Optical Fiber Sensors
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Lecture 11
Sensor Performance characteristics

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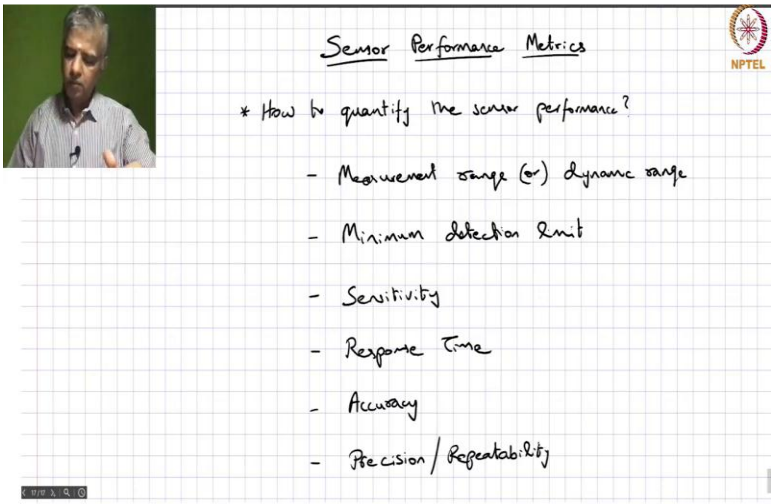

Hello, so far, we have been looking at the design of an optical receiver for an optical sensor. So, we started with looking at the front end, the PIN photodiode, APD photodiode, how to extract current from that, when light is incident on it, how to extract current efficiently from those photodiodes when light is incident on it, how to amplify them and so on. So, how to build your optical receiver effectively. And in the last lecture, we looked at signal to noise ratio issues. Specifically, we looked at the typical noise sources as far as the receiver is concerned.

So, now it is time to take a step back and quantify the performance of an optical sensor collectively. So, what do I mean by that? Well, how do you tell that one sensor is better than another? So, how do you compare two sensors? So, you need to have some quantification as far as the sensor performance is concerned. So, that is what, we are going to be talking about, what are the typical performance metrics of an optical sensor? So, when we talk about performance metrics, so, what we are saying is how to quantify the sensor performance and then, what are the typical type of metrics that you can think of?

So, one would be obviously the measurement range. So, range or in some cases, it is also called the dynamic range of the sensor. Next, will be the minimum detection limit. So, what is the minimum quantity that you are going to be able to measure in terms of the sensor, then you have things like sensitivity, how well the sensor responds to some change in the parameter that you want to, want to be measuring?

Then you have things like response time of the sensor and more importantly, perhaps, because most of these are talking about some deterministic quantities, but there is a certain level of uncertainty involved with any of your measurements. So, how do you quantify that uncertainty? So, then you start thinking about things like accuracy and then you talk about precision or repeatability and so on.

And then of course, there are other things like the linearity of the sensor and then if there is any hysteresis effects and so on. So, there could be other parameters also, but you would find that those are all not very common. So, there are certain applications where, the way the sensor is designed it exhibits hysteresis, we need to quantify the hysteresis and so on. But those are some special cases. So, let us look at how these quantities would work.

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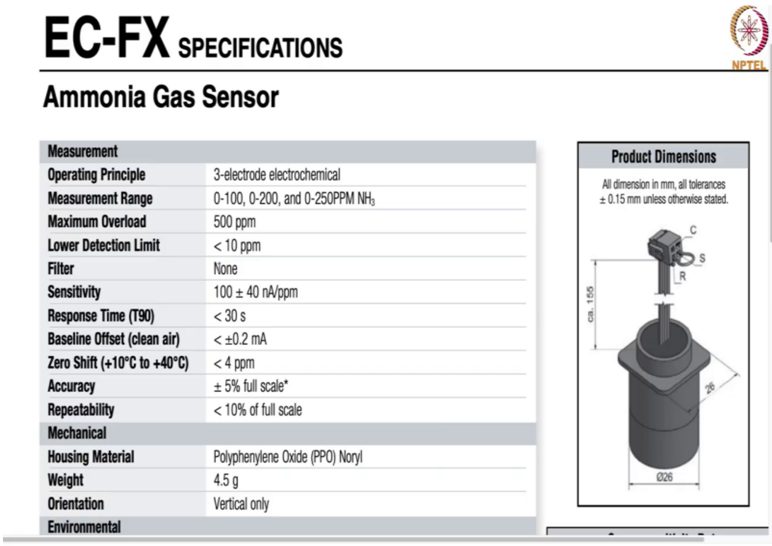
EC-FX SPECIFICATIONS

