Advanced Measurement Techniques in Fluid Mechanics and Heat Transfer
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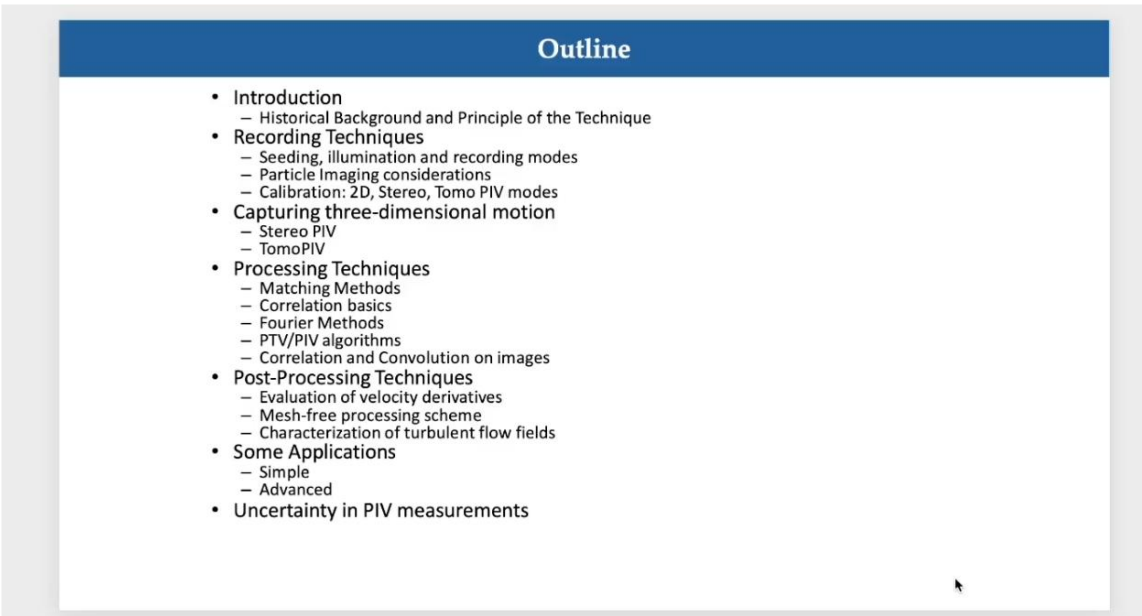
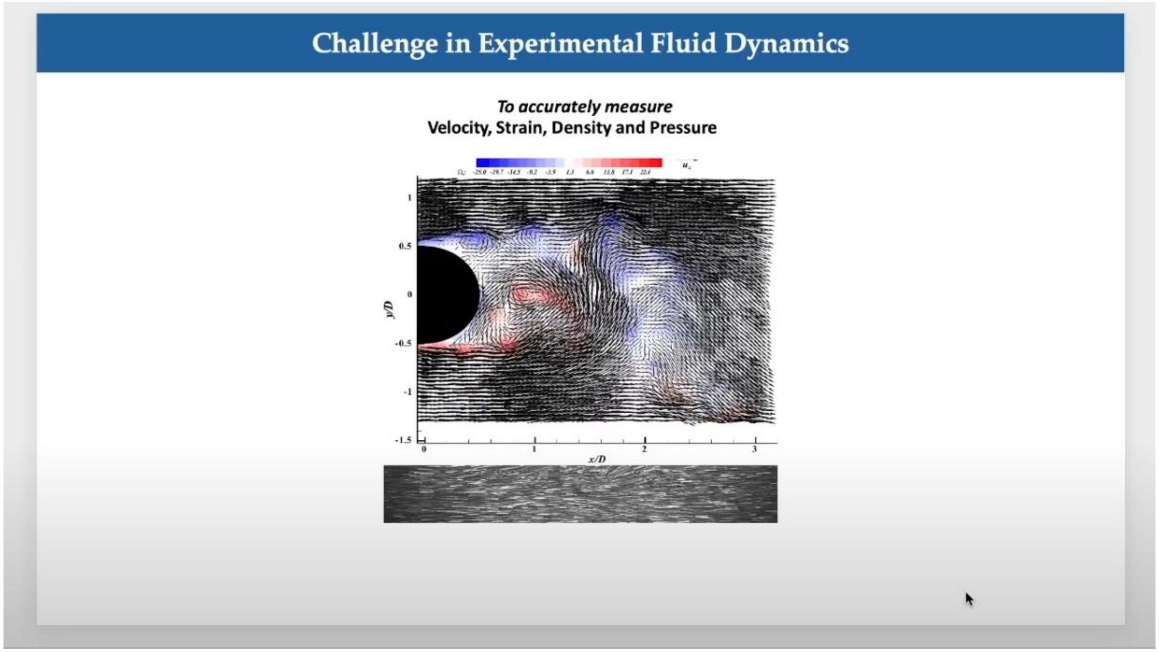
Week – 08
Lecture - 37
Particle Image Velocimetry – 7

Okay, in this lecture, we are going to look at and basically revise particle image velocimetry and also give some examples. These are not lab demonstrations; they are examples from my research work as well as from the research work that is happening at NAL. So the lecture notes are partly courtesy of Dr. L. Venkat Krishnan of CSIR NAL. And so let us look at, let us do a quick recap of what we taught.

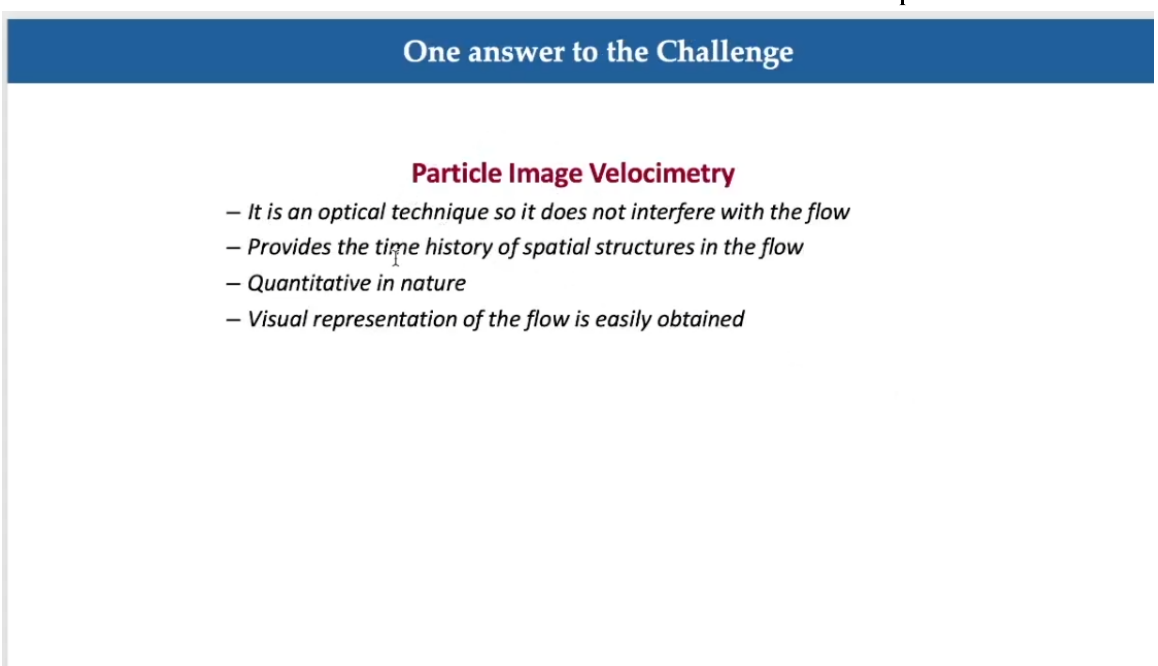


In the last few lectures. As we can see, we covered all these things that are recording techniques, you know, stereo PIV; we did not cover TOMO PIV. Then processing techniques, such as how you can do what correlation is, what the Fourier method is, and post-processing techniques, are also included. We're going to talk a little bit about the uncertainty in the PIV measurements in this particular lecture, as well.

So if you recall, to summarize PIV, we first have to look into the challenges of experimental fluid dynamics. That is, for example, this is a flow behind a bluff body where you can see that this flow is very intricate. We can see there are lots of small-scale structures, large-scale structures, and a lot of twists and turns in the flow. So the idea is that if you really have to do the measurement properly, you have to accurately measure the velocity, the strain, the density, and the pressure. And this is the challenge in experimental fluid dynamics.

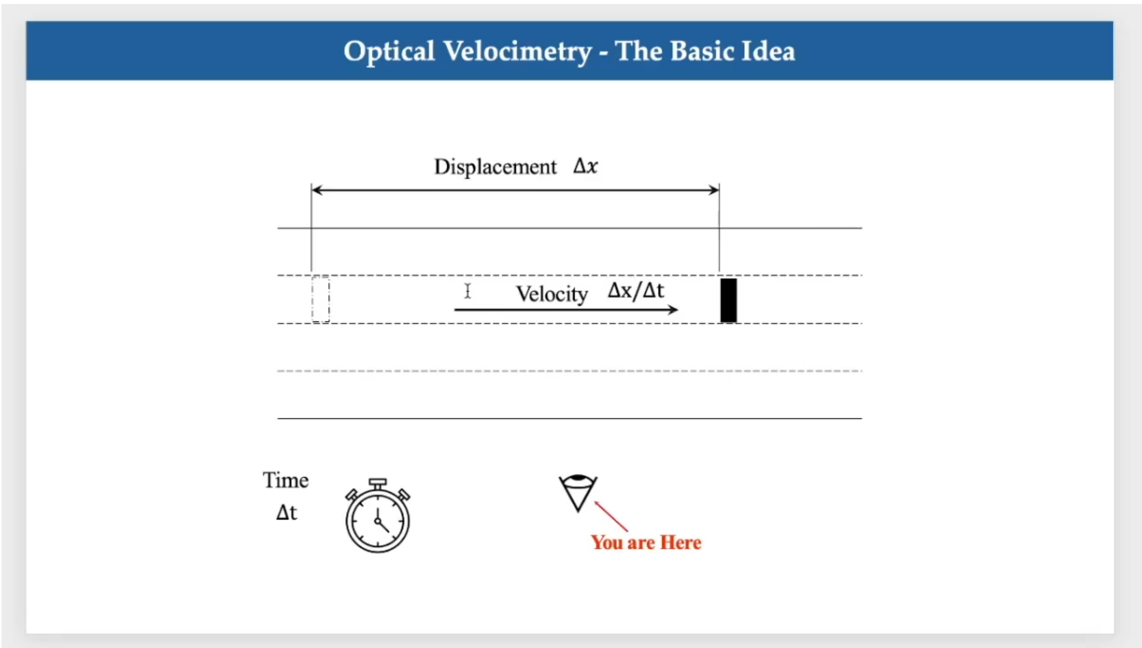


That means you need to resolve these measurements. So that our answer was particle image velocimetry, which is an optical technique, as we know by now, and which does not interfere with the flow at all, unlike probe-based measurements. And if you do, you know, at least low-speed PIV, you can get an idea of the spatial structures that are present in the flow; therefore, it is very quantitative in nature, and it is also very visual. So the visual representation actually, you know, enables us to understand and have insights into the flow field. At least look at the spatial structure.

