulence that is mainly driven by buoyancy) to the forced convection arising from vertical wind shears (leading to mechanical production of turbulence which homogenizes temperature structure) in determining the form of the fluid boundary layer. It is the ratio of turbulent kinetic energy produced thermally to that produced mechanically and can be written as

$$Ri = \frac{g}{T} \cdot \frac{\frac{dT}{dz}}{\left(\frac{du}{dz}\right)^2} \tag{7}$$

The equation can be simplified by equating g to $10 ms^{-2}$ and rewriting it in finite difference form. It can be shown that the range of *Ri* within which the wind profile law (6) is strictly valid is in fact very small; $-0.01 < Ri < 0.01$. Nonetheless, small deviations outside this range are not significantly influenced by the effects of free convection and there inevitably exists a turbulent layer close to the ground in which $u(z)$ varies logarithmically.

The aim of this experiment and the eight tasks below is to observe wind profiles over surfaces of different roughness lengths and to try and understand the structure and scale of the turbulent airflow near the ground.

Preparation

Calibrate the anemometers you plan to use prior to leaving the laboratory using a fan or high-pressure gas driven system to ensure that all three show the same reading and response (within some error margin), noting any offsets. Familiarise yourselves with the functions of the anemometers and try to determine the response times of the wind meter and thermistor respectively. You will be using three or more digital hand anemometers primarily Testo 405i thermal anemometers (RS part number 913-2575) with data logging using the tablet provided, although older turbine based anemometers (RS part number 180-7111) are available to supplement these. You will be able to set up the instruments to record the maximum and minimum wind speed value attained after enabling the record mode and calculate the average reading value for the last 10 records. The update rate for the turbines is approximately 0.8 s hence the average reading given is of the previous 8 to 10 seconds. Further details and specifications are found in the instruction booklets provided. It is always worthwhile checking the meters again when on site to ensure they agree within your determined error bars. See appendix 2 for some additional guidance on data-logging from the RS anemometers using an RS232 cable. Loan laptops are available to help with this activity.

As you will be working off site for some of the time, and deploying a rather large (>3 m tall) sensor array you are likely to attract attention from members of the public and occasionally the police. You should therefore put together and practice a short impromptu talk for these occasions, explaining who you are and what you are doing.

Building your sensor array for the 1st time in the field will be challenging, and you will inevitably find you are missing some hardware. For this reason, you should first build a sensor array around a variable height tripod / vertical boom in the lab and make sure you have all the necessary functionality and data logging working well before moving outside.

Before leaving the building to collect 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 weather using the cloud and pressure charts and the satellite images provided for the SouthEast/London area. For local information interpolate between the site measurements from http://weather.lgfl.org.uk/

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 familiarizing yourselves with the charts and notations used by synoptic meteorologists and forecasters, while also providing a record of the prevailing weather conditions when your measurements were made.

Tasks

1. Using the anemometers erected at several heights above any reasonably uniform and sufficiently extensive level area for fully developed boundary layer flow, observe the mean wind speed $\bar{u}(z)$ as a function of height z to give a wind profile. (As a rule of thumb, the wind profile at a distance x downwind from the change in surface roughness will be characteristic of that surface up to a level $z_{max} = x/40$. Anemometers must be confined below this level to record fully developed flow.) Record the wind speed at regular intervals of less than 10 seconds for about 10 minutes to obtain a time series at a range of heights and hence calculate $\bar{u}(z)$. Note that the upper limit to the frequency of oscillations in the record is governed by the speed of response of the anemometers, which is to be found.

   At a constant height, z, obtain a simultaneous time series record of horizontal and vertical wind speeds, $u(z)$ and $w(z)$ respectfully and temperature, T. Taking into account the response times of the anemometers and thermistor, explain any correlation you observe.

   Repeat this procedure over two different surface types, such as grass or water. Comment on the magnitude of errors for your readings.

2. Write a short program to calculate the autocorrelation $R(\tau)$ for the wind speed time series and plot $R(\tau)$ against lag time, τ (refer to Appendix 1 for autocorrelation details). Explain, qualitatively, what you observe and compare your plot to that for a randomly generated sequence of numbers. Estimate the *outer scale* of the turbulence, S and compare values of S at small and large heights, by finding the time the correlation first goes to zero.