Ammonia Gas Sensor

Measurement	
Operating Principle	3-electrode electrochemical
Measurement Range	0-100, 0-200, and 0-250PPM NH_3
Maximum Overload	500 ppm
Lower Detection Limit	< 10 ppm
Filter	None
Sensitivity	100 ± 40 nA/ppm
Response Time (T90)	< 30 s
Baseline Offset (clean air)	< ±0.2 mA
Zero Shift (+10°C to +40°C)	< 4 ppm
Accuracy	± 5% full scale*
Repeatability	< 10% of full scale
Mechanical	
Housing Material	Polyphenylene Oxide (PPO) Noryl
Weight	4.5 g
Orientation	Vertical only
Environmental	

And to give you an example, let me go to a commercial sensor that is available in the market. So, this is an ammonia gas sensor. So, this is made by, I think, Honeywell. So, you know what are the typical specs do we see for this gas sensor. First of all, it is not an optical sensor, I am just picking something up out of the blue, just to give you an idea about the sensor performance metrics. And just to give you examples for the kind of numbers that you are likely to see whenever you pick up the specification sheet for a sensor.

So, it has got measurement range, it has got, well, there is a maximum overload also defined for this in, in this case, it is a sensor that works up to a certain range, and you can probably push it to a higher value, but beyond a certain point, it might suffer some irreversible damage. So, that is what you are talk about the overload limit. But so, there is a difference between this number and this number. So, what is happening between that what we are saying is, when we say 0 to 100, that is the range over which rest of the specifications are supposed to work very well.

And, and beyond that, you might still get a response, but there are those will not conform to the other specifications. So, they are not mentioned as part of the measurement ranges, then there is a lower detection limit, which says, I am not going to be able to do good performance below that, typically, because of noise issues that we talked about previously. So, you would have a limit like that and then there is a sensitivity number. So, the sensitivity is, in this case, you have a certain concentration of the ammonia gas.

And, and you are trying to extract a parameter at the receiver. And, and that parameter is for an electrochemical sensor, it is a current electrochemical current that comes about. So, the sensitivity is defined with respect to slope of the current that you get for unit change in the concentration of the ammonia gas. And then there is a response time. So, yeah, what is the typical time over which you can, beyond which you can get reliable readings. So, that is what readings that conform to once again all the other specifications.

So that is what we talk about as a response time. And then there is some offset and zero shift and all, that those again are not typical, but then you come to accuracy, which is, I will define what accuracy is and then there is repeatability. So, how well, if you do the same measurement multiple times, how well can you be able to reproduce the results that you are getting? So, those are some typical numbers.

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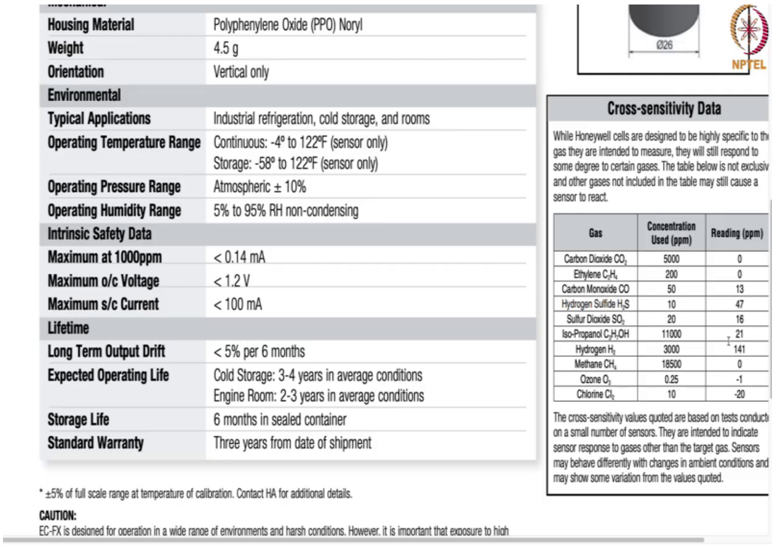