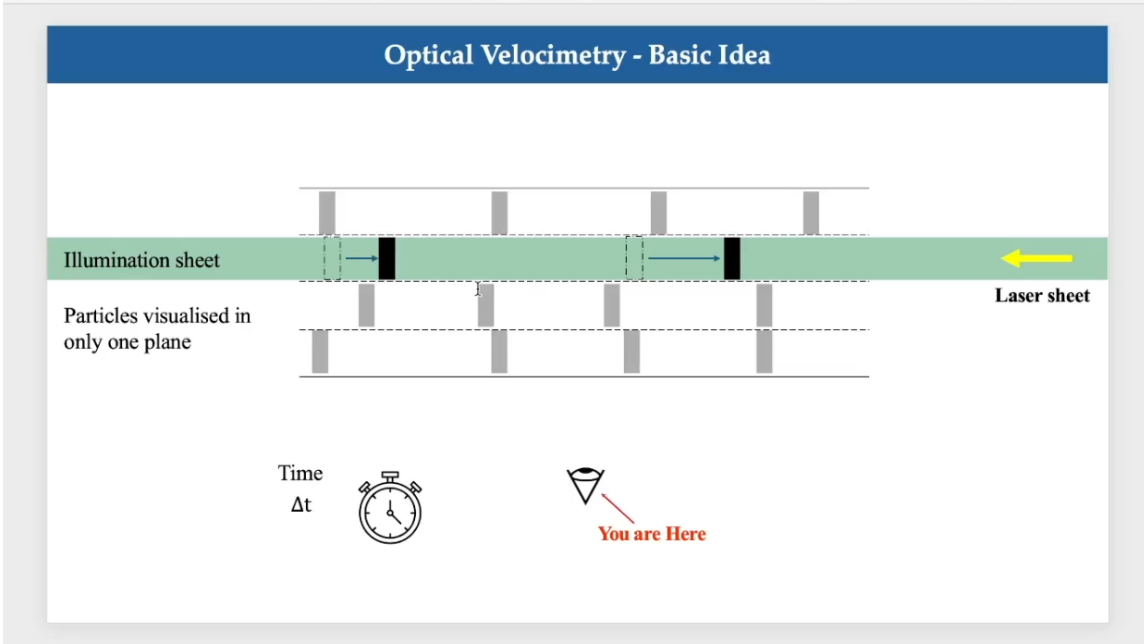


High-speed PIV will enable you to resolve both the spatial and the temporal structures.

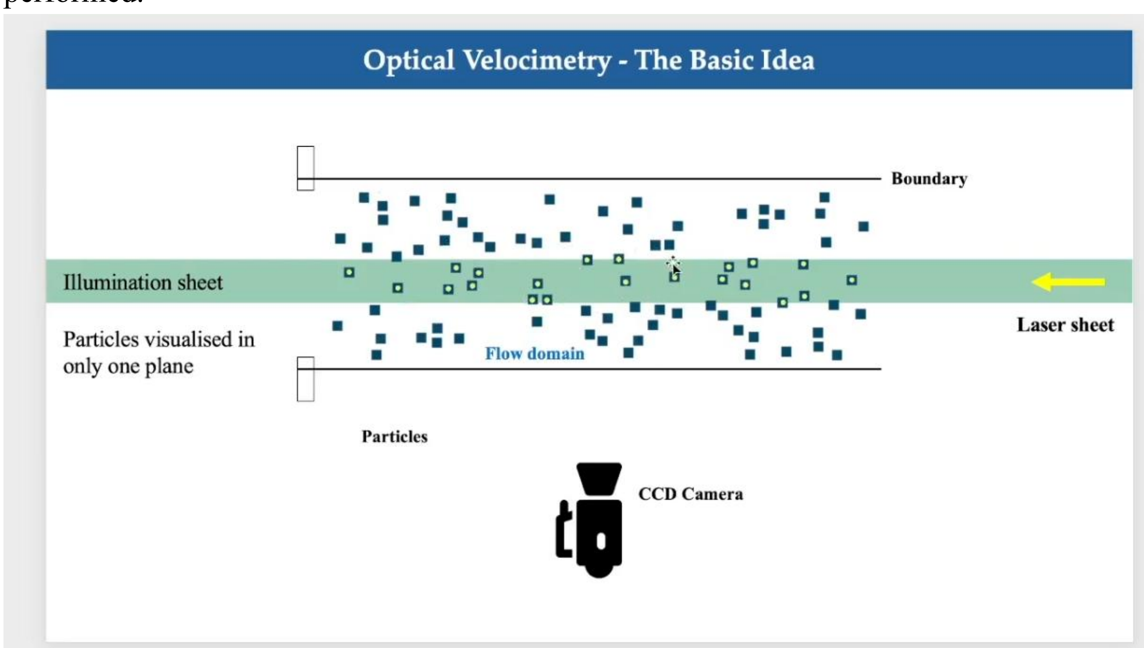
But unlike, for example, LDV, the temporal resolution may not be very high. It depends on the kind of camera and the laser that you have. Okay, so the idea was very simple: if there is a displacement, say for a fluid parcel, this is optical velocimetry essentially, and if you can calculate the distance that it has traveled or the displacement that it has suffered in time Δ t, the x component of the velocity in this case will be the displacement in the x direction divided by the time interval that has elapsed. So basically, you wait with a watch and take two images.

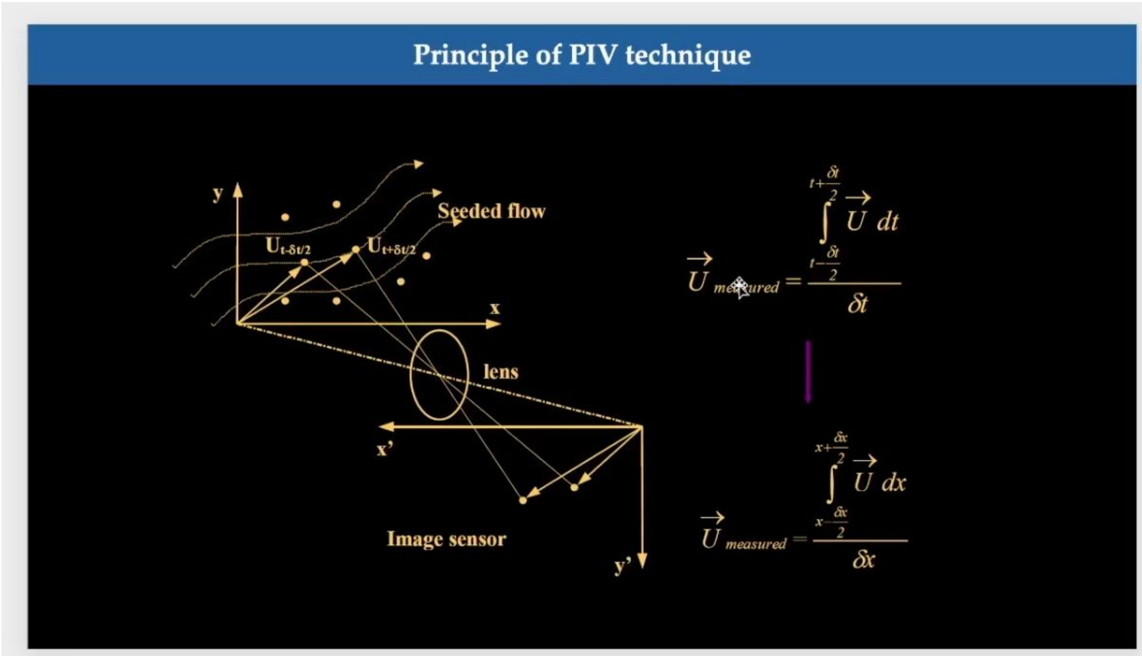


That is, in a very natural way, the very basic premise of velocimetry. Of course, we showed that we do it by using a laser sheet, which has a finite width, by the way, and the particles that are within this laser sheet, which has a finite thickness, or within the plane of the laser sheet, are the particles that are only visualized. So, you can understand that it is the same thing: the particles are moving, different particles are moving in this laser sheet, but these particles are only visualized inside this laser sheet. Whatever is outside, we have spent a lot of time explaining how the out-of-plane component of motion can actually lead to errors in the measurement, even in 2D measurements. So these are basically the tracers.

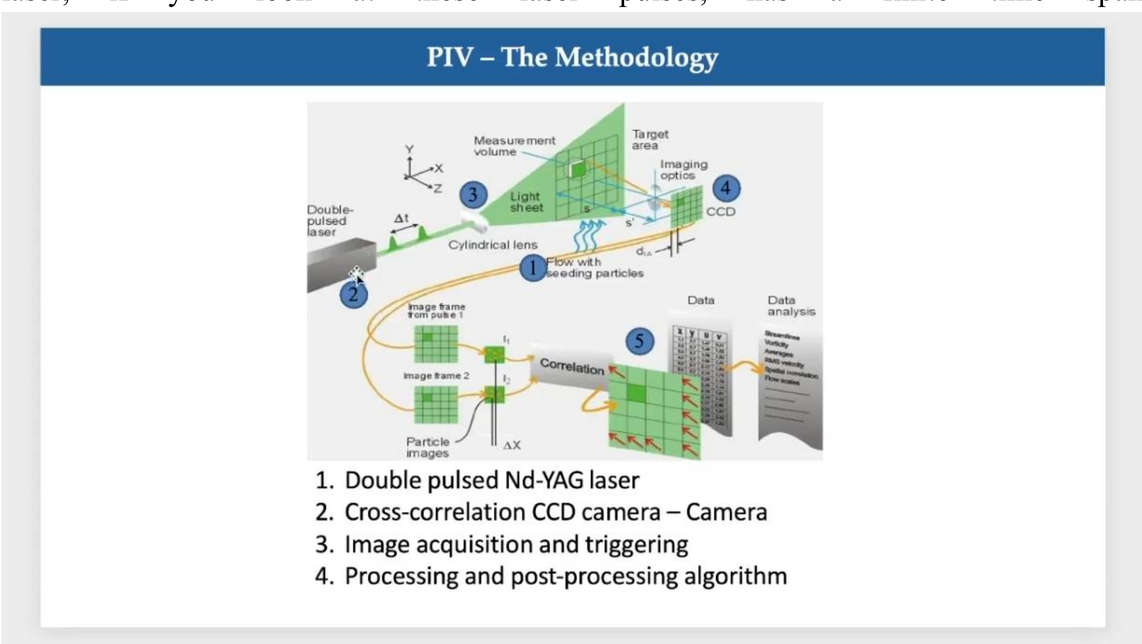


We already talked a lot about tracers and how they should faithfully follow the flow field and what kinds of systems are there. So you visualize those particles that are inside this laser sheet. That's why you have those yellow dots over there. So the idea is that by using a lens and a camera assembly, you record the positions of the particles, kind of, and this is a seeded flow. We assume that the seeded particles, you know, follow the flow field quite faithfully, and then you can measure, within that time interval, what the velocity is, okay? So this is like an integral way, and you know, this is how you measure the spatial velocity, spatial or the temporal velocity, okay? So, this is how the measurements are performed.





This is a very simple principle of the PIV technique. So, you have to summarize it this way. What we have used is a double pulsed laser, which has a finite Δ T between the two pulses. Remember that this Δ T between the two pulses is kind of controllable. So the laser, if you look at these laser pulses, has a finite time span.



