Advanced Measurement Techniques in Fluid Mechanics and Heat Transfer
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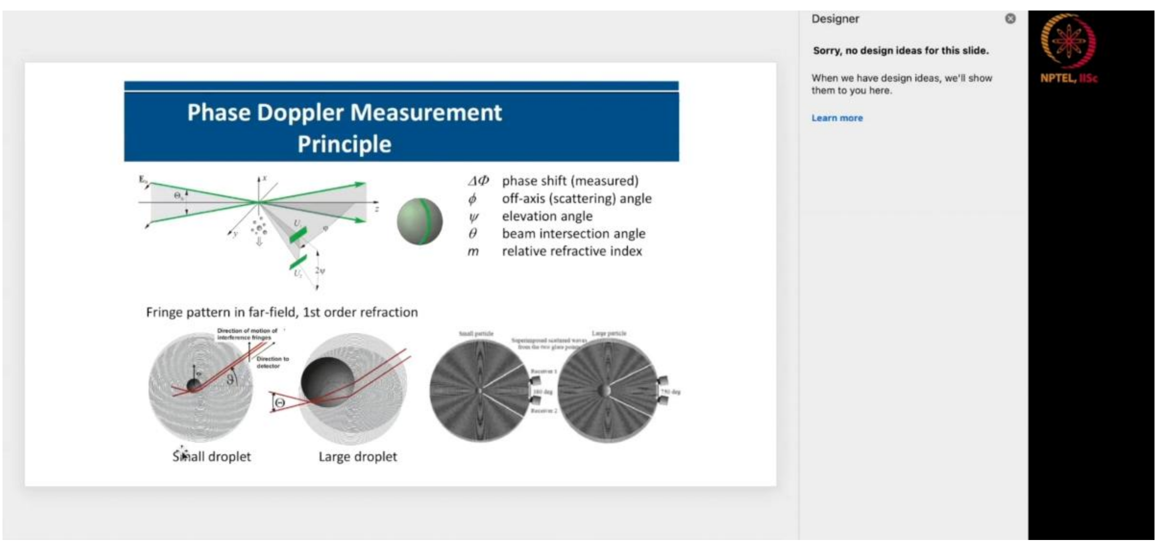
Week – 10
Lecture - 47
Phase Doppler Particle Analyzer – 2

All right, so in the last class, in the last lecture, we talked about how the phase-Doppler measurement technique actually works. I wanted to add a little point here that when we talked about the fringe spacing, if you look at these two rays, they act like two glare points. And when the glare points are close together, the fringes are far apart. Uh, which happens in the case of these small particles. When the particle is large, these glare points are further apart; therefore, the fringes are actually closer. So that is what happens with these two glare points and why they actually interfere.

Uh, that is because if you can think of it like a double slit experiment. Young's double slit experiment where you have two slits. The two glare points are basically the two sources that are far apart. So they actually interfere, and they will give rise to these fringe patterns.



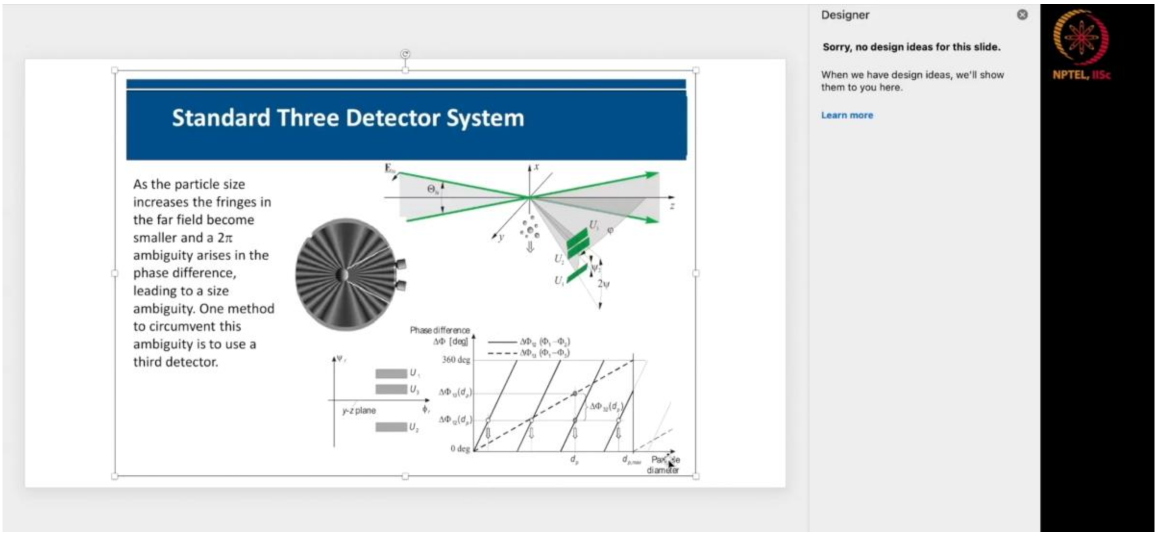
So, for the smaller droplets, the glare points are close together. Therefore, the fringes are far apart. And for the larger droplets, the glare points are farther apart. So the fringes are very close together. So this is what we mentioned, and we stated that because of measuring the velocity bias, we introduced this frequency shift.

As a result, the fringes were moving. So, therefore, in principle, while you could calculate the fringe spacing and infer the diameter of the particle because you know these two clear points will lie on the meridional plane or a meridional circumference, in reality, you cannot because that frequency is very high; therefore, you had to resort to something like uh. What we call here is the phase shift between these two detectors. And we also talked about selecting the detection angle. But now the time has come to ask how you actually realize these phase Doppler techniques.

