Course Name: An Introduction to Climate Dynamics, Variability and Monitoring

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INTRODUCTION TO PRINCIPLES OF MEASUREMENT AND INSTRUMENTATION – PART 3

Good morning class and welcome to our continuing lectures on climate dynamics, climate variability and climate modeling. In the last class, we discussed an important parameter for instrument characterization, the instrument response time which is related to the response of an instrument to step changes in the parameter value. However, most of the actual physical parameters do not vary in a step change method. Most climatological and meteorological variable parameters vary in oscillatory method, periodic oscillations. For example, if you think of the air temperature, then if you continuously log the temperature throughout the day, It will be low in the morning, rise up in the afternoon, fall back down towards midnight and again start to rise in the morning. So, it will have an oscillatory structure to the signal of temperature.

For a simple case, so most of the parameters are oscillatory in nature. So we have to also understand how the instrument responds to such oscillatory signals. For a simple case, we will model the physical variable as a sinusoidal function around some mean value. The actual physical variable value at the given time t is the mean $\bar{x}$ plus a sinusoidal component given by $Asin(2\pi ft)$, where f is the frequency of the signal.

$$x_a(t) = \bar{x} + Asin(2\pi ft)$$

So, we can say the parameter average is 1. So, $\bar{x}$ is 1. This is the sinusoidal. The amplitude is 1 I think and sine 2 pi of t. So, f is 1, $\bar{x}$ is 1 and a is 1 for this signal.

In such case the steady state instrument response can be shown to be and again we are not deriving this it can be derive. How does the instrument response if the actual physical variable is of this function is the instrument response is $x(t)$ is equals to $\bar{x}$ again the actual mean plus $\frac{A}{\sqrt{1+(2\pi f\tau)^2}}$. Remember tau is the time response. So, the amplitude is lower. It is lower by $\sqrt{1+(2\pi f\tau)^2}$ and the phase, there is a phase difference between the actual signal and the instrument response.

$$x(t) = \bar{x} + \frac{A}{\sqrt{1+(2\pi f\tau)^2}} sin(2\pi ft - \varphi), where, \varphi = tan^{-1}(2\pi f\tau)$$

This phase difference is given by this term psi and psi is $tan^{-1}(2\pi f\tau)$. So, this $2\pi f\tau$ term becomes important both in decreasing the amplitude that is being measured and changing the phase of the signal response. So, it is seen that the response is reduced in amplitude-by-amplitude response R which is $\frac{1}{\sqrt{1+(2\pi f\tau)^2}}$ and shifted in space by psi. Clearly, the f tau value has to be small for the instrument to record correct amplitude. Of course, if f tau is tending towards 0, then this becomes just A and this becomes tan inverse 0.

So, this is 0.0. This will not of course happen. We will have a non-zero value of $f\tau$. But it should be small to get accurate values.

In fact, we can define something called a cutoff or corner frequency. What is it called? It is called cutoff or corner frequency, which is given by f_c as $\frac{1}{2\pi\tau}$. Remember tau is second. So, this is units are in second inverse. So, corner frequency fc is given by $\frac{1}{2\pi\tau}$.

So, when f is equals to f_c, then $2\pi f\tau$ becomes $2\pi f_c\tau$ which is equals to 1. So, this becomes 1 plus 1. So, the amplitude response becomes $R = \frac{1}{\sqrt{2}}$. So, if the actual amplitude is A, the measured amplitude becomes $\frac{A}{\sqrt{2}}$. And the psi becomes $tan^{-1}(1) = 45^{\circ}$

So for a given exponential time response, we can define the corner frequency as the maximum frequency whose signal can be measured with some reliability. f should be at least significantly lower than f_c to have proper values of a and proper values of the amplitude response to come up. However, this is kind of the cutoff frequency or the corner frequency. If the signal has frequencies higher than this, then we have a problem. So, this kind of shows us how to pick instruments.

Given that a signal has a certain frequency f, and we have an instrument with certain frequency, certain time response tau, we see whether $\frac{1}{2\pi\tau}$, the corner frequency is less than f or greater than f. If the corner frequency is greater than f, then we do not have a problem. However, if it is less than f, then we do have a problem and the instrument will not be recording the values properly. And this you can see here in this figure. So, this is the response of an instrument to a fluctuating quantity.