3. Evaluate the *gradient Richardson number, Ri*. Is it in reasonable accord with the limits

-0.01< Ri <0.01 for neutral stability conditions to hold? Is your assessment of stability and your measured wind speed profiles sensible in relation to your synoptic description of today's weather?

4. Plot ln(z) against $\bar{u}(z)$ to determine the surface roughness length, z_0. z_0 is typically 1/10 the height of the roughness elements, is your value consistent with your chosen measuring site?

5. u^*, the *friction* or *eddy velocity*, is representative of the magnitude of the velocity fluctuations in the turbulent boundary layer flow and reflects the turbulent shear stress near the ground. Are u' and w' comparable in size? If so, it is justifiable to assume equality of u' and w' such that $u' = w' = u^*$ and so

$$u^* = (u'w')^{1/2} \tag{8}$$

Calculate u^* from your data and using the gradient of your logarithmic wind profile confirm that the value of the *von Karman constant* is $k = 0.4$.

6. Shearing stress within a turbulence free or *laminar* boundary layer is written as

$$\eta = \rho v \, du/dz \tag{9}$$

where η, the *molecular diffusivity of momentum* or *kinematic viscosity*, is independent of height and equal to 1.5 x 10^{-5} m^2s^{-1}. The turbulent shearing stress may be expressed in the analogous form

$$\eta = \rho K_M(z) \frac{du}{dz} \tag{10}$$

where $K_M(z)$, the turbulent diffusivity of momentum or *eddy viscosity*. Confirm that $K_M(z)$ does in fact depend on height by showing it is equal to ku^*z. Using your data show that the turbulent diffusivity a few meters from the ground is several orders of magnitude greater than the molecular diffusivity. Comment on the significance of this result.

7. Finally, devise your own experiment as an extension to the tasks above. You may want to investigate the form of wind profiles over other surfaces and locations, or perhaps look at the roughness lengths for different obstacles. These are just suggestions, there are plenty of other ideas to be found in the listed reference books - the choice is yours!

Appendix 1

From “Dynamical Meteorology – An Introductory Selection” A. Ibbetson, Chapter 11 p143

Autocorrelation is a way of describing the statistical time variability of the wind speed flow. For the wind component u' along the mean wind direction, the autocorrelation $R(\tau)$ is calculated from the product of the velocity fluctuation at any instant, $u'(t)$, and its value at a time τ later, $u'(t+\tau)$. This product is calculated at each successive instant of time, the average value of the product is calculated over a suitably long period (usually several minutes), and is then divided by the total variance. Thus we may write

$$R(\tau) = \frac{\langle u'(t)u'(t+\tau)\rangle}{\langle u'^2\rangle}$$

provided that the variance, u'^2, does not change appreciably with time. The maximum possible value of R is evidently 1 (when $\tau = 0$), and we expect R to decrease as the time lag, τ, increases. In practice, the autocorrelation is usually estimated numerically by first digitising the continuous record of wind speed: the value of the wind speed is read from the record at suitable intervals of time, usually determined by the time interval between successive measurements.

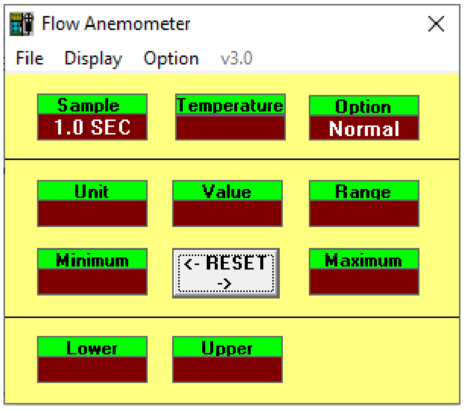
The shape of the autocorrelation curve $R(\tau)$ obviously depends on the structure of the turbulence. Provided $R(\tau)$ eventually decreases to zero at large values of τ, the area under the whole autocorrelation curve $\int R(\tau)d\tau$ is therefore a measure of the period associated with the largest eddies in the turbulence, denoted S. Using Taylor’s “frozen turbulence” model, where the turbulence is assumed to be “frozen” into a fixed pattern which then moves along with the average wind speed, the physical size of the largest eddies would therefore be $u(z)S$.

Appendix 2.

Setting up COM ports for data logging using the RS 180-7111 turbine based anemometers.