What are the standard systems, and what are the planar systems? What are the dual-mode systems? That is what we are going to do next. So if you look at a standard, I will call this a three detector system. Take a very close look at this particular picture over here. So this is a particle. Now, as the particle grows large, the number of fringes between these two detectors becomes, you know, more and more fringes that start to accumulate, okay? Because, as you know, if the particles get large, the fringes are very close spaced together.

As a result of that, what happens is that you have what we call a 2π ambiguity. Let me try to explain that over here. So this is the particle diameter, and this is the phase difference. Okay, so now if you are moving along this line, as the particle diameter increases, the phase difference also increases. This we know from this particular equation already because of the linear relationship, right? Phase difference increases as the particle diameter increases, so it grows and grows and grows until it reaches 360, and then it starts from zero again.

However, you are measuring only a single phase, so your measurement is splitting out these, which have the same phase, okay, but in reality... So you do not know whether the particle is of this size, that size, or this size. Because all of them share the same, you know, uh phase difference, and the phase difference has moved up to 360 degrees, it starts again, so you populate a greater number of fringes essentially, okay, uh in between these two detectors.



Therefore, you do not know whether you are measuring just $\Delta\Phi$, or $2\pi+\Delta\Phi$, or 3π, or 4π, etc. So there is an ambiguity of 2π, as you can see. You do not know whether there is a 2π or what kind of a 2π prefix you have in front of it. In essence, your particle diameter could be way off, but there is some ambiguity. But the same phase can be shared by different particle diameters because you do not know whether it is 2π, 3π, or 2π and above.

So this leads to size ambiguity. This happens when the particle size increases; the fringes in the far field become smaller and smaller. That is what we said, that when the particles become larger, the fringes become smaller and smaller, and therefore you get a two-part ambiguity. To solve this problem, we introduce a third detector. Which is closer to Detector One, for example.

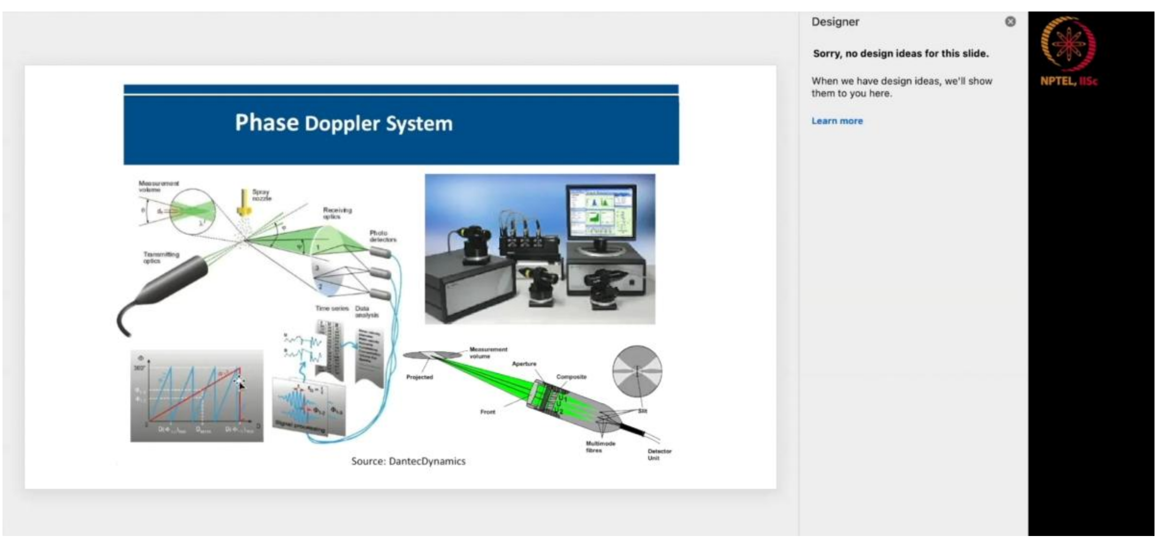
So what this detector does is measure another phase. So it measures the phase; for example, in one detector, the black lines measure the phase difference between one and two. The second detector, represented by this dotted line, measures the phase difference between one and three. So this is the third detector. So this measures the phase difference between these two, and then the normal detector, and you measure the phase difference between these two, right? Okay, so what happens now is as follows: you know, these are the same.

So these are the ambiguous lines. Now you have this dotted line, which represents a third detector. A second phase difference, right? Now what happens is that, and this grows like this, and this is the maximum particle diameter that you can get because then you get another ambiguity into the picture. So what happens is that, say you use the first two detectors and you measure a phase right there, right? And then you measure the third detector, okay? Which measures the phase like that. So this detector will give rise to a certain diameter, and then you add, and then you measure the phase difference between detectors 3 and 2, and this will actually give you the particle diameter.

So you basically match the two detectors, the readings from the two detectors, and where you think at that diameter, where these two readings are kind of the same, is the diameter that you choose. So this is how this thing actually works. So this is how you remove the ambiguity by using a third detector. And then you kind of, you know, find out that, okay, for this particular diameter, the third detector is giving me this and the initial detectors are giving me that. So now you kind of correlate the two and find out what diameter will actually satisfy these two readings.

And that is how you nail the diameter. So, for example, over here, okay, you cannot have that because this detector will give you a different particle size. This detector, if you use it, will give you a different particle size. So this measurement cannot be this diameter; it cannot be this diameter either. It cannot be this diameter either because the phases don't match.

Okay, the phases, the phases that give the diameter, do not actually match. So essentially, it is the phase difference between detector 3 and detector 2 that actually gives you the particle size. So, that is a unique function of the particle size. Think about it. That is exactly what it is.