So these are typically on the order of nanoseconds, but there is a pulse-to-pulse separation that can be on the order of microseconds. And we can go even lower than that these days. So we have already shown that by using a cylindrical lens or a combination of concave cylindrical and spherical lenses, you create a measurement volume, which is basically a light sheet. And this is the area that is illuminated. Now we divide the area into multiple interrogation windows that we see over here.

This is what we call the measurement volume. And this is the measurement; this is the... Interrogation area: what we image on the imaging plane, which is typically a CCD, so the flow is seeded with particles.

You image it, so there is the object distance, the image distance, and the target. Once it is imaged, then you get two frames; it is a double exposure or two frames, or a double frame. This is a cross-correlation CCD camera. So the images from pulse 1 and pulse 2 are recorded, and you take out these interrogation windows. You have the intensities, and you also have the displacement inbuilt because the particles have moved during this Δt.

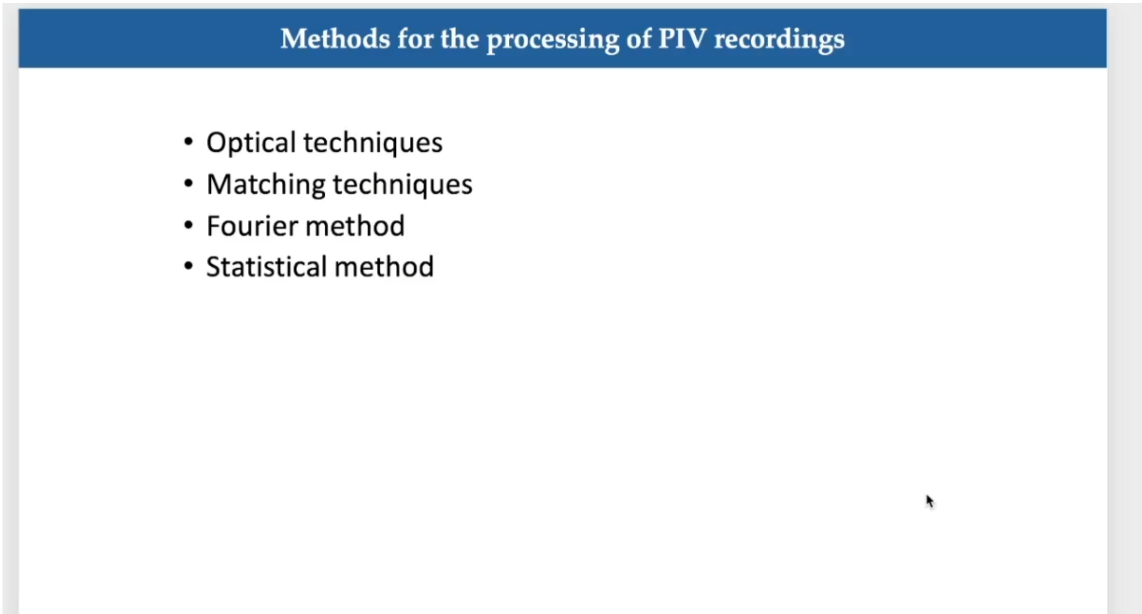
And this Δt time is chosen in such a way that the particle has some finite displacement. Too small a Δt may not lead to any tangible displacements at all. So you need to have some idea about the flow field to choose this Δt; you cannot go completely blind. So you need to have an idea of whether the flow is like 50 m/s or 100 m/s and accordingly adjust this Δt so that you know what kind of displacement we are looking at. So these are the two images.

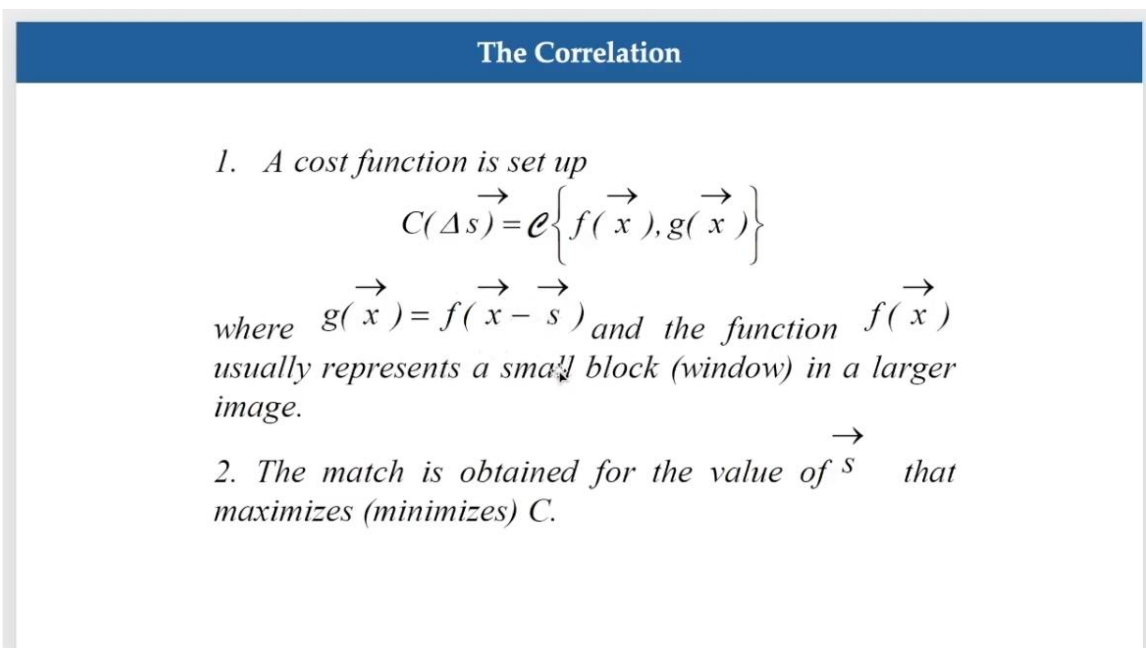
These are the particle images. You take out the interrogation window. This has an intensity which is I_1, and this is an intensity I_2. The particles may have moved by a distance of Δx. Then you perform the correlation, which is typically done using a Fourier transform.

And then you get velocity vector. You get one velocity vector for each window. For each of these measurement windows. So the idea is that the ensemble of particles in these measurement windows basically moves as a unit. They actually have the same velocity, and that is what the correlation does.

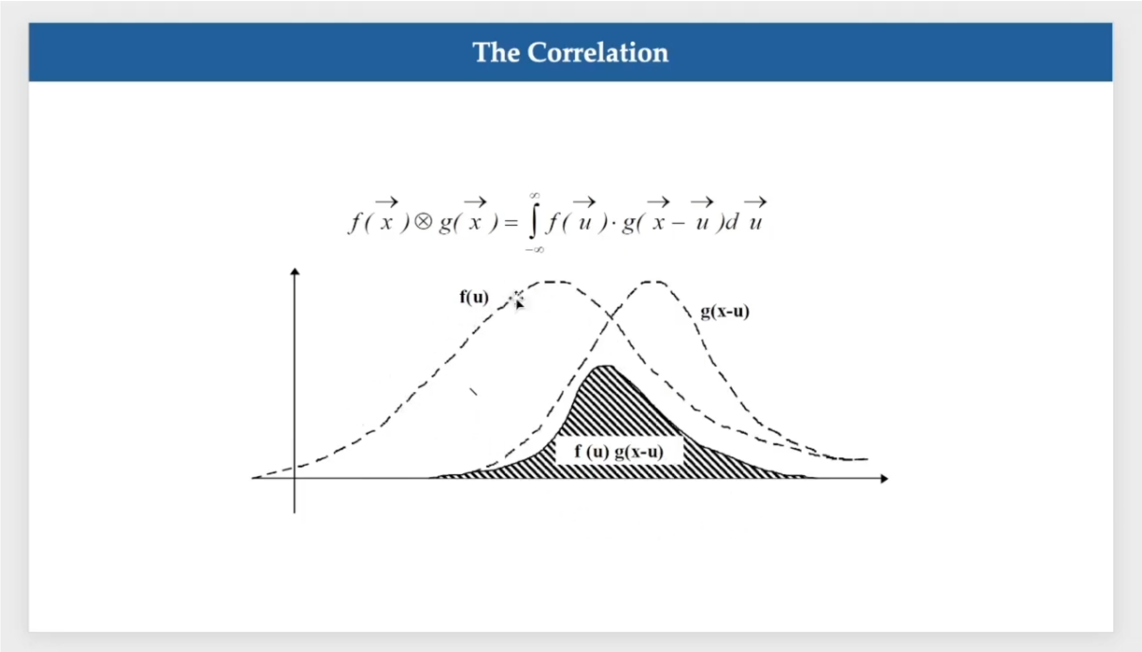
So it finds the most probable velocity, essentially the maximum velocity or maximum displacement, by minimizing the most probable displacement and maximizing the correlation. So the idea is that it involves four steps, or rather a fifth step, which is the first four steps. The first two are basically the hardware, and then you have the third step, which is basically triggering. So triggering is also very important because when the laser shines, the camera should be ready to take the image, and then you do processing and post-processing algorithms, and you can find out different things. Once you get the vector field, you can find out vorticity, you can do averages, you can find streamlines, and you can do lots of stuff.

These things are already covered in detail, but this is a bird's eye view of what happens in a nutshell in a PIV. So the methods of PIV, processing of PIV are many. So you have the statistical methods, the Fourier methods, and the optical methods, all of which we have covered in detail. So the idea was basically, if you have to summarize it very crudely, you set up a cost function. Between f_x and g_x, where g_x is f_x - s, the function usually represents this: f_x represents a small block or a window in a larger image, basically the interrogation window size.