The actual instrument frequency is 1, $\bar{x}$ is 1, A is 1. The exponential time constant is in the first case is 0.1 units.

So, this is 0.1. So, it goes up. So, it is 10 by 2π. So, here 2π is actually 6. So, it is 10/6.

It is 1.34 something like that. The corner frequency f_c is 1.3. The actual frequency is 1. As a result, we are getting reasonably because the actual frequency is lower than the corner frequency, there is no problem.

However, if the exponential time constant is 1, then this is 1/6. So, 1/6 is around say 0.3 something like that, like not 0.3, 0.18, 0.17 something like that. So, your corner frequency is 0.17, while the actual frequency is 1. So, the actual frequency is much greater than the corner frequency. And as a result, you see a huge decay in the, you are not getting the amplitude, or the phase correct.

So, that is the problem. Your frequency values have to be less than the corner frequency. The next point, next section we will go into is data acquisition systems. These are also often called data loggers. This is the system that is used to acquire the data that the sensor is sensing. So, what do we mean by that? You have a sensor, the sensor is sensing the physical parameter and converting it into some variable which change has to be collected and given an output value by the data logger or the data acquisition system, once which acquires the data from the sensor itself.

So, acquisition and storage of data from a variety of sensors is done by a data acquisition system or a data logger. Typically, these devices work with multiple types of sensors. There may be pressure sensors, wind sensors, humidity sensors, radiation sensors, all involved. They are programmable and makes measurements either in batches or continuously. It can acquire data from multiple types of sensors using a multi-way connector block.

We will discuss this when we are looking at this. Basically, there is something called a multi-way connector block through which multiple types of sensor data can be acquired all together. It has an inbuilt computer which runs a locking program to determine what to measure and when. So, the sampling strategy, what to measure when is kind of programmed inside this data logger to an inbuilt computer, a microprocessor or something like that. It has a computer-controlled switch called the multiplexer which selects the particular sensor from which to acquire data.

Usually, a sequential switching is done to collect data from each sensor sequentially. So, you collect data first from say pressure sensor, take say 50, 60 rapid pressure measurements, then go to the temperature section. take 100 temperature measurements, then go to the wind speed section and get 100 wind speed measurements, again switch back. So, this you have a rapid fire sequential process of switching on and off from different sensors. This is done by the computer-controlled switch called the multiplexer.

Designed to operate with low power requirements in remote sites and have rugged weatherproof housing. Often climatological and meteorological data are planted in remote sites say high arctic or Antarctic peninsula top of mountains they will not have dedicated electrical connectivity. So they are often designed to operate with low power requirements they may have a solar cell inbuilt that will use it to power up a battery it can run continuously. And it should also have rugged weatherproof housing if there is a heavy weather snow, hailstorm storms etc come on the system can still be protected. They also usually have an inbuilt clock to time the data acquisition events more accurate systems will be connected to the satellite GPS for time evaluation.

So, here is a small example of such an automatic weather sensor data with a lot of, this is kind of your temperature sensor actually. There are other types of sensors also connected, wind speed, humidity, etcetera, etcetera, radiation measurements and others. This is your data logger. All of this sensor information is coming into this data logger. There is an automatic programming may be inside storing this data and this may be beamed back to the Wi-Fi or being stored in a data card that can be taken out under after certain period of time.

So here are different types of sensors, voltage sensors, pulse sensors, we will discuss them later in the class. This is the data logger proper. You have this multiplexing switch which is switching between the various types of sensors. Then you have an analog to digital converter which is particularly useful for the voltage conversion. We will see why voltage sensors that give voltage output require an analog to digital converter.

Once the data is converted into a digital format, it is sent into a microcomputer where it is processed, some initial processing is done and then stored in memory, memory card. A pulse type counter, so it kind of counts frequency of certain events like the frequency of rainfall for example. And this kind of goes again into a microcomputer and it's in the stored memory. The time stamp for the data acquisition is taken from the real time clock.

So data types and acquisition methods. The first type of data that data logger collects is called count data. These are recorded as a succession of pulses associated with discrete events that are recorded in order to determine how many of these events occur. So they are recorded as a succession of pulses, maybe electrical pulse or a voltage pulse that record discrete events. And we determine how many events occur, the times when they occur, so their time stamp and the event occurrence rates, how many per minute are occurring. Example, tipping of a bucket of a rain gauze detector.