Because this is between detectors 1 and 3. This is between detector 1 and detector 2. And this basically is a unique function of the particle diameter and the phase difference between detector 3 and 2. That is 3 and 2. Essentially, this is how you nail the system, but remember there is a maximum limit again, after which you will have this kind of problem happening once again.

Okay, so you know, the normal PDPS system comes with a three-detector assembly just because the fringes in the far field become smaller and smaller. You get this 2π ambiguity where you are not sure what your particle diameter is by just measuring the phase because there is a 2π. Uh, you know, 2π added onto the top of it. All right, so this is how you do it. This is, for example, a spray nozzle.

And this is, again, the two laser beams, frequency-shifted. They merge at this particular point. You created that. So this is basically the detector. And this is basically the third detector, as we saw it.

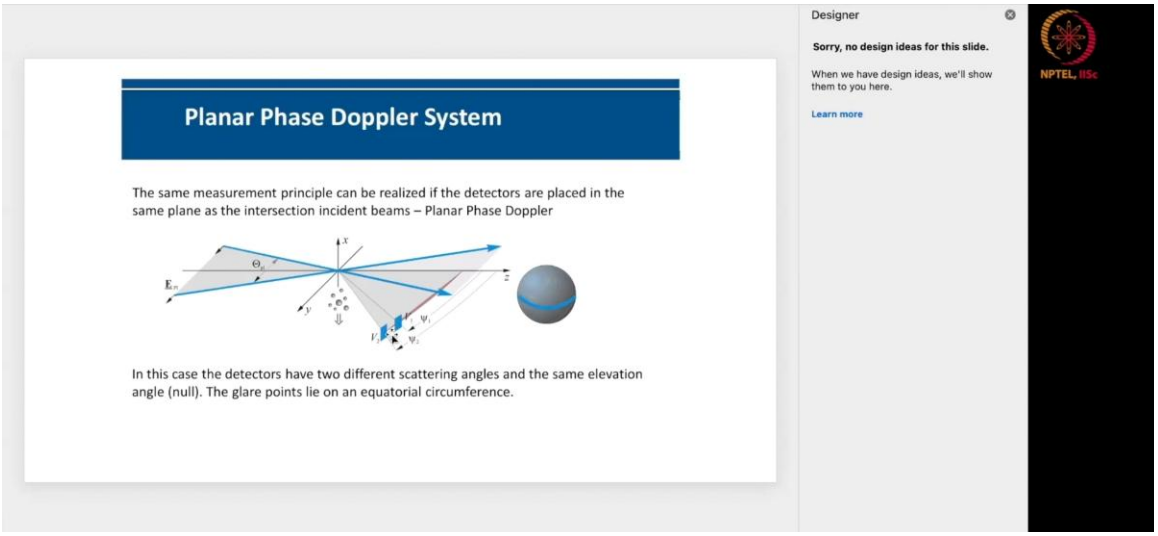
And this is how you correlate the two diameters by looking at the two phase shifts. And then what happens is that this may be segmented lenses, actually. So the segmented lenses actually focus on three photodetectors. And from the photodetectors, you get this Doppler burst, essentially. These signals are the same signals that we saw earlier.

Let me just pull up that example. This is the same as what you saw. Okay, so this is exactly the signals that you see over there. And you know, this is how you actually do it. And this is how this entire system actually looks, you know.

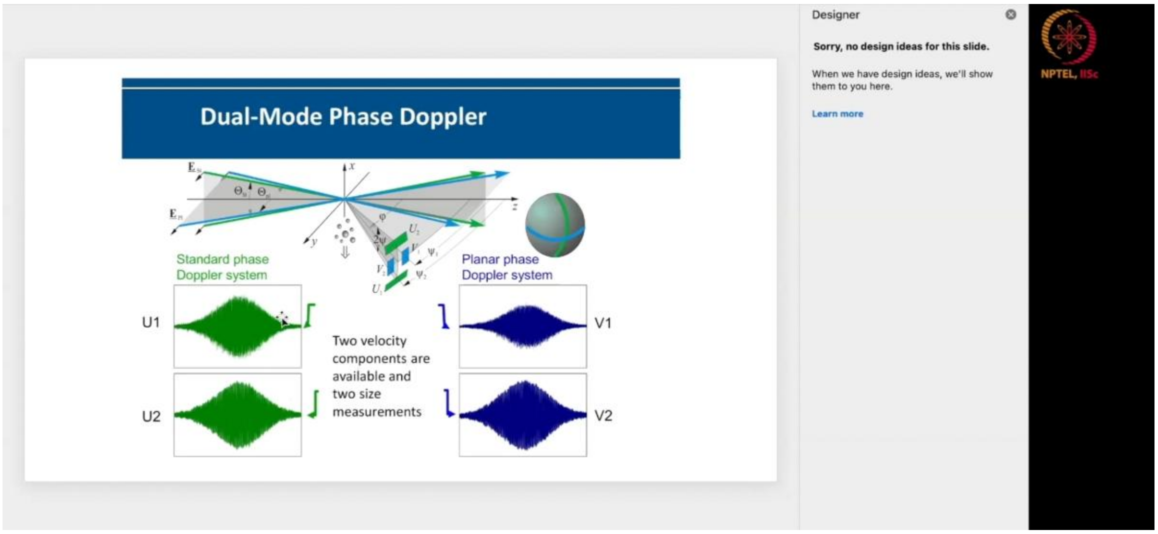
So these are the different detectors. And you know, all the detectors are housed. It can also be focused on multimode fibers and then go to our detector unit. So you have, again, composite lenses which focus the beams at different slits. It passes through different slits, and then it kind of goes into the detector unit.