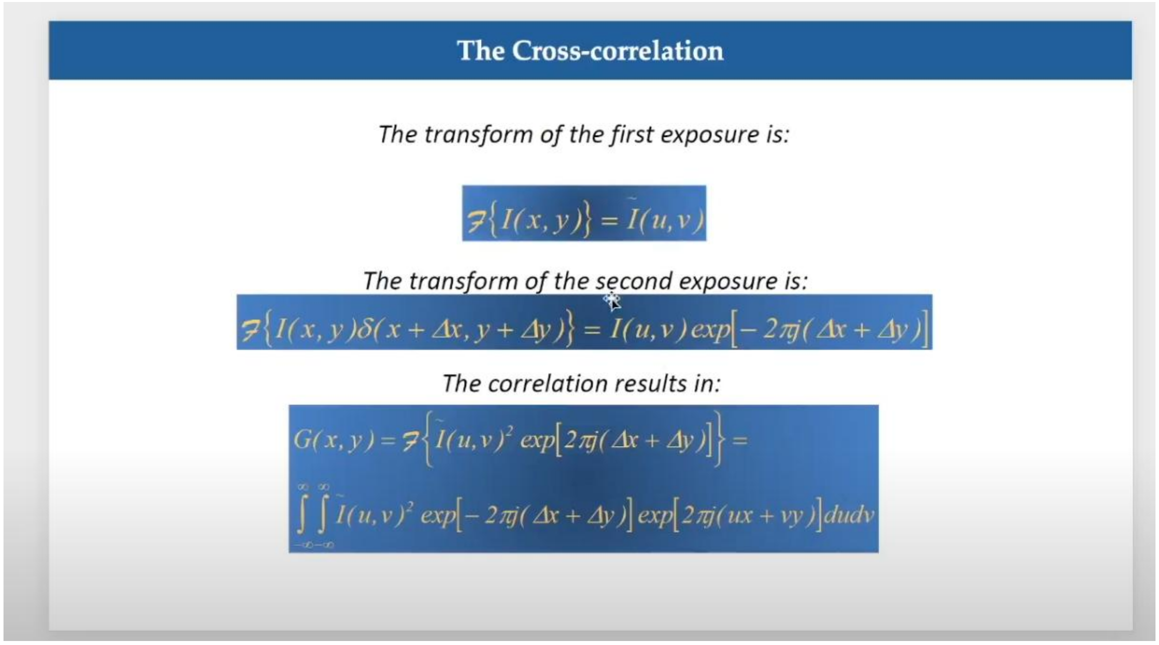




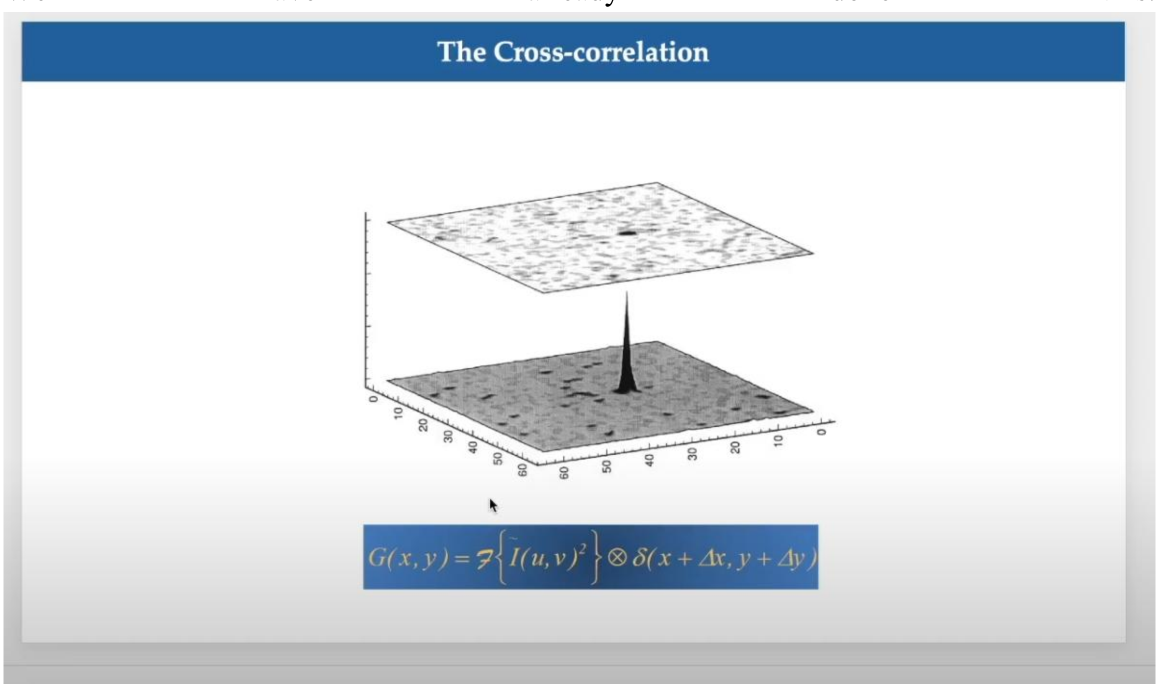
The match is obtained for the value of s that maximizes this cost function c, so that is like a most probable. Okay, so we try to match for what value of S this is maximized and C is maximized, okay? And the function F, which we have already seen, consists of a point spread function, the geometric image, and all those elements are embedded in this function. And we just have, it represents a small block or a window in a larger image because it's an ensemble. Remember, we are trying to do a pattern match because you cannot track individual particles; therefore, you are doing a pattern match between the two images. And this is how the correlation actually works.



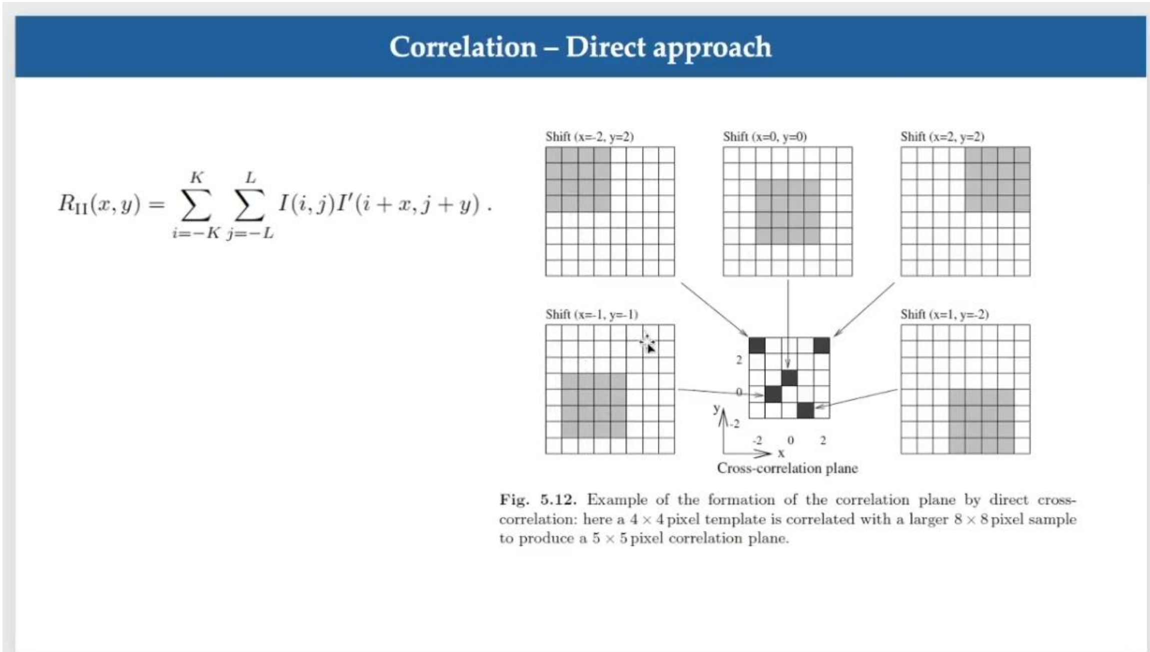
So this is fu, this is gx minus u, and then you kind of get the correlation function. The cross-correlation, how do you do it in FFT? You basically transform the first exposure, which gives you the first power spectrum, and then you transform the second exposure. which now has a displacement of Δ x and Δ y if you look at it. This is the image, and then there is a Δ function, and then the correlation result is g, which is basically this, as you can see over here, and ultimately you get a correlation peak, okay? Because you remember the Wiener theorem, right? That we have covered in kind of detail. This is how it happens in Fourier space, essentially.



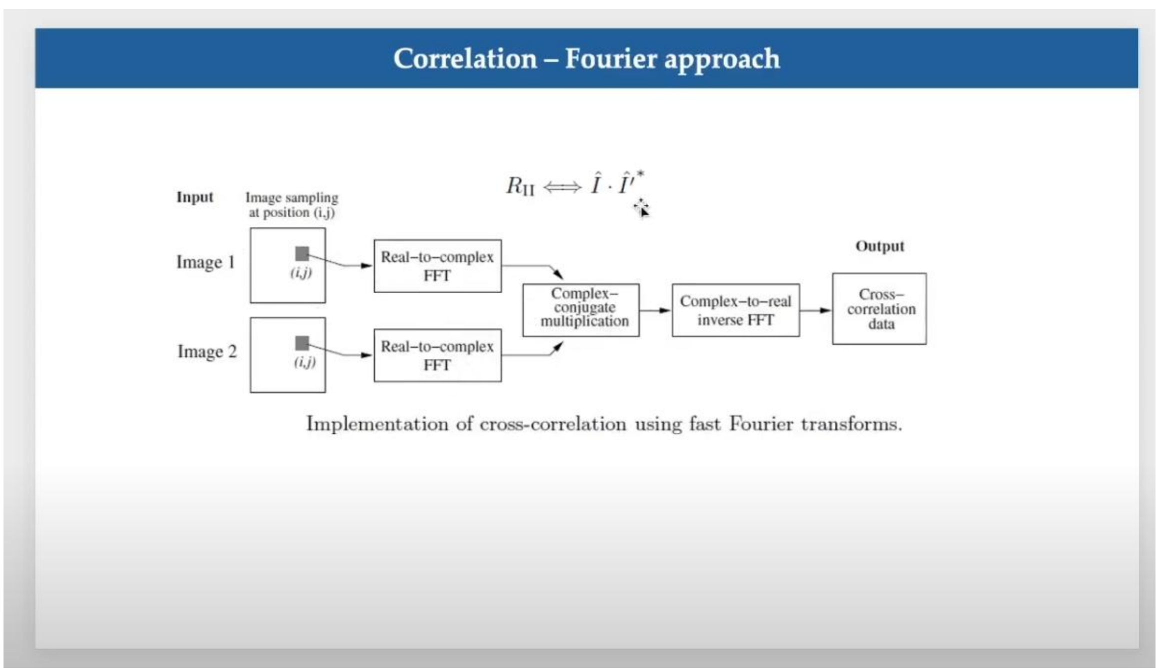
Alright, so this actually shows a displacement, and that displacement D is actually the peak at a displaced location D, which gives you the number of pixels that the velocity at the displacement vector is in terms of pixels. So this is the direct approach correlation; you know that we also covered that there is a four-pixel by four-pixel template, and then there is a larger eight-pixel by eight-pixel sample. So you do this between image I_1 and I'. We have already done this.



This is the shift. You are basically shifting this template everywhere. And this gives rise to a 5-x-5 pixel correlation. This we know. It is 2m plus 1 and 2n plus 1. So this is how the correlation actually occurs.

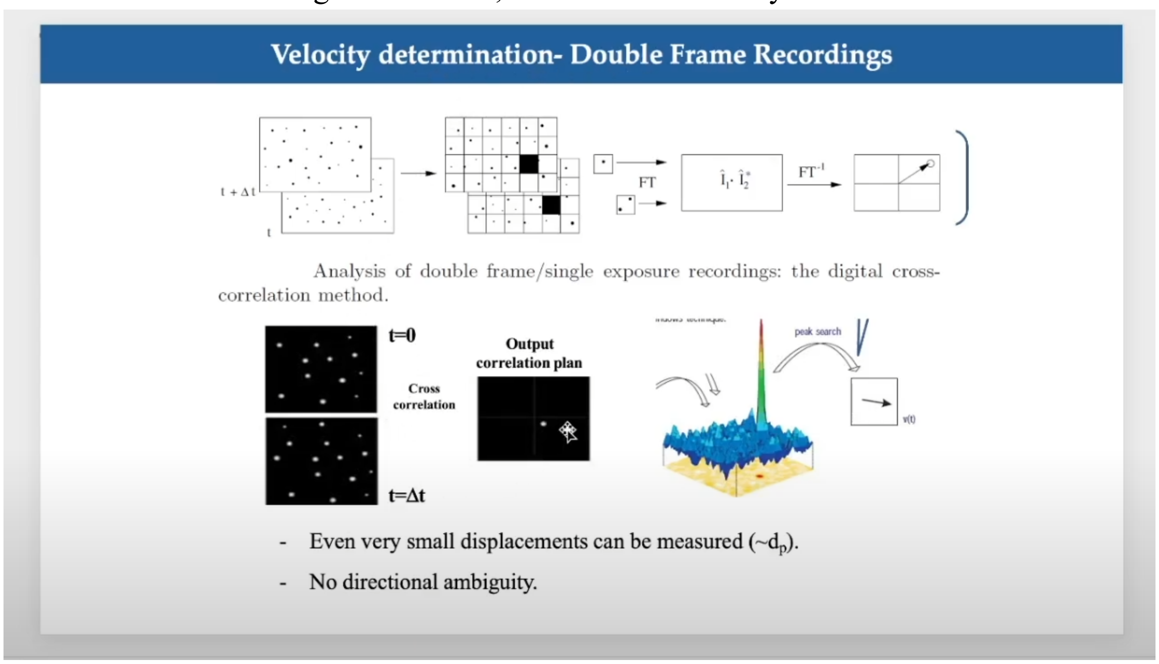


This is a direct approach. The Fourier approach will be to take the two images, perform the real to complex Fourier transform, and then multiply the complex conjugate like this. This will give you a complex to real inverse Fourier transform, and then you will get the correlation data. So this is how most of the fast Fourier transforms actually work. So there is a direct approach, and then there is an indirect approach. So the indirect approach involves doing an FFT, then performing a conjugate multiplication, and finally an inverse Fourier transform.