A COM port is a serial data port that used to be a common feature of PCs, and is used by a wide variety of equipment for data logging and computer control. It is becoming less and less common to find multiple COM ports on a single machine, and they are often replaced by a USB <-> COM converter. You will need to set a number of these up if you are data logging from an array of RS 180-7111 turbine based anemometers, this is something of an art form and the guide below gives you some technical detail on the process.

As an aside, it is a common student misconception that "connecting a computer will make it easier", getting dissimilar pieces of hardware (possibly from quite different generations of technology) to talk to each other is a common and sometimes frustrating lab problem.



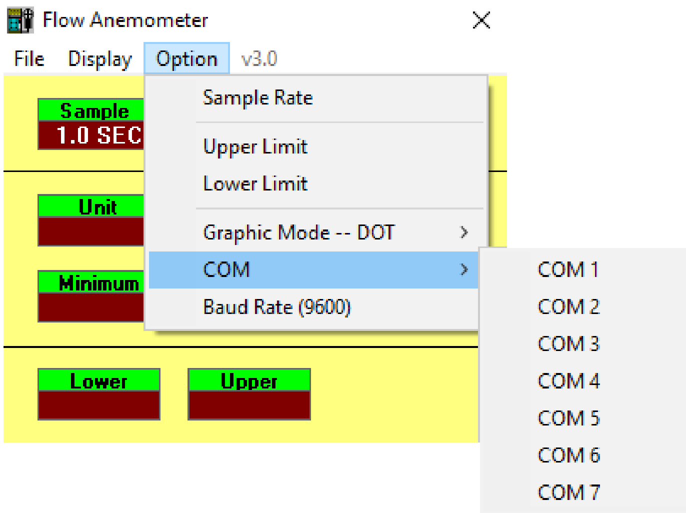
Setting up Flow Anemometer:

- Install USB-RS232 converter

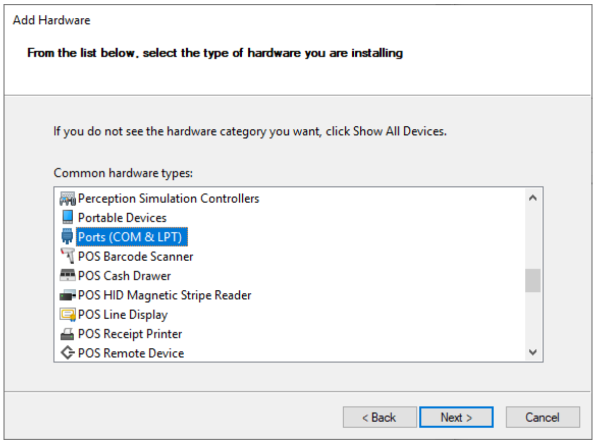
- Install Flow Anemometer

After installing the software, run Flow Anemometer.

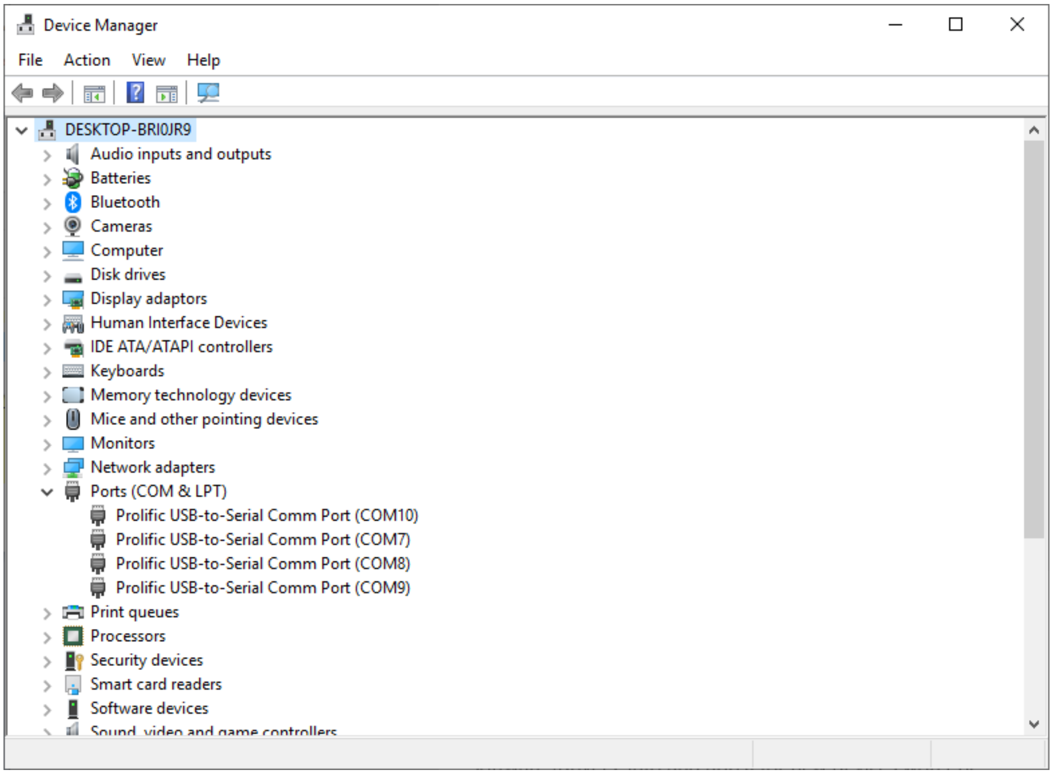
Selecting Option → COM will bring up a list from COM 1–7. This list allows you to set which ports will be communicating with the software. A maximum of 7 anemometers can be connected to one device.