And then you do signal processing and you do all these things in the software in the background. So this is how this thing actually happens, to be clear, okay? Now, since this can be done, why not do what we call a planar-phase Doppler system? The same measurement principle can be realized if the detectors are placed in the same plane as the intersection of the beam. So you are basically here. One detector is here; another detector is here. But they are actually in the same plane, at two different scattering angles.

So the detectors have two different scattering angles, but they have the same elevation, which is essentially a null elevation. Instead of going down the meridional circumference of a particle, you go around the equatorial circumference. You go along this equator, and you can also go through this meridian. It depends on when the detectors are stacked at an elevation. That means this detector and this detector are elevated.



You go along the glare points on the meridional circumference. But in this particular case, you go for detection along the, you know, the equatorial circumference, okay, so these are the two things that the two detectors are doing: they are at angles of psi 1 and psi 2 from the major optical axis. So this is what you are going to get, okay, so this is the planar Doppler, so the elevation is null and therefore the glare points lie on the equatorial circumference rather than here, which was the meridional. All right. Other than that, there is not much difference between these two.

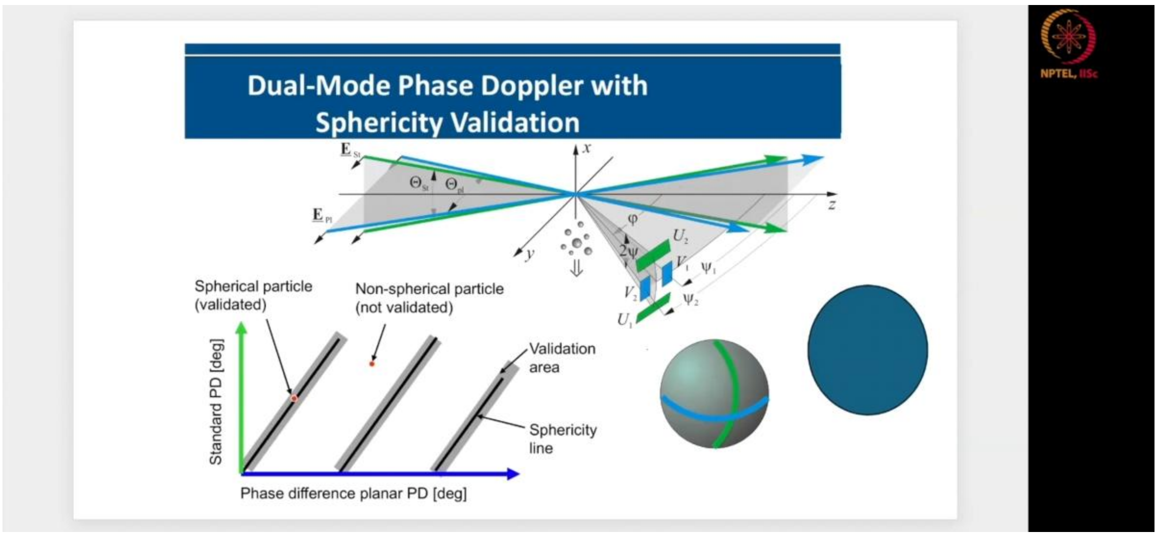


All right. So now, if you look at it in a dual-mode Doppler system, you basically combine the best aspects of both. You combine a standard Doppler phase system where you have the two detectors, U1 and U2, at a certain elevation. Okay, so this is the elevation angle, like what we did, and this is the standard U1 and U2 Doppler bursts. So, these two velocity components are available, along with two size measures, okay, because of this. And, you know, then you have the plane R measurement, okay, where you again get these two signals, which are between V1 and V2 now, placed at the same plane, with no elevation, while these two are at two elevated locations.

away from this particular plane, U1 and U2. V1 and V2 are in the same plane. So they will also give rise to this kind of Doppler burst. In effect, what you are doing is using the standard Doppler to measure the droplet size along the meridional circumference, because it will give you two size information. One will provide the size information using the meridional circumference. The other will be the size information along the equatorial circumference, right? And then there will be two velocity components that will also be available.

Using these two detector assemblies. So the idea is: why do we do that? We will move on to the next slide to explain why we actually perform this kind of measurement. We understand that this corresponds to meridional, green corresponds to meridional, blue corresponds to equatorial, and these two detectors are placed at an elevation. V1 and V2 are placed in the same plane. So this is the thing that you should keep in mind when you are actually doing this measurement. So the dual mode phase Doppler has, therefore, a sphericity validation.

What does it do? It takes measurements because you have particles, basically, or droplets, which are mostly spherical, but some of them may not be spherical to begin with. And remember, we need spherical particles to use the equations that we derived. So in essence, what we do is measure the droplet size using the meridional circumference and measure the droplet size using the equatorial circumference. So this is basically the standard phase difference using a standard Doppler effect.



This is the phase difference using planar Doppler. What happens is that if both of them give rise to the same size or basically the same phase, that means the droplet is spherical because for a droplet, this and this do not make any difference at all. So you should ideally have a line, and the droplet diameter will fall right on the top of it. Okay, all right, uh, but if it is non-spherical, what will happen is that the standard, uh, phase Doppler, because it is non-spherical, means it's probably elongated along one of the sides, one of the meridional, uh, circumferences or the equatorial circumference, depending on whether it is elliptical or whether it is something else. For example, I will just take this, uh, example over here; it can be like this, okay? That can be one thing, or it can be the other way around.

So both of these things are possible. So then it will not lie in this particular line because they won't give you the same phase difference. As a result of that, it will lie somewhere else. At a moment, if it lies somewhere else, you have to reject that particular measurement because those are non-spherical. So in a typical experiment, there can be spherical particles; there can be non-spherical particles as well. When they are non-spherical particles, you have to reject those non-spherical particles in some way.