So, if you want to determine the velocity, what happens is that you take these two images, and the output is that bright spot, which is the correlation. And this will be located at a distance of d. Which is that, okay? So it is the same way. So you take the two images, do the interrogation windows, then do the Fourier transform of these windows, and actually do it for all. And for one such ensemble, if you do the power spectral analysis, and then if you do the inverse Fourier transform, you will get a displacement that will shift this peak, okay, at a distance of d.

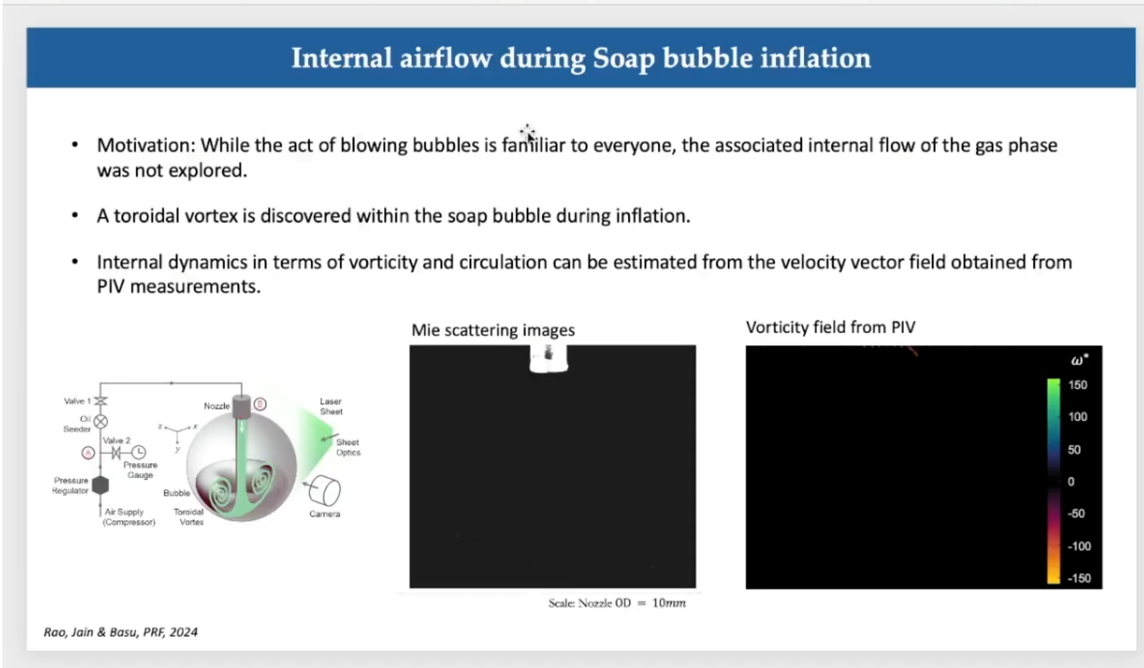
So this will be at a distance of d from the center. As a result of that, the displacement dp is actually where this bright spot will appear, which is basically this peak. If you look at it from the top, it will resemble a bright spot. And then there will be noise. Okay, so if you search for the peak, this will be the peak, which will be a single bright spot, and then there will be a background noise, which is basically due to the other terms.



Okay, but this is the peak which is supposed to be at least two or three times higher. This will represent a bright spot, and the distance of the bright spot from the center is going to give you the displacement. So the peak will be located at a distance D. Even for small displacements, this can be measured, and there is no directional ambiguity. Okay, so it can be located anywhere from the center.

Okay, anywhere on this plane. So you can also know the directions. That means you can determine the velocity, not just the distance. Understood? So this is what happens. So you search for the correlation peak, and that is exactly what happens. This is also, we covered it in great detail in the lecture.

So the idea is to perform a Fourier transform, multiply, obtain the power spectrum and the power spectral density, then do an inverse Fourier transform, and finally search for the peak. And the peak should be located at some distance from the center. So once you locate it, you know what your displacement will be, and hence you know the velocity. So very small displacements can be measured. So now we look at some of the PIV demonstrations, which come mostly from my lab and a little bit from L.

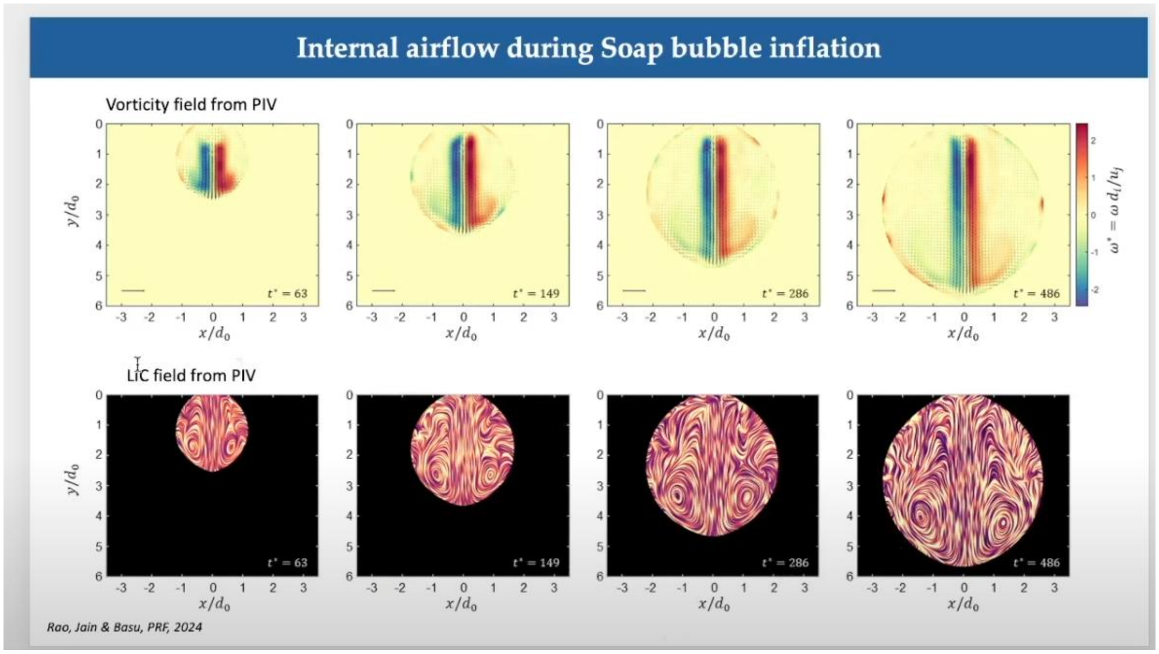


Venkat Krishnan's lab at NAL as well. So this is, for example, what we did over here; I will give you some examples across scales. This is, for example, a millimeter-sized bubble, and we are trying to inflate this bubble, okay? This bubble is being inflated as you blow a bubble, essentially. So we are trying to see what happens to the flow field inside this soap bubble, okay? So, to determine the internal dynamics, we perform PIV measurements, okay? So, as we know, this is the Mies scattering images if you look at them. So these are the Mies scattering images. You can see that this is strongly seated, so you can see the flow structures.

You can see the toroidal vortex. You see, the flow is actually rotating here. And here you can see the corresponding vorticities. This is determined from the flow structure images, and you can see those lines; those are the velocity vectors. Okay, so you see the vorticity and the velocity both in this kind of experiment. And this is within a several millimeter-sized bubble.

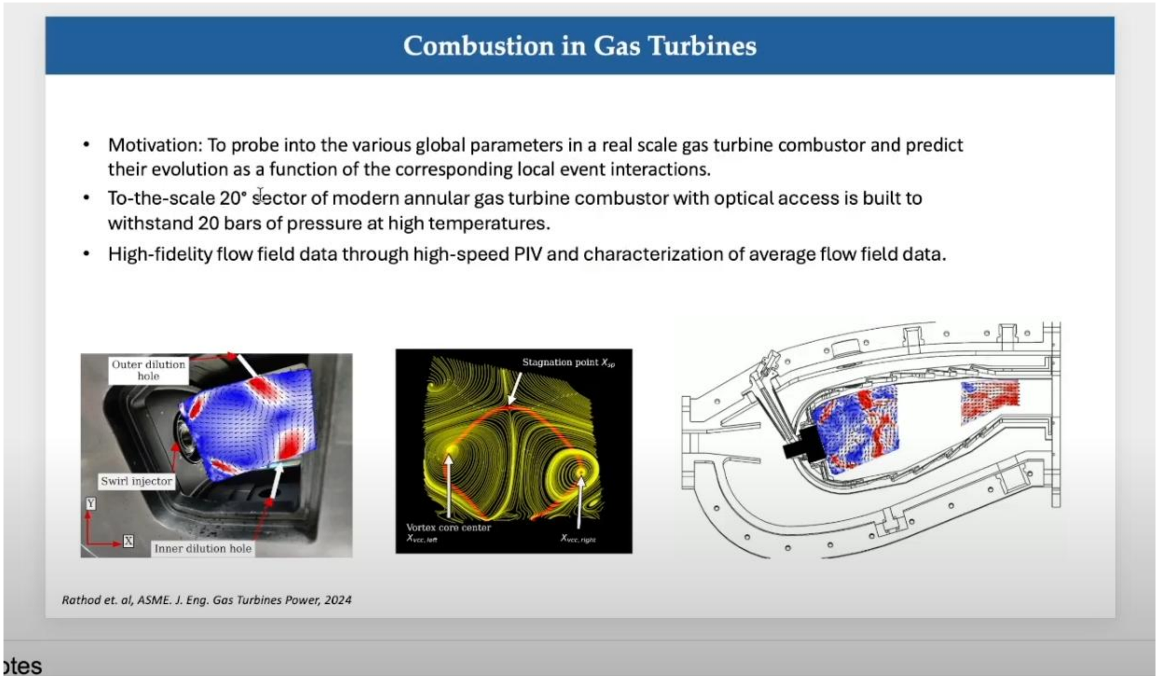
Okay, it's actually pretty large, but still small enough that it is within the bubble. Remember, this is the flow within the bubble, not outside of the bubble. So this you can see that this is a time resolved PIV. That means you are basically doing it at high speed, but the idea is still the same. You can measure the velocity field, and you can measure the vorticity field once you know the velocity at each point.