Housing Material	Polyphenylene Oxide (PPO) Noryl
Weight	4.5 g
Orientation	Vertical only
Environmental	
Typical Applications	Industrial refrigeration, cold storage, and rooms
Operating Temperature Range	Continuous: -4° to 122°F (sensor only) Storage: -58° to 122°F (sensor only)
Operating Pressure Range	Atmospheric ± 10%
Operating Humidity Range	5% to 95% RH non-condensing
Intrinsic Safety Data	
Maximum at 1000ppm	< 0.14 mA
Maximum o/c Voltage	< 1.2 V
Maximum s/c Current	< 100 mA
Lifetime	
Long Term Output Drift	< 5% per 6 months
Expected Operating Life	Cold Storage: 3-4 years in average conditions Engine Room: 2-3 years in average conditions
Storage Life	6 months in sealed container
Standard Warranty	Three years from date of shipment

* ±5% of full scale range at temperature of calibration. Contact HA for additional details.

CAUTION:

EC-FX is designed for operation in a wide range of environments and harsh conditions. However, it is important that exposure to high

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Cross-sensitivity Data

While Honeywell cells are designed to be highly specific to th gas they are intended to measure, they will still respond to some degree to certain gases. The table below is not exclusiv and other gases not included in the table may still cause a sensor to react.

Gas	Concentration Used (ppm)	Reading (ppm)
Carbon Dioxide CO_2	5000	0
Ethylene C_2H_4	200	0
Carbon Monoxide CO	50	13
Hydrogen Sulfide H_2S	10	47
Sulfur Dioxide SO_2	20	16
Iso-Propanol C_3H_7OH	11000	21
Hydrogen H_2	3000	141
Methane CH_4	18500	0
Ozone O_3	0.25	-1
Chlorine Cl_2	10	-20

The cross-sensitivity values quoted are based on tests conduct on a small number of sensors. They are intended to indicate sensor response to gases other than the target gas. Sensors may behave differently with changes in ambient conditions and may show some variation from the values quoted.

And of course, there are some other special numbers. In this case, you have what is called cross-sensitivity data, it is very, very important that in you are trying to pick up one quantity. How sensitive it is to some other quantity, in this case, we are talking about a gas sensor. So, you are supposed to pick up only ammonia, but then your electrochemical process, in this case, maybe sensitive to other gases as well. So, this is sort of the specification with respect to that.

And so, what we see is that hydrogen can cause the largest sort of uncertainty in your reading. So, you might, if you have such a level of hydrogen, then you might have a significant reading on your sensor, which might confuse your reading because your sensor reads say 200 ppm, some current value corresponding to 200 ppm. And then you do not know whether it is because of ammonia or whether it is because of hydrogen. How much of it is due to ammonia, how much of it is due to hydrogen. So, that there is an uncertainty that comes into the picture.

So, cross-sensitivity for a lot of practical applications is one of the key parameters that you want to look at, it is not good enough, if you make a sensor that just measures what you want to measure, it is also important to quantify how well it is able to measure in the presence of some other changes, some other quantities that are present, then (()) (11:04).

So, just wanted to give you a general idea of how to read specification sheets and what are the typical parameters that are mentioned in a specification sheet. So, let us go back to where we were at, and let us try to quantify all these parameters, all these metrics in a little deeper way.

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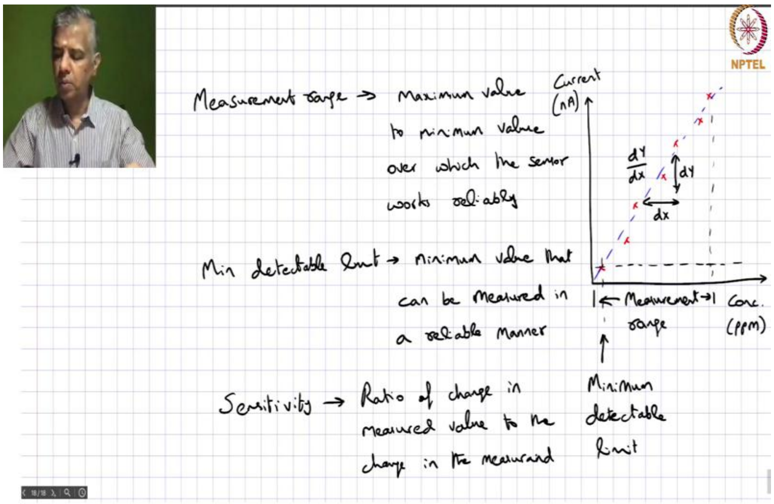

So, the first one is the measurement range. So, to quantify that, let us look at like what in this case an ammonia sensor would do. So, you have, as far as this sensor is concerned, you have your concentration, which is expressed in parts per million, and then you have current that you are reading, and like we saw on the specification sheet, it could be in the order of nano amperes.