Okay. So, typically, it is not just a line. You have a band around it, which is basically a threshold. That means you allow a degree of sphericity.

Okay. Maybe 90%. Okay. So that means this too, well, this can be considered to be roughly spherical. No, this is not exactly spherical. Okay. Is that correct? Unit a little bit, so this is not, this is a little bit elongated, for example, but it is kind of spherical, so we can live with it. These bands are therefore basically for that, to allow for a certain margin, a certain threshold, but if it lies away from that threshold, okay, you reject that particular measurement because of the sphericity.

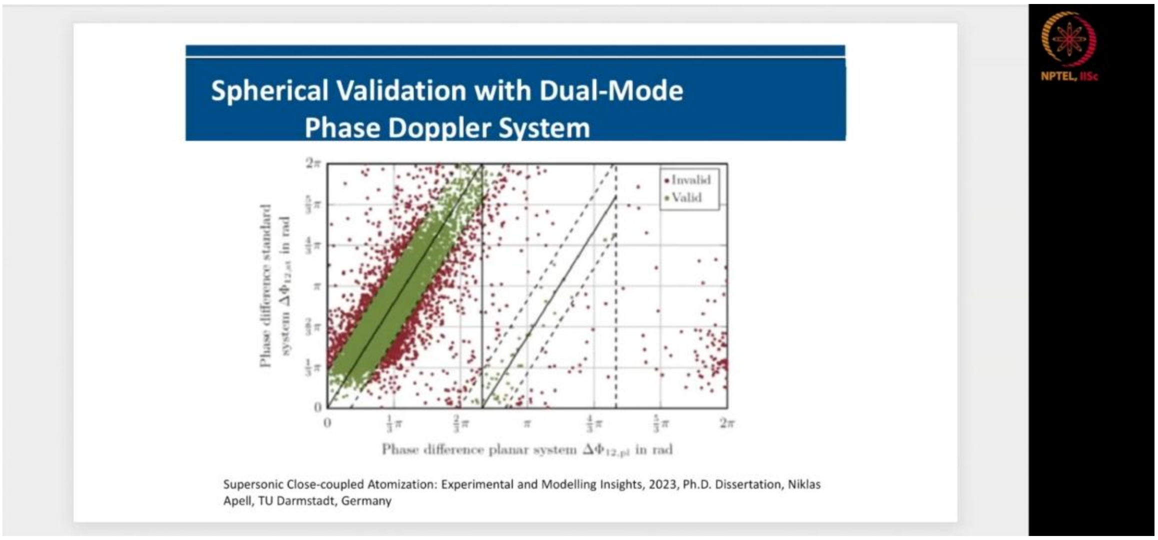
Validation is not done because you have two different phase Doppler phase measurements coming from the two detector arrays, one in the plane and one in the elevation. You have to reject it when your meridional and equatorial circumference measurements do not align. Basically, the glare points do not align with respect to one another. So this is, for example, you know, particles, which, if the particle is 0.7, whether you accept it or not, okay, it probably will be rejected.

So this can be used for the sphericity validation. Some of the equipment does have that because it actually pollutes your measurements, so to say. So this is, for example, from Nicholas Apple, who has been our collaborator on the Indo-German Science and Technology Center project. And this is on supersonic, closed-coupled atomization. Well, closed-coupled atomization is something that we can talk about later, but that is not the subject here. This is basically a supersonic flow interacting with water in this case, which gives rise to droplets of various diameters.

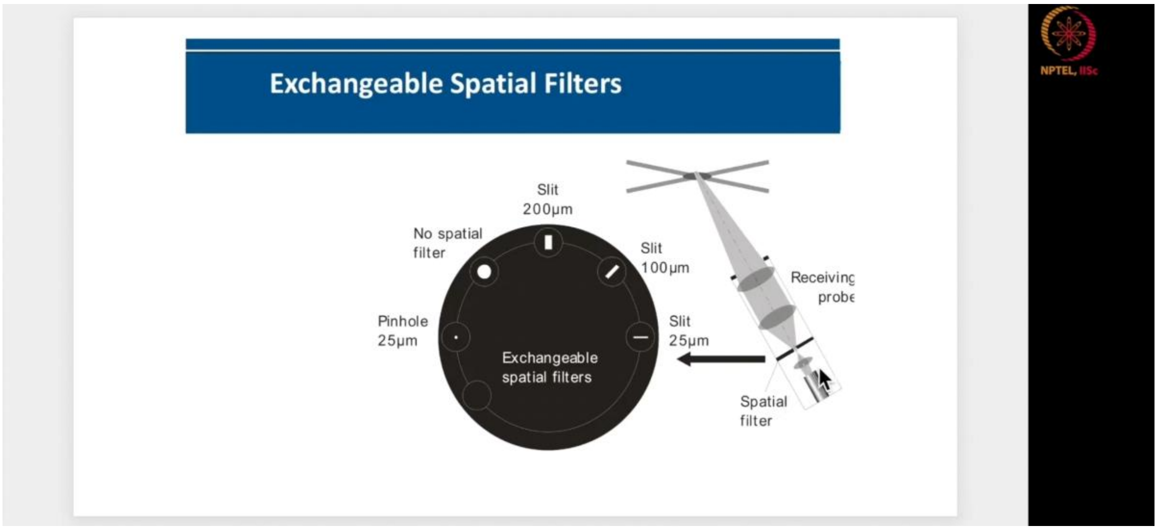
And because the flow rate is high and the atomization characteristics are pretty catastrophic, you get droplets that are of different sizes. Some of them may even be ligaments, for example. So they are not spherical at all. But all of these will actually scatter light, and they should actually give rise to a phase difference, and they would spit out. So if you are doing it across the meridional circumference, that is not good enough because that will give you a measurement that is not correct.