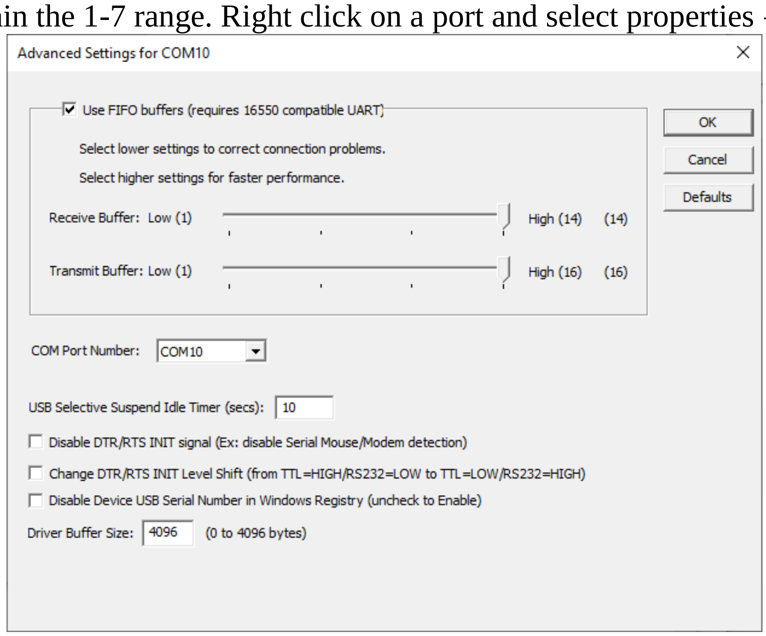
Close the software and connect the anemometers via the USB-RS232 adapter(s). If you are connected to the internet, Windows should be able to automatically install the relevant drivers. If not, open Control Panel → Hardware and Sound → Device Manager → Action → Add Legacy Hardware → Install the hardware that I manually select from a list (Advanced).



Scroll down to Ports (COM & LPT) and select Next until the install is complete. Scan for new hardware in the Device Manage, and you should see something like below (with as many anemometers as you have connected).



In this case, four anemometers have been connected and they each have an assigned COM port, but only one is within the 1-7 range. Right click on a port and select properties → Advanced.