And then, of course, you know, we also see examples of how the flow structure, just a qualitative visualization, will also give you an idea of what the flow structure is inside this. So this is an example where you have done the PIV in very complex geometry. So you can see this is the vorticity data, and then you can do all kinds of mathematical wrangling on the data. So this is to identify that the LIC is to identify the structures.



From the PIV data. This is the vorticity from the PIV data. As you know, vorticity is this. So all these things we have done during the soap bubble inflation experiment. So this is complicated. Okay, and this is one level above, so I showed it for millimeters.

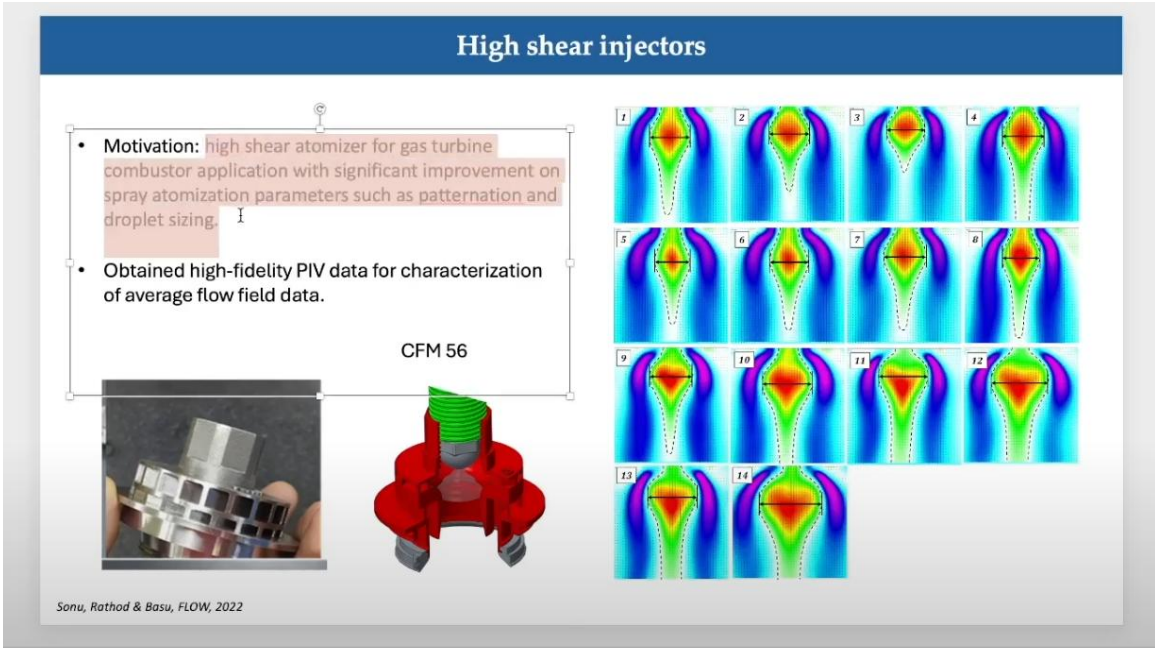
Now, what if we actually go to two meters? This is the flow within an actual gas turbine, so you can see this is a 20^0 sector of a modern annular gas turbine combustor with optical access to withstand, you know, 20 bars of pressure. So, one needs to see the flow field inside this combustor. You can see this is the combustor that is used for power generation and also in aviation. The aircraft has these combustors, for example.



So, you need to see the flow inside this combustor. So the motivation is pretty simple: to probe into the various global parameters of this real-scale gas turbine combustor and predict their evolution as a function of the corresponding local event interactions. So, this is a 20^0 sector combustor with an optical axis built to withstand 20 bars of pressure, and this is high-fidelity flow data that is obtained through high-speed PIV. So you can see, this is the high-speed PIV, which actually shows the vector field, and in the background, you have the vorticity field. You can see it is a very fast measurement as well as quite complex to begin with. So this is done on a scale that is much, much larger than the bubble we mentioned.

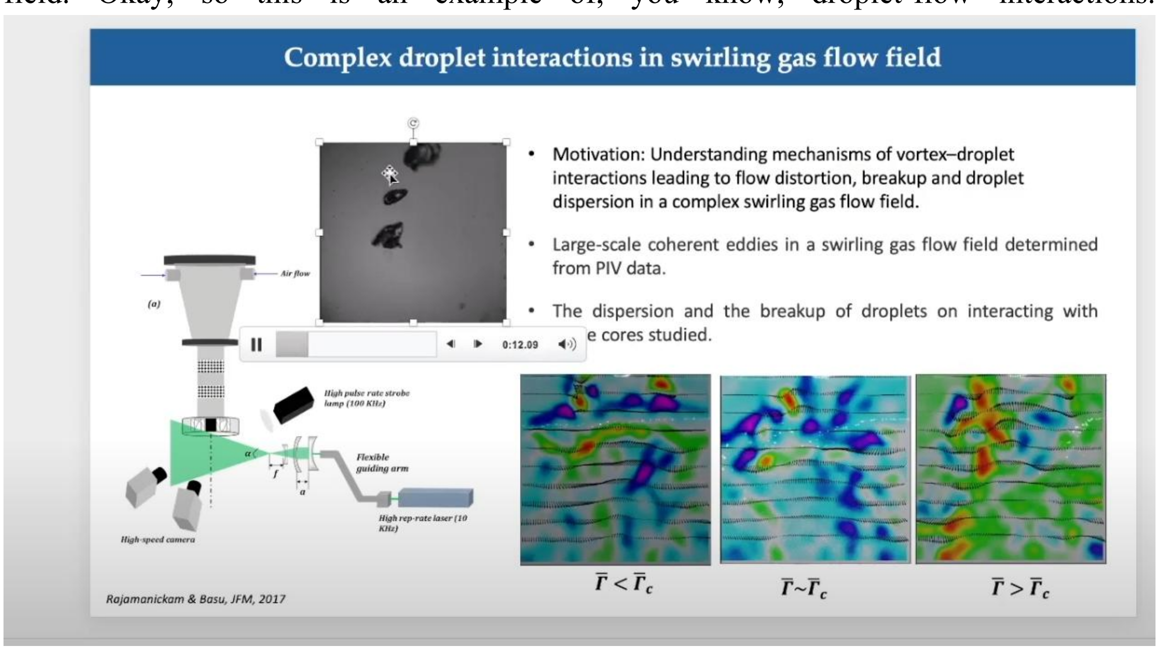
So this shows that how PIV can be used for any system, small scale or large scale. And here you can see that if you take this data and average it, you get these beautiful flow structures. So this is like an average over time that you get. And remember, here you have all those perspective distortions and other types of stuff because you may not be exactly 90 degrees with respect to the flow.

This is another thing that we did. This is a high shear injector. This is a new class of injectors that are to be used in the AMCA combustors. So, this is a multi-phase system now. So you have to do not only flow field measurements but also droplet sizing, which kind of reminisces of PDPA and other types of measurements. So you can obtain very high-fidelity PIV data for the characterization of the average flow field.



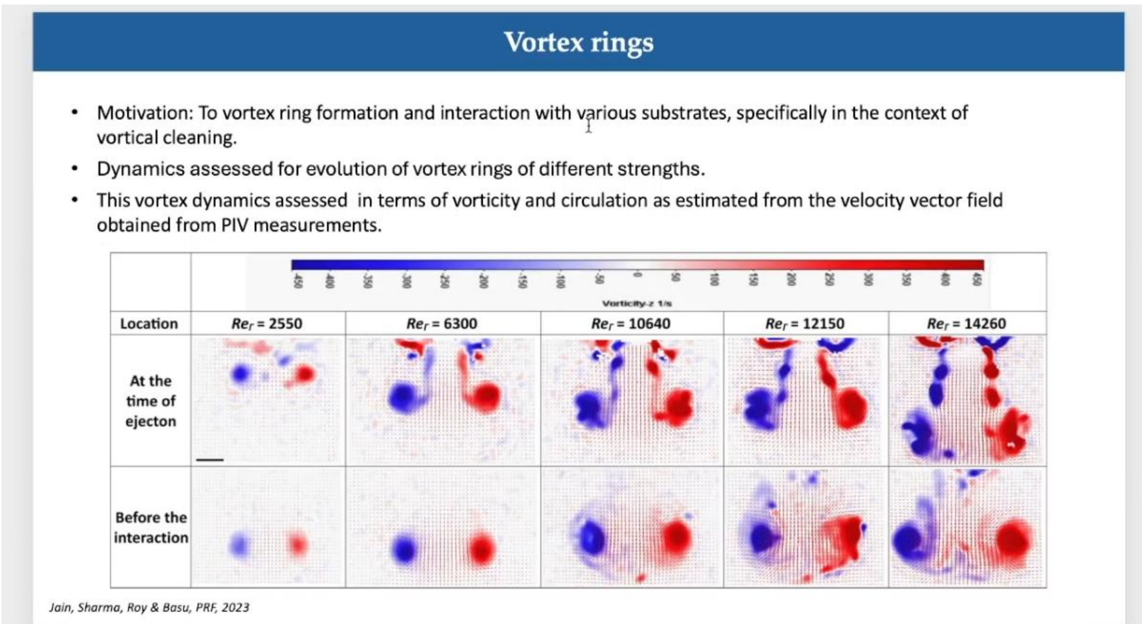
So you can see that this is the kind of time-averaged flow field data that you get. Okay, so this is one, two, three, and four. So these are under different flow conditions. Let's not focus on what those are, but you can see the spectacular, you know, flow field patterns. And these are again colored with vorticity, but you can see the, you know, the arrowheads, which show the PIV.

Okay, and this is, of course, complex; you know, the interactions of the droplet in a swirling flow field. So you can see, this is how the droplet actually interacts with the flow field. Okay, so this is an example of, you know, droplet-flow interactions.