So, as a result of that, you can see that these are the lines once again, and you can see that this is one third phase; for example, you see that all the particles, I mean this is size, so it has a variety of sizes. By the way, it is not one size, so therefore it gives rise to several phases, and you get the different phases and different particle sizes and all these things, okay? But this is basically the phase difference between the planar system and the standard system.

This is standard. This is planar. That is what we talked about. So all these phase differences correspond to different types of particle diameters. As you can see, you have a band. So most of the, about, I think, 90% of the measurements actually fall within this green band. And the red ones are the ones that are basically rejected because they failed the sphericity test. Though it looks like a lot, there are actually a lot more particles in that range.



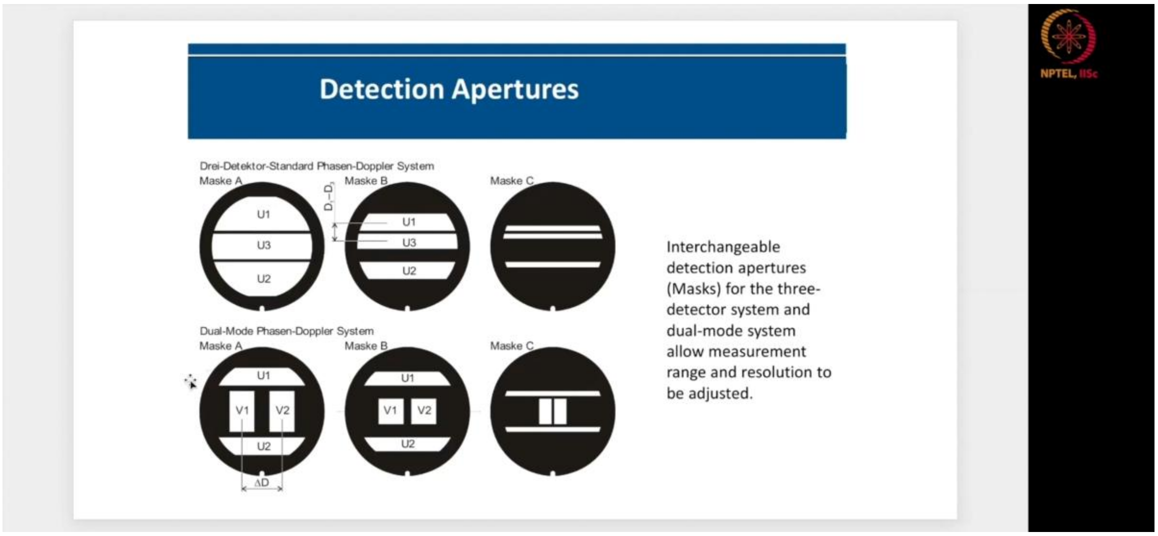
Most of the particles or droplets in this case are spherical. Only a few of them actually, or a few percentage of them, basically lie outside the threshold. So this is basically the phase, the spherical validation with dual-mode phase Doppler measurement that we can see over here. All right. So that is what the key thing is.



Now you also use what we call filters, spatial filters. And we will see why we do this. For example, this is without any spatial filter. This is with a slit filter.

This is another slit. This is a slit that is being placed horizontally. So this spatial filter is placed in the receiving part. When you actually receive the beam or the light from that measurement volume before you focus it on your fiber optics or your photomultipliers, you use a spatial filter in the path. This spatial filter can be like no filter at all, or it can have slits of different kinds, and then it can even have a pinhole. All these filters are routinely used.

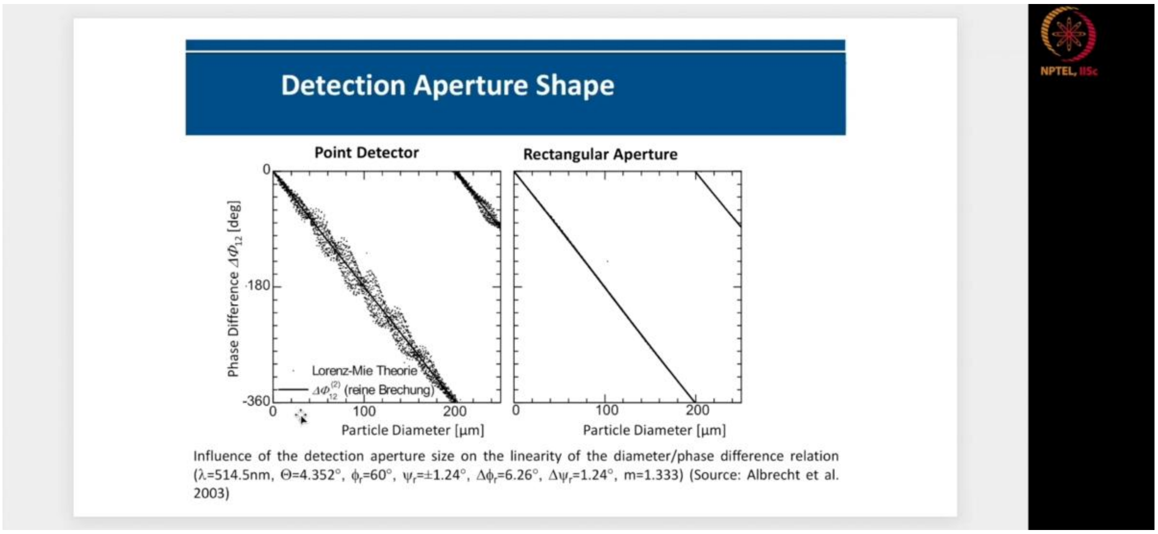
You know, this is the spatial filter selector. OK, so then you have the segmented lens, which basically focuses it on different multimode fibers. So these are for V1 and V2. and U1 and U2, roughly. So the spatial filters are regularly used for the phase Doppler receiving optics portion.