So, we are looking at some change in current as a function of concentration, hopefully, it is a linear relationship, we will see why linearity is important, but you may be making measurements like this and so on. So, at different concentration values, you have different measurements done. So, if you do a linear fit to that, so, it might start, it might look something like that. So, then the question is, what is measurement range?

Well, measurement range corresponds to the minimum, the range between the maximum value that you can pick up and, and the minimum value that you can pick up. So, let us look at this, let us define that. So, measurement range is maximum value to minimum value over which the sensor works reliably, reliably as in, it meets most of the other requirements, other specifications also. So, in this case, what we see is, we can say, it starts working from here, and then up to this point, it is able to maintain this linear relationship.

And, if you try to push this even further like we saw in the specification sheet, it might respond, but it may not respond, it may not conform to these specifications. So, this is your measurement range in this case. So, your measurement range is between this and what we have over here. Of course, you may argue that the measurement range may not be exactly starting from 0, why?

Because there is some uncertainty involved in the measurement and that uncertainty may be built into the sensor, meaning there is a certain noise flow that you have, below which you are not going to be able to pick up any measure measurable signal. So, that noise flow would be somewhere like this.

So, you would say that there is some, when you are measuring the current and you are looking at the display, even without any ammonia present in the environment, you might have the display vary between in the last few digits of your, few bits of your ADC maybe. So, the last few significant, least significant digits, maybe there is some very variation. So, that puts a cap on this measurement. So, you would say that, if that is the case, then this corresponds to what is called the minimum detectable limit.

So, as the name itself suggests the minimum detectable limit, once again, talks about minimum value that can be measured once again in a reliable manner. So, it conforms to all the other specifications. So, that is the minimum detectable limit. And in some ways, you might, you may argue that, when I am talking about measurement range, it should not be from 0, it should be from the minimum detectable limit.

And of course, you would be right, because, for all practical purposes, this answer is useful only beyond that minimum detectable limit. Then there is sensitivity. And, this is in terms of the usage of that word, sometimes it may be a little confusing, because of the fact that when we say sensitivity in an optical communications perspective when people talk about sensitivity, they are talking about the minimum power level that should be incident on the receiver.

So, that you can maintain a certain bit error rate in a digital communication system. So, it is saying, you need a bit error rate of 10 power minus 9. So, to achieve that bit error rate, what is the minimum power, that should be incident on this receiver and that is what we call as the receiver sensitivity. So, that is a term, that is very widely used in optical communications, but in measurement, in sensors, sensitivity takes a different sort of definition, the sensitivity here corresponds to the slope of this line.

So, for a certain change in concentration, what is the corresponding change in current that you get? So, it is the slope of this line over here. So, this is dy over dx, where dx corresponds to this one and dy corresponds to change in this. So clearly more sensitive, the better because then you can get nice change in the, in your display for a small change in the, in the parameter that you are trying to measure, in this case, the concentration.

But you have to be careful about that, because if it is highly sensitive, it might fill your ADC very quickly, meaning you have a certain, say, let us say you have a milliamps of current and you convert that to, say, you have a factor of 10 power 3 with your trans-impedance gain and then you convert that to a voltage. So, milliamp becomes more like a volt.

So, your typical ADC swings between, say 0 to 1 volt, and then you would fill the ADC very quickly, so then beyond that, your ADC is not able to read any value. So, that in some cases corresponds to the maximum value of your measurement range. So, there is a trade-off between the sensitivity and the measurement range, if you want high sensitivity, maybe, your measurement range will be limited.

Because, you are not able to support such a large change in the, in this case, the current from a nano amperes to milliamperes. So, that is 10 power 6 units, and what determines the smallest unit you can pick up, that would correspond to the least significant bit of your ADC. So, if it is a 10-bit ADC, then you say, 2 power 10 levels you can support. So, that corresponds to, if you are swinging from 0 to 1 volt, then that corresponds to roughly a millivolt is what you can say.