So, a rain gauze detector collects a certain amount of water, then it tips to empty the bucket. So, say it collects a 10 millimeter of rain and then it tips again. So, the number of tipping events kind of time how many 10 millimeter amount of rain was collected over a certain period of time. Acquisition, usually these are voltage pulses and require a digital counter to store the number of pulses received and the corresponding timestamp. So, these are voltage pulses, usually a digital counter type of device used to store the number of pulses received and corresponding timestamp.

The value of the counter is read after fixed intervals by the microcomputer. So, this is the simplest type of data acquisition method. Another discrete data type is the frequency data. Frequency data is also discrete like count data except that the obtained data is periodic in nature. So, the rain, the bucket tipping of a rain gauge is aperiodic.

There are no fixed periods over which it is supposed to happen. However, consider a cup anemometer which is used to measure wind speed. The cups are rotating around the shaft and the rotational motion of the shaft gives a measure of the wind speed. The cup anemometer has a shaft axis that produces a regular pulse stream as it rotates about its axis. So, for example, suppose at every 60-degree rotation of the shaft, a pulse gets triggered.

So, the number of pulses gives an idea of the angular velocity omega, which is basically $\frac{d\theta}{dt}$ the rate of change of angle with time that the shaft is encountering and that gives the value of the wind velocity. The periodic pulse stream say 1 per revolution or 3 per revolution measures the rotational frequency revolutions per second and helps to measure wind speed. So, here again we are counting pulses, but the pulses are coming as a periodic data. Here acquisition of frequency counter. So, remember in the previous case in count data we have just a digital counter where number of pulses in the time stamp was taken.

We did not expect any periodic information there. So, nothing else was done with that. Here a frequency counter is used which determines the total number of pulses received over a predefined interval. So, again if we take the ammeter example, suppose we count the total number of pulses received per second, and suppose each revolution has 3 pulses. So, if you have say 18 pulses obtained per second then it is 18/3, 6 revolutions per second the shaft has angle go and that is the angular velocity of the shaft. This predefined interval is called the gate time which we have taken as 1 second in my example.

The frequency then becomes $f = \frac{N}{t_{gate}}$. The number of pulses counted by the gate time. Some acquisition instruments have their own inbuilt oscillation frequency, f oscillation. For example, quartz oscillators, which you will find in many of the watches. So, they have their own natural frequency f oscillation. If n pulses are recorded in such a device, then the interval between the pulses is n by f oscillation.

Frequency is known and n pulses have been obtained over a certain time with this frequency. Then the time interval between the pulses is n by the f oscillation, $t = \frac{N}{f_{osc}}$. So, this way either you can get the frequency data with the time, gate time is fixed or you can get the time interval data with the frequency of the oscillation over which this N is going to be obtained is fixed. Finally, we have the variable voltage data.

So, this is the continuous signal. The last two cases were discrete signals. Here, the sensor gives a continuously variable voltage signal. Hence, we have a real valued analog signal which is continuous with time. And the data acquisition system needs to digitize the data before acquiring it. Because it gives you an analog voltage signal, we need to digitize it before we can acquire and store it.

And for that, we need an analog to digital conversion system, an ADC. Maybe an analog to digital converter, it's also often called. These are subsystems within the data logger that converts an analog signal to a digital one. A common type of ADC is the voltage comparator. So, a voltage comparator is a type of ADC that returns 1 if the input is above a certain threshold value or 0 otherwise.

So, let us understand the problem. We have a continuous voltage signal coming from your sensors, and we want to convert it into a discretized data. How do we do it? One method is using a voltage comparator. So, voltage comparator is an electronic circuit which returns 1 as output if the voltage is above a certain pre-programmed threshold value or 0 otherwise. This is good, but how does that help? The electronic device usually have a set of multiple voltage comparators.