So this is, for example, the filter. This is mask A, mask B, and mask C. So all these different types of dual mode are written in German, but these are masks. The interchangeable detection mask for the three detectors and dual mode system allows you to change the measurement range and resolution. So you can change the resolution by controlling how much light actually enters. And this enables you to change both the measurement range and the resolution by using masks and filters.

So that is what you use. And these are of different kinds, different types of mass, and different types of configuration. So the shape of the aperture also kind of matters. In this particular case, for example, this is the influence of the detection aperture size on the linearity of the diameter and phase difference relationships. So this is, for example, the phase difference, $\Phi_{1,2}$, and this is the particle diameter.

This is a point detector, and this is a rectangular aperture. As you can see, these are from the Lorenz-Mie theory, and you want a linear relationship because you are doing a calibration-free measurement, so the particle diameter and the phase difference should be very unique; there should be no non-linearity coming into the picture. So this is for the point detector system, and it is using rectangular structures. And this is measured against very large diameter particles that you can see here. This is also the same plot, which means how the spherical validation was done by Nicholas Apple. So for highly focused measurement volumes, such as high-density sprays, a slit effect can lead to incorrect measurement sizes and correct size measurements.

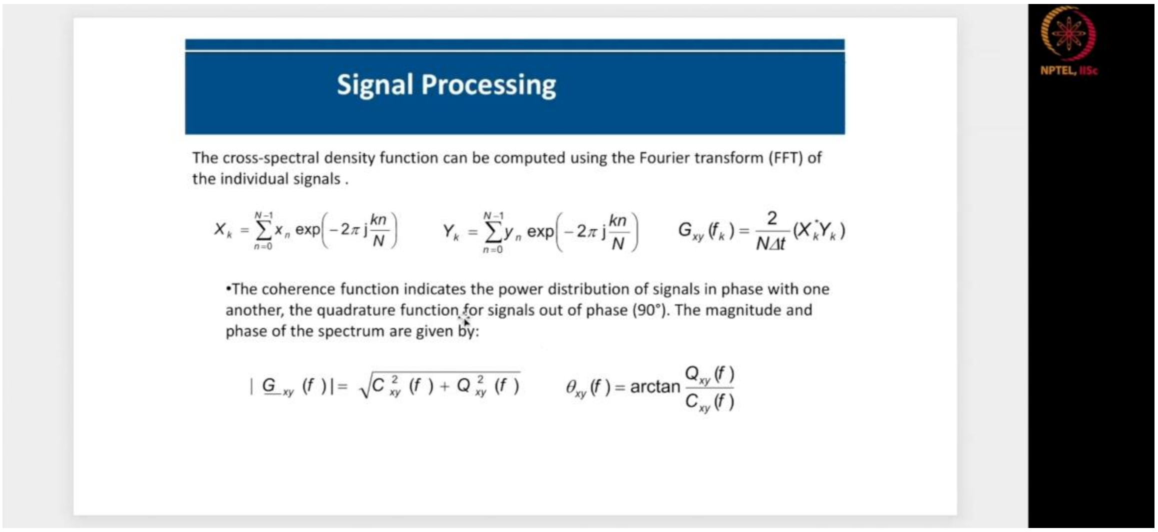


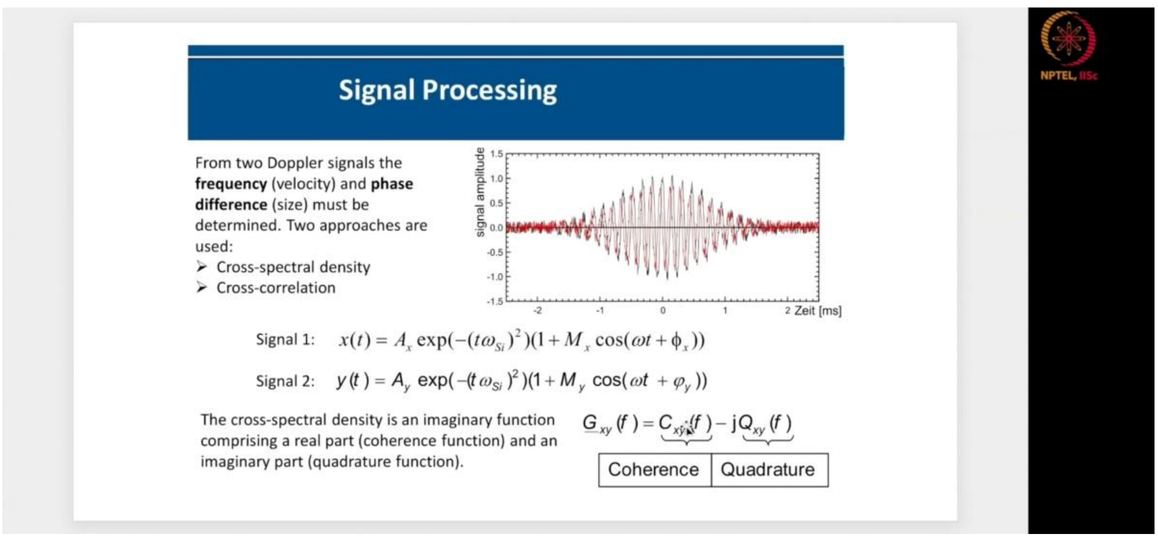
This is also something that you should note. So the detection volume, the projection of the slit aperture for highly focused measurement volumes in high-density space, for example, must be addressed. And the slit effect can lead to incorrect measurements. So we also need to recognize that these parts can be read up separately. So these are, for example, the recognition of the Gaussian beam and the slit effects.