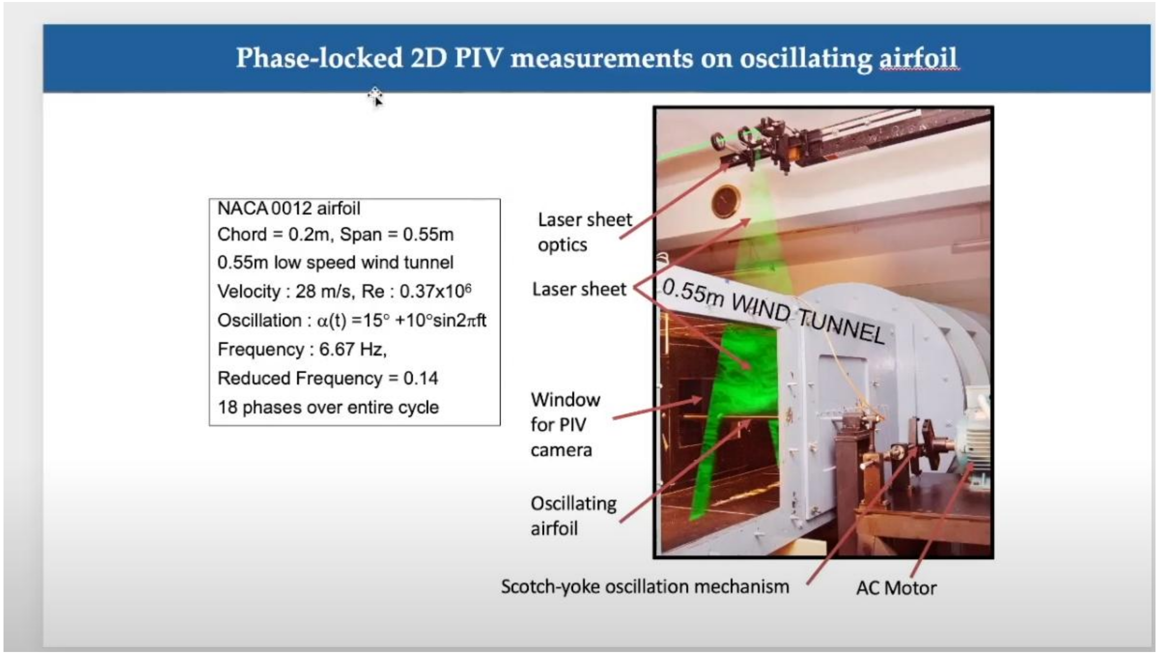


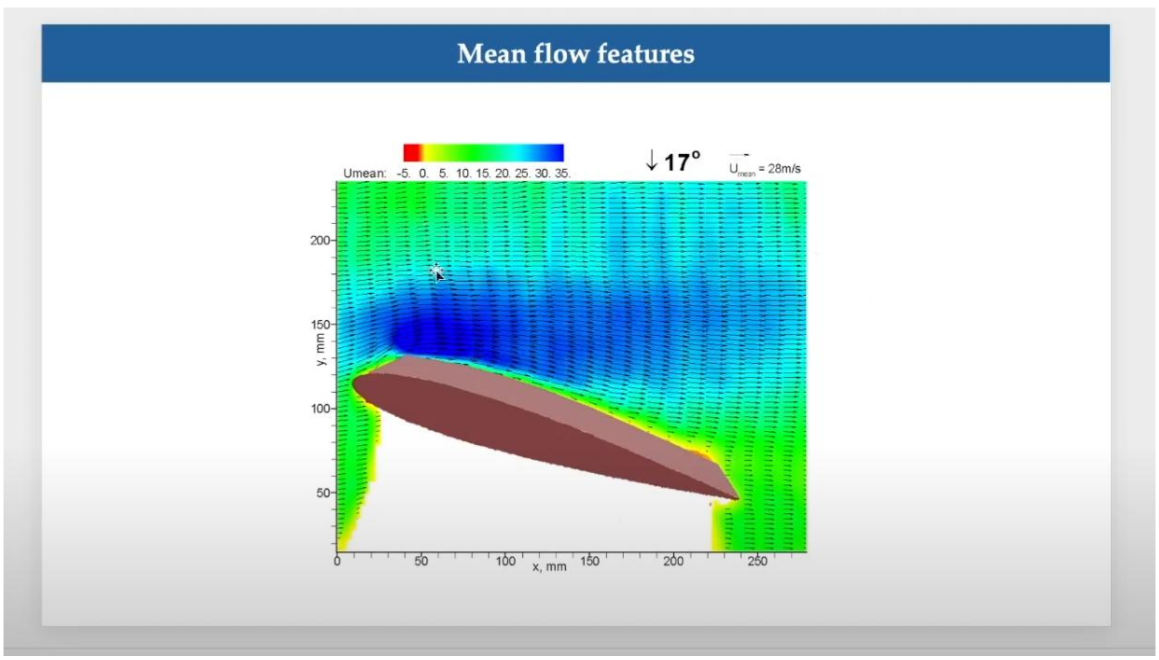
And these are some of the other things. These are all videos. which basically shows how the droplets are dispersed by the flow field. So there is the flow field, and you also have the droplets coming and injecting into the flow field. And this is the arrangement of the PIV. Once again, here, of course, we use a laser-guided arm because the laser is located somewhere else. And then again, we create a sheet, and then we observe this flow field in the presence of large droplets.

And you can monitor the droplet as well as you can monitor the flow field. So this is brilliant. We have also done work on this kind of vortex rings, for example. This is a vortex ring formation and its interaction with different substrates, specifically in the context of vortex cleaning.

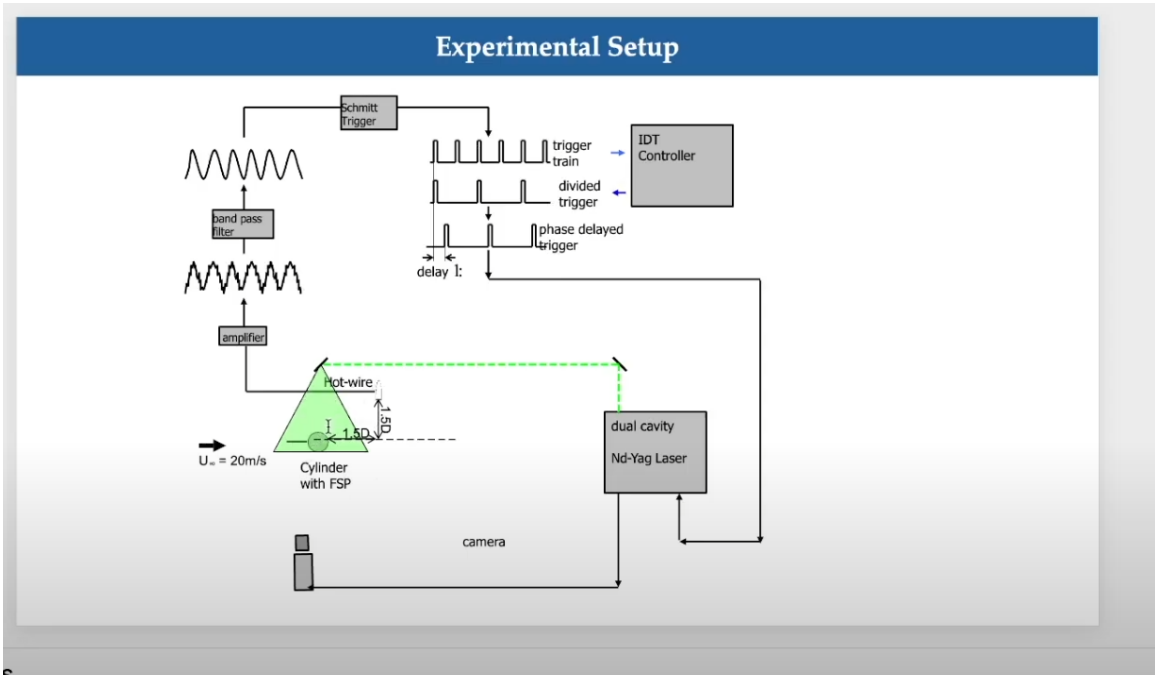


So this is the interaction of the vortex with the porous media. You can see the intricate flow structures at different Reynolds number combinations. So, all these things have been done in our lab. This is from Venkat Krishnan's work, which shows phase-locked 2D PIV measurements. So this PIV measurement, you know, because it is phase locked, that means at certain angles only it will take the measurements, and because it is situated in an oscillating aerofoil and with an AC motor, this is the kind of stuff that Nal has done; this is the mean flow features over the aerofoil, and there are dynamic features also, so you can see it is velocities of about 28 m/s.

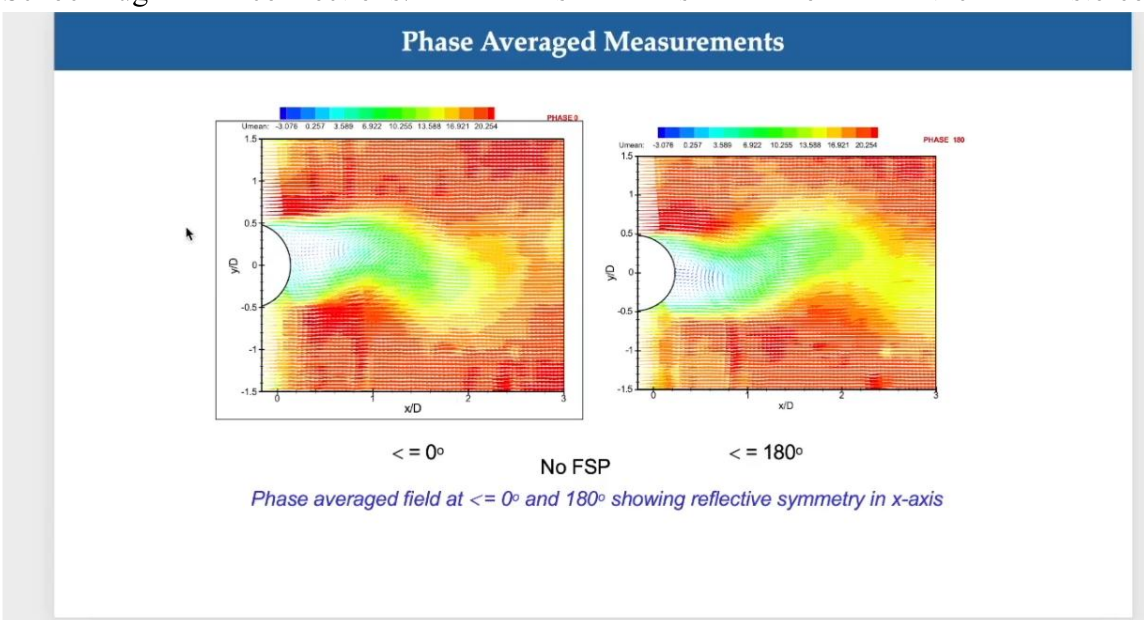




This is phase-locked measurements over 2D measurements on a cylinder. So you can actually see what the rate of vortex shedding is. Okay, this is the kind of experimental setup. Here, hot wire anemometry is also used as a probe measurement at a particular location. So you can see that all these things are done again by the YAG laser and the delay. And the bandpass filter, so all these things are features that we have covered already.