Set in an ascending arrangement of threshold values. So, suppose your ADC has a set of multiple voltage comparators with individually programmed threshold value. So, one has a threshold value of 0.1, the second 0.2, third 0.3, fourth 0.4 going up to 1 volt as V_N. The same voltage signal is given to them all. And the signal voltage determined as lying between the greatest threshold value for which the comparator returns 0 and the lowest threshold value for which the comparator returns 1. Suppose the actual voltage is 0.57. Now, this is above the threshold value for V_1 equals to 0.1. So, it returns 1. It is above the threshold value of V_2 equals to 0.2, so it returns 1. V_3 equals to 0.3, it returns 1. V_4 equals to 0.4, it returns 1. V_5 equals to 0.5, it returns 1. V6 is 0.7, now the voltage is below the threshold, so it returns 0. V_7, 0.7, 0. So, you get 1, 1, 1, 1, 0, 0, 0, 0, where the V_5 and V_6 is where the 1 to 0 transition is taken. So, the greatest threshold value for which the comparator returns 1 and the lowest voltage threshold value for which the comparator returns 0. The electronic device returns an input of the form 111000 and the determination can be made rapidly, and all the comparators can be made to operate in parallel.

And this way we know that the actual voltage is between 0.5 and 0.6 volts. Of course, you can have 1000 comparators there and you can have a much finer resolution also if you want to. The output of an ADC is a numerical value that is expressed in a binary number system, 1s and 0s. The maximum value that can be expressed in a binary system of n bits is $2^n - 1$. Suppose you have 8 bits, the maximum number of numbers that you can represent with the 8-bit system is $2^8 - 1$. Hence, an ADC with a larger number of bits can represent a voltage range with better resolution.

So, for a voltage span V_{span}, the ADC resolution is delta V goes to $\Delta V = \frac{V_{span}}{2^n - 1}$. What does it mean? Suppose your voltage range is 1 volt to 10 volts. So V_{span} is 10-1, 9 volts. All right, your bits is 8, so $2^8 - 1$. So, the minimum difference between two threshold values in the voltage comparator can be this value, V_{span} by $2^8 - 1$.

Below that, its resolution, it cannot resolve because you have more number of, more numerical value than data. So, if you have a bigger, ADC with a bigger number of bits, say it is a 12-bit machine, then to the power 12 minus 1 and your ADC resolution increases. So, ADC with better resolution will give a much finer voltage value determination than ADC with a coarse resolution. Not only is this resolution of the magnitude, we also have to do a resolution of the frequency. Do a proper sampling, the signal also needs to be sampled sufficiently rapidly for its temperature, temporal variations to be recorded.

Because the voltage signal may have its own frequency. Is the ADC able to capture that frequency? If the sampling frequency is f_s, second inverse, so suppose it is taking 100 samples per second. So, fs is 100. It is taking 100 samples means the ADC is sampling the actual continuous voltage 100 times in a signal. Then the maximum frequency in the signal that can be properly recorded is called the Nyquist frequency which is $0.5f_s$. So, if the signals, the maximum frequency captured in that signal is 0.5 into 100 that is 50. If the signal has a frequency greater than 50 seconds inverse, then we have a problem because the ADC will start to generate spurious low frequency signals coming from these frequencies that are being only partially recorded. Hence, what is done is an anti-alias filter is usually present in the ADC to remove such high frequencies from the sensor signal. And of course, if the main set of frequencies in your sensor is greater than the Nyquist frequency, then you should have an ADC with a higher sampling rate. And ADC is usually connected to multiple sensors using a multiplexing switch which can change the input to ADC from one type of sensor to another based on the data acquisition system computer instruction. So, if you see the table here, here we are looking at the voltage resolution of the ADC for different resolutions. The full-scale range is 5 volts.

So, it is 0 to 5. V_{span} is 5. If 8 bit ADC is used, maximum value is 255. So, 8 by 255 voltage resolution is 19.6 millivolts. 10-bit, maximum value is 1023 values it can store. So, the voltage resolution becomes 4.9 millivolts. So, you can see a rapid drop, right? Similarly, 12-bit, you will get 1.2 millivolts. So, you have a bigger bit ADC, better is the resolution of your instrument.

And this is the multiplexing switch. You have an ADC converter. These are the various channels which are measuring voltages for various types of sensors. And you can switch rapidly using this multiplexing switch. Sample say 100 times or 200 times and then switch to another.

So, we will stop here today. We will just discuss what is called the automatic weather station in the next class and start with various ways of measuring climatological parameters.