So these are measurement points from pure reflections. These are measurements of pure refraction. Over here. And this is a symmetric receiver mask.

The measurements from pure refraction are validated. This is not validated by the way. And these are measurements from pure reflection validated. So this is how you take the measurements. Now we do a little bit of what we call signal processing. In signal processing, what we have is that from the two Doppler signals, the velocity, the frequency is related to the velocity, and the phase difference is related to the size.

So, the two approaches are commonly used. One is called the cross-spectral density, and the other is called the cross-correlation. We will see what it is. So, the cross-spectral density function is computed using the Fourier transform of the individual signals. You perform the Fourier transform of the individual signals. Then what you do is define something called the coherence function, which is nothing but the conjugate of X, one signal with Y.

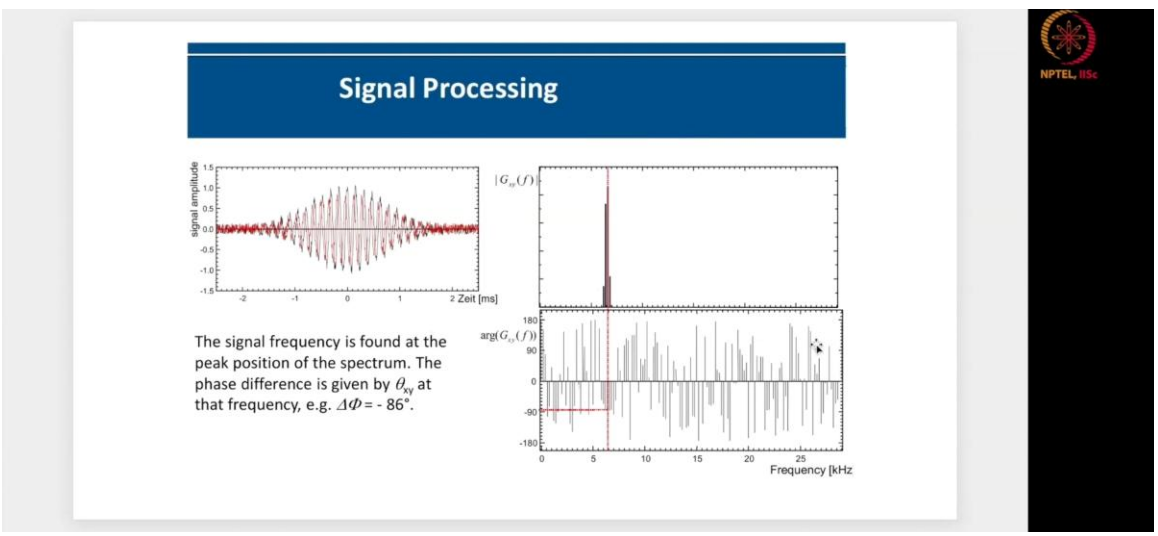




So the coherence function indicates the distribution of power or power distribution of signals in phase with one another. So the quadrature function, on the other hand, the quadrature function for signals that are out of phase, what happens is that if the signal is completely in phase, all the power will be contained in the c, and if all the signals are out of phase, then all the power will be in the quadrature function. So the coherence function, will actually, so the cross spectral density function is this; the coherence function will contain the functions in phase, and this will have the out of phase. So basically, if you take the tangent of the angle between the, you know, The complex plane between the quadrature and the coherence function, the theta that you will get, uh, well, is the one that indicates what the power kind of distribution is, uh, between the two. Okay, so in other words, uh, what we do over here, this is signal one that is x, this is signal y, as you can see, that uh.

They have their amplitudes. Then there is a phase difference. So the cross-spectral density is an imaginary function that contains a real part, which is the coherence, and an imaginary part, which is the quadrature function. So the coherence function actually relates to, I mean, if the two signals are in phase, the coherence function will grow, and the quadrature function will grow if they are out of phase. This is in the complex plane. And you realize why they are complex.

So the coherence function indicates the power distribution. The magnitude and the phase of this are therefore given by that. So this is how you process the signal. So you convert these signals. First, you take an FFT, convert that into the Fourier space, and then multiply the signals. Basically, you take the conjugate and multiply it with the other one, and then you get what we call the cross-spectral density, which is now composed of a real part and an imaginary part.



The real part is basically... The coherence function provides the real part, and the imaginary part comes from the quadrature function. And this is what it is. So in phase, all will be in coherence; out of phase completely will be there in the quadrature function. So that is how you basically process the signal. So what happens after the signal processing is done is that you will get, this is your overall cross-spectral density, and this is the argument.

Now you will see that this power is more or less at a particular frequency; this is the frequency, and then you calculate what kind of phase corresponds to that particular power. So the phase that you receive. So this phase, for example, comes out to be around 86 degrees. And this is what you use to calculate the diameter.

On the other side, you can see that they are sporadic. I mean, they are all at the noise level. But here, of course, you can also use some kind of signal fit. But this is the principal signal and this is what you get here. Okay, so this basically means that the frequency signal is found at the peak position of this particular spectrum. So the phase difference is given by theta xy, which is basically nothing but this.

At that frequency, you will see that theta xy is about 86. So this is at its peak. At the peak, whatever your theta x1 is. That is what you are going to find out. So, that is how this particular signal processing part actually works. In the next lecture, we are going to look at a few examples. But this is where we end the signal processing portion of the PDPS.