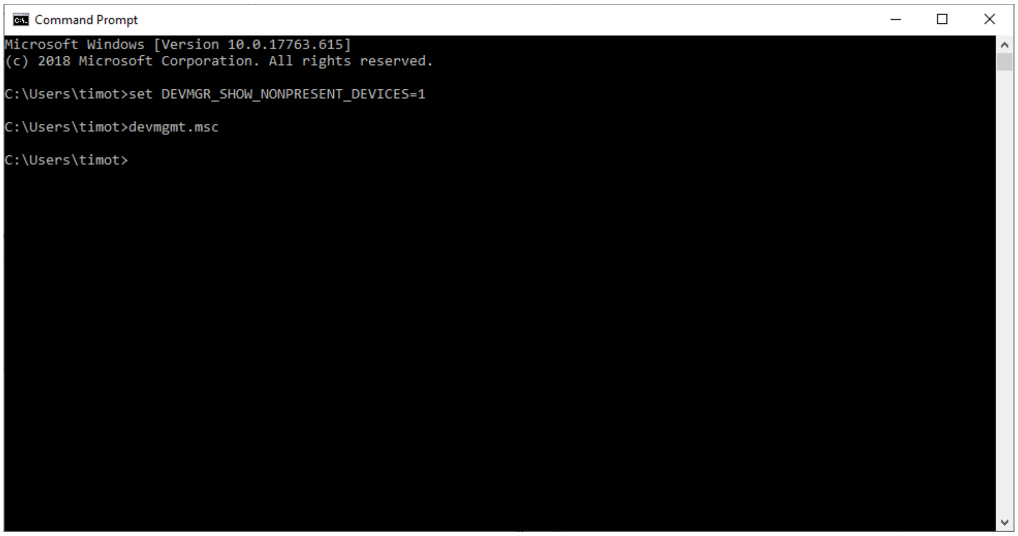


You can reassign COM Ports to a different value by selecting from the drop-down menu.

You may find that some ports between 1-7 are already occupied by software or other devices. In this case, close device manager.

Press the Windows key and type CMD, then input the two commands seen below.

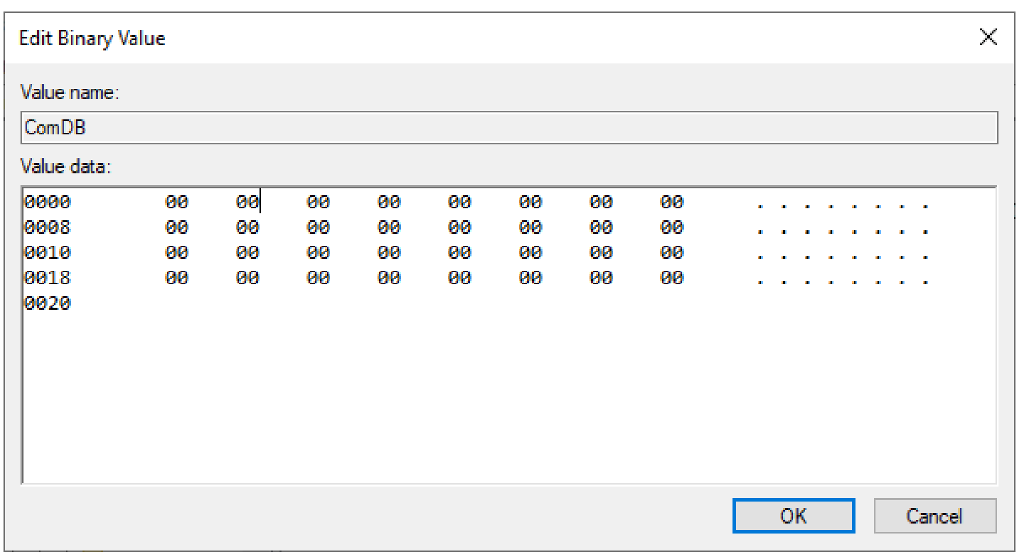
- set DEVMGR_SHOW_NONPRESENT_DEVICES=1
- devmgmt.msc



After the Device manager has reopened, select View → Show hidden devices. You can then reassign the COM ports of the software/hardware that was hidden as above.

The nuclear option:
If there are still active ports that do not display when you perform the steps above, you may have to manually remove the assignments in the registry.

- Click start → type ‘run’ and enter → type ‘regedit’ and enter
- Navigate to HKEY_LOCAL_MACHINE\SYSTEM\CurrentControlSet\Control\COM Name Arbiter
- Now on the right panel, you can see the key ComDB. Right-click it and click modify
- Set every value to 00



- Restart your computer and perform the steps above to assign the COM ports.

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.

"Dynamical Meteorology – An Introductory Selection" Edited by B. W. Atkinson, 1981
"Essentials of Meteorology" D. H. McIntosh and A. S. Thom, 1973
"Fundamentals of Atmospheric Physics" Murry L. Salby, 1996
"Boundary Layer Climates" T. R. Oke, 1987