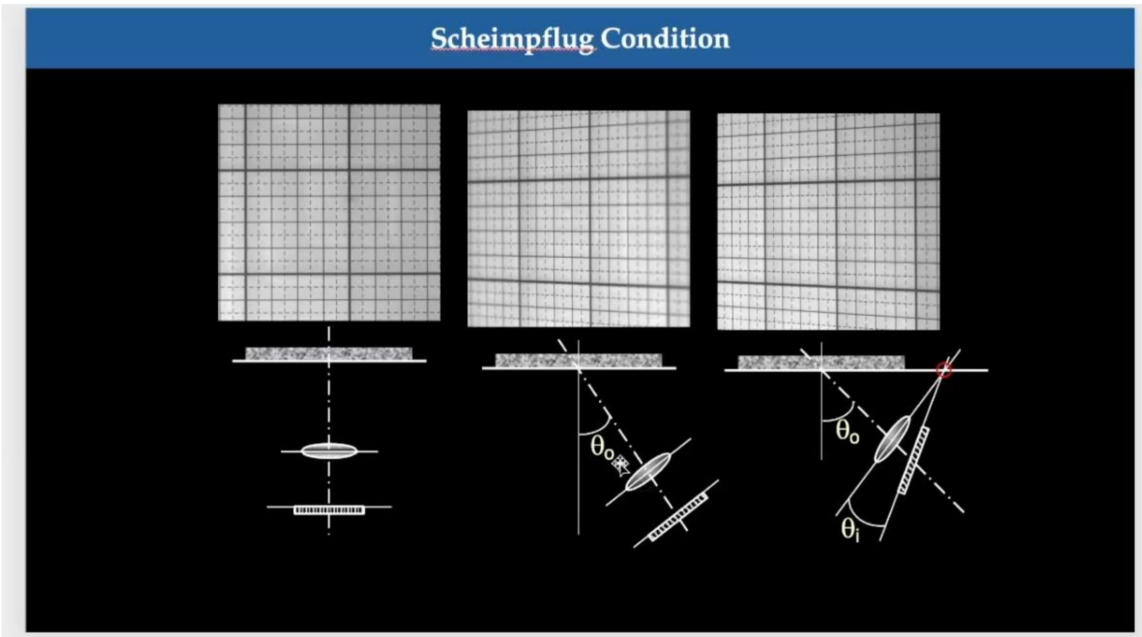


These are some of the phase-averaged measurements, which are at 180^0 and at 0^0 with respect to the reflective symmetry in the x-axis. These are the phase-averaged measurements; more on the phase-averaged measurements. So we have also covered Schoenflug connections. This is for the stereo.



This is when it looks straight and when there is perspective distortion. Schoenflug connection; actually, you know where the object plane, the lens plane, and the image plane all coincide at a particular line. This is the line. So it looks like a point in the other projection. So this has two angles. It has zero where the lens is placed, and the imager is positioned at a slightly different angle with respect to this.

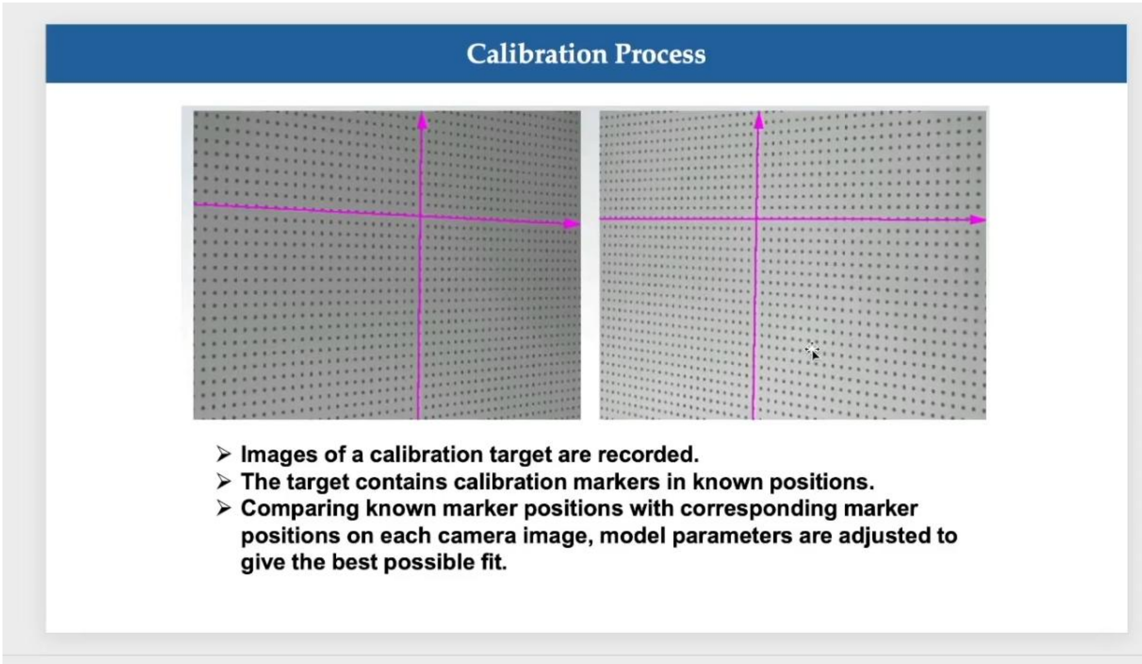
This is the Schoenflug condition. And you can read more about it on the internet or in any other book. We also covered it in a little bit of detail in our PIV lectures. This is how the calibration process is carried out. So what happens in the case of stereo PIV is that the images of the target are recorded, and the target contains calibration marks. So comparing the known mark position with the corresponding marker, we adjust the model parameters to give the best possible fit.

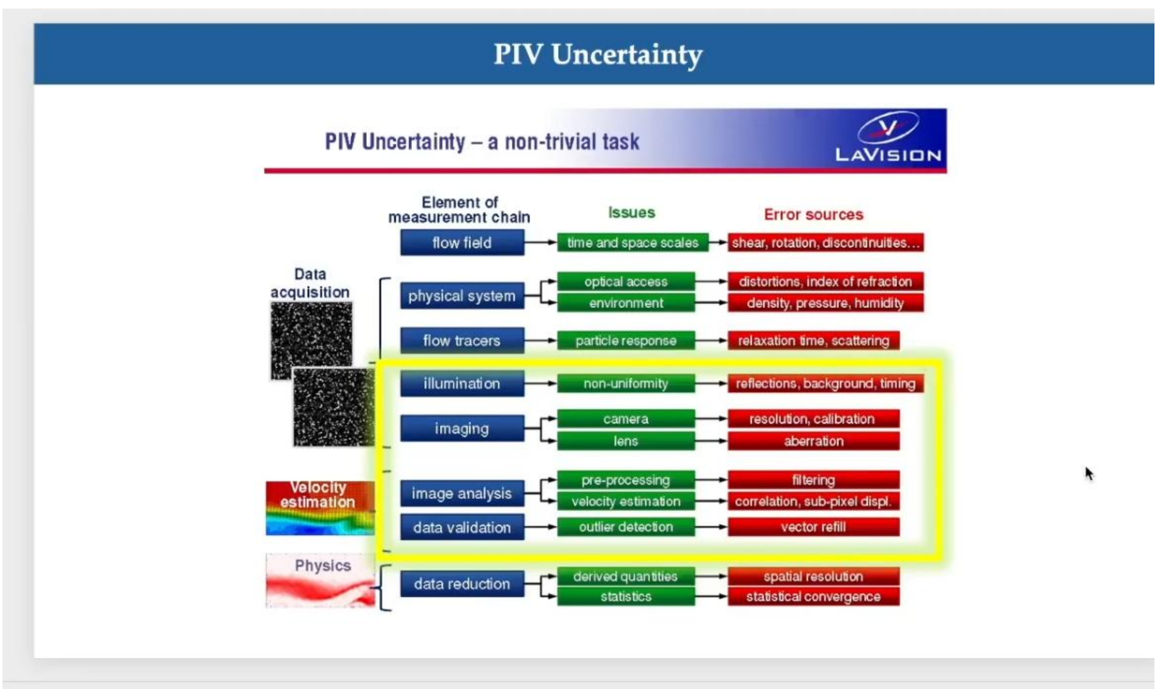


So, this is how perspective distortion actually happens. So, stereo PIV; these are stereo PIV measurements on a Δ wing. You can see the shim fluke connection. This is the optical axis. The camera is located at a slight angle.

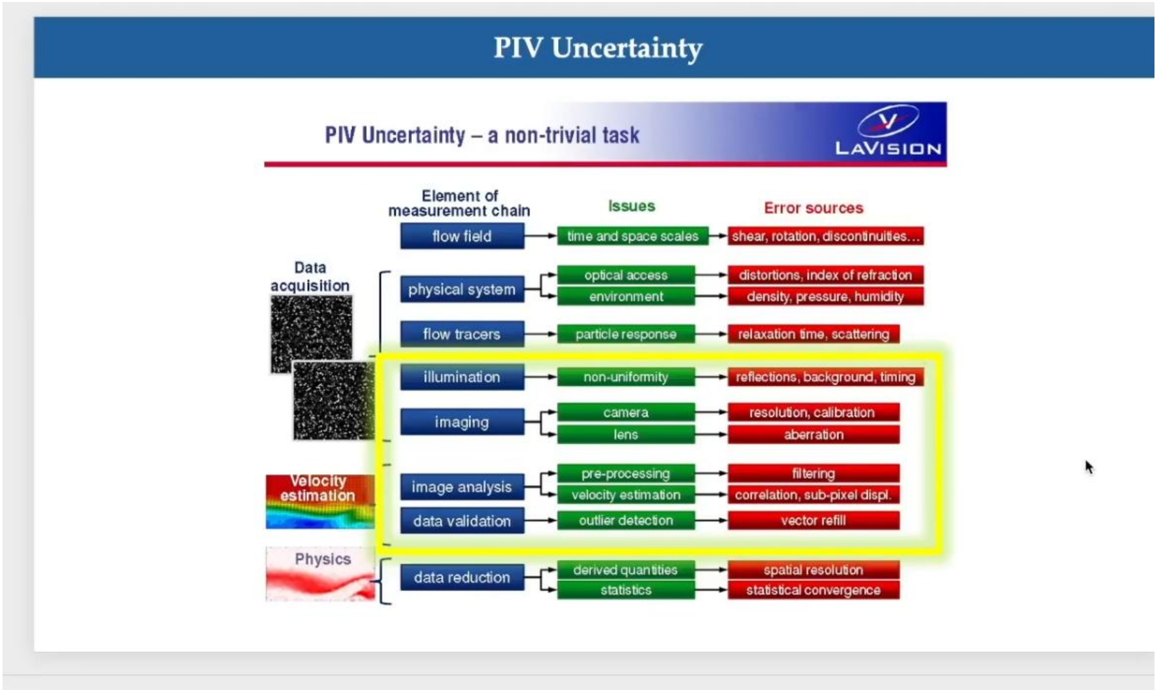
So this is how the measurement is actually carried out. And this is the measurement of the different planes under different flow conditions. This is actually stereo PIV measurements. This is more stereo PIV measurements of the Δ wing at low speeds. This is PIV measurements of an air blast atomizer, which is basically a similar type of atomizer to those we showed earlier in our measurements as well. So, for uncertainty and error, we will just spend a minute or two; the uncertainty stems from errors.

The uncertainty can be many things, largely considered as the distribution of error, which is assumed to be Gaussian, but it could also be something else. So there are random error sources, like, for example, low seeding densities, mean out-of-plane motion, shot-to-shot variation of the laser sheet, misalignment, background noise, and very strong shear, which prevent particles from flowing; then there are bias errors, like scaling error, timing error, and peak locking error; all these errors lead to uncertainty in the PIV measurements. So it is a nontrivial task. You can see there is data acquisition, there is velocity estimation, and there is physics, which is essentially fluid mechanics. So, you have the flow field, physical system, flow tracers, illumination, imaging, image analysis, data validation, and data reduction.





And then there are issues. We have optical access issues, space and time scales, non-uniformity issues, and velocity estimation issues. We have outlier detection-derived statistics, etc., and these all lead to error sources in shear distortions, resolution issues, filtering issues, and correlation issues. All these issues come into the picture.



This is taken from LaVision, and this shows that this is a non-trivial task indeed. So there are many references, as we have already covered this in detail, mainly from this book. There are other books and other kinds of things that are also available. We have taken many things from our own work. So I think this is where we completely end the PIB lectures. And thank you.