So, that is corresponding to the 30 dB some of from the millivolt to a volt you can support. So, those are some of the considerations that you have, but in this case, what we are talking about sensitivity is change in, ratio of change in measured value to the change in the measure end. The measure end, in this case, is actually the concentration, the measured value is in terms of current. So, that determines the sensitivity. So, all these are fine. Now, what about response time?

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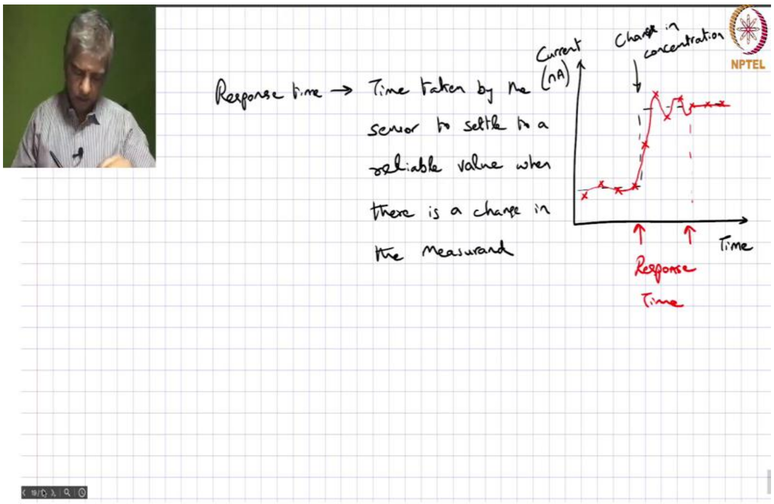

So, once again, when we are talking about response time, you are saying, okay, whenever, so, we are now we are switching with, we are switching to something with respect to time. So, here we are once again measuring the current but we are measuring some change in this current, for a unit change in concentration. So, let us say you start with one concentration level and at this point, you are jumping to another concentration level.

Now, if you make multiple measurements or measurement over time, you might see something like this, at this concentration, you have something like this, but when there is a shift in the concentration, so it starts responding like this, then maybe to overshoots this, then maybe tries to settle down at a particular value after some time. So, if you connect these, you would probably get something like this, and then it settles to a value. Now, the response time now is defined as from the time this change in concentration happens.

So, what is happening here is at this point you have change in concentration. So, you have a change in concentration and then how long does it take to capture that? Well, it oscillates around a certain value, and then finally, it settles down to some steady-state value. So, you would say that at this point it measures reliable number. So, then this is what you call as the response time. So, response time is the time taken by the sensor to settle to a reliable value, when there is a change in the measurement.

So, that is what we call us response time. And, of course, you want typically a fast response time, which means that what controls response time, well, you would say that the receiver bandwidth is probably one of the most important things, that will limit the response time in a fundamental manner. So, you need to have as quick response as possible, which means we need to have as higher bandwidth as possible as far as your receiver is concerned. So, the receiver bandwidth has to be very high. Then finally, we come down to quantifying accuracy and precision. So, let us try to go into a new page and try to do that.

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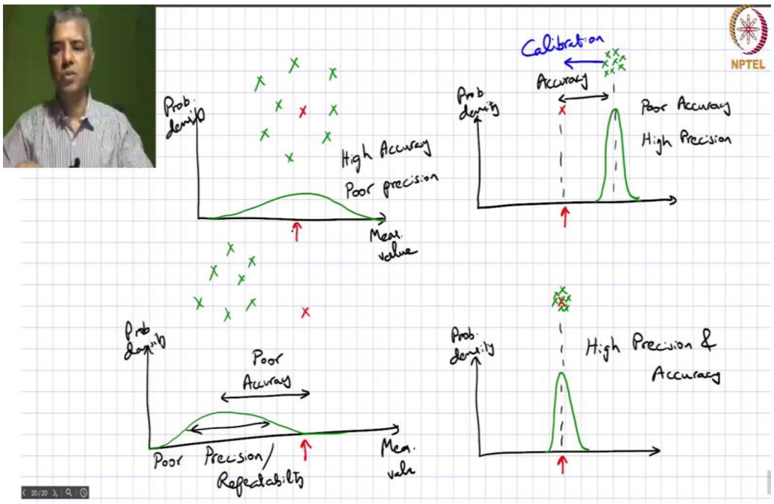

Let me show you four different scenarios. And let us see how accuracy and precision would work. What do we mean by accuracy? What do we mean by precision? Both of them in certain ways, talk about the uncertainty in our measurement. But let us say this is my target value. So, that is what I am supposed to measure. So, I have a certain concentration at a certain time, and I should measure that value with respect to the current. And so, I am going to try to represent this in two dimensions. So, let us see how this works.

Now, you could have a case where you are making measurements and, in this case, let us say it is with respect to position, so this is my target value, but I make a measurement where, it is roughly like this, it is a bunch of points around the target value. So, that could be one scenario. Then there is another scenario where your target value is like this. But then you have a bunch of points very close to each other, that are somewhere over there. So, this is another scenario.

Then yet another scenario could be where, you have the target like this, and then your measurements are like, sort of all over the place, but they are also at a different place. And finally, there is case where you have the target like this and then all your measurements around this. So, it is very easy to tell, which is the most preferred case, well, you directly say that, okay, I want, if I am looking at my probability density of were my points are, my measured values are with respect to whatever quantity or measuring, you would say that, okay, this is my target.

And with respect to the target, I have a probability density like this. So, it is fairly close to the target and then the probability density also works out to be, around that value. Now, the same thing if I plot here. So, this is probability density of my measured values. And once again, here we are saying, okay, this is where I am with respect to the target, this is my target, but my measured values are still bunched together, but they are off from my target value.

So, but they are still nicely bunched together. Then, compared to that, if you look at what is happening over here, so this is my probability density, once again, as a function of the measurement space, the values of my measurement, this is my measured value. And my target is here, but my measured values are like spread out around my target, it is widely spread around my target.

And finally, we come to this case. If I look at the probability density once again, of my measured value, you have the target here, but then it is nice and broad, away from the target. So, with respect to all of this, let us look at what is, let us define what is accuracy and what is precision? Well, accuracy corresponds to this deviation, this deviation from the target value. So, that is what we call us accuracy. So, we have a certain, we are expecting a certain value, but your sensor gives you a different value of measurement. So, that, but then there is not a whole lot of uncertainty around that measurement.

So, that is the good part over here, there is not much uncertainty. So, which is worst case of all of this? Well, the worst case would correspond to this because my accuracy is very poor, but it is also accompanied by a wide variation in my measurement. And that wide variation. I am just making multiple measurements here, and it is going, giving me all those values. That wide variation is what we are talking about in terms of precision, precision or repeatability. So, this is a case where we say this is poor accuracy, poor precision or repeatability, this is the worst case.

And this is like high precision, as well as accuracy. This is a case of high accuracy because the central value is still reasonably accurate. But this is poor precision because there is a lot of uncertainty in terms of the measurement. And here, this is poor accuracy because my sensor value is, the measured value is off from the expected value, but it is got high precision, high level of repeatability, you keep making multiple measurements, you get the same value. So, that is corresponding to fairly high precision.

So, those are the different cases that we can see. Hopefully, that gives you some idea of what we mean by accuracy, what we mean by precision, repeatability, it also brings up the question, which is more important to you, accuracy, or precision? Well, that is a tough question. In an ideal world, you want both. So, you want your sensor to be both having high accuracy as well as high precision. So, you can make your measurements like what you do in this case.

However, if you were to compromise on something, you could potentially take a case like this, where you say it is poor accuracy, all right. So, it says, okay, I am expecting 100 ppm and it shows me 120 ppm, but if it is scaled, if it is 50 ppm, it is showing 60 ppm, then it is scaling, in terms of the measured value. So, if it is some scaling error like that, that is impacting your accuracy, that is something that we can handle, all you do is you do a next step was calibration.

So, through calibration, you can move, if you measure that value, you can make it, you can do your process your data and say this, it means this value. So, that way poor accuracy could be handled by calibrating your instrument, but you cannot do anything about poor precision, because that is talking about a random error. That is very low level of repeatability in your measurements every time you do it, it is giving you a different value and all that.

So, there is not a whole lot you can do from a sensor perspective about something like that, but what you could possibly do to deal with it is to make instead of making 1 measurement, you make 10 measurements and then you take the statistical mean of those measurements and you say okay, that is the value that it should correspond to.

So obviously, in a case like this, if you take a statistical mean that would converge at the target value. So, poor precision would have to be dealt with by taking much many more measurements than what you plan to do. So, hopefully, that gives you a general scope, general idea of all the different sensor parameters and we will go on to look at the actual design of specific sensors and when we do all these sensors, we will come back and revisit these quantities and see how well each of those sensors are performing.