Spray Theory and Applications
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Lecture – 15
Non-intrusive spray measurements techniques

Good Morning. We will continue our discussion of Non-intrusive Measurement Techniques apply to sprays. I will first start by making a quick list of some other techniques that are commonly used and then we will look at the theory and principle of operation of those instruments.

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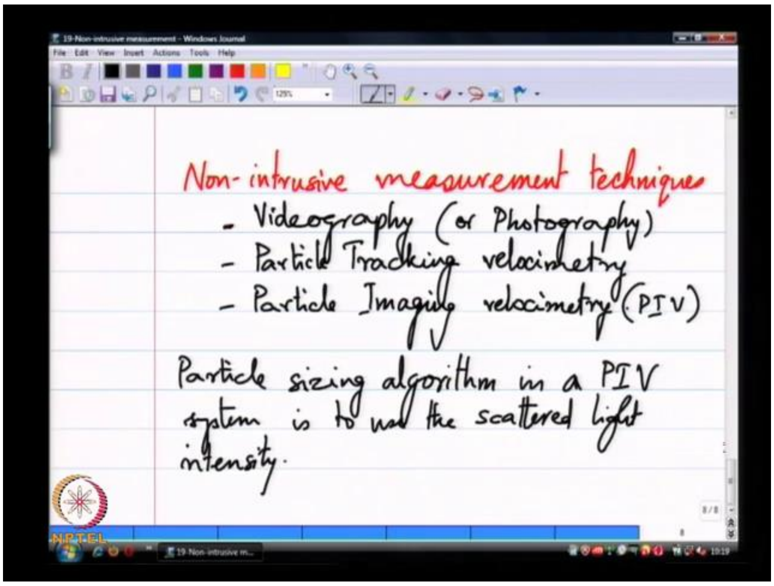

The word we looked at couple of different non-intrusive measurements, we looked at videography or photography in more specific sense, and we looked at particle tracking velocimetry, as well as particle imaging velocimetry. The particle imaging velocimetry is a technique, that is used to obtain the velocity field given a certain set of particles that are in motion, but for this specific case of a spray we are also interested in size. So, there are techniques, there are algorithms that have been developed to sort of ride upon particle imaging velocimetry algorithms to give us both size and velocity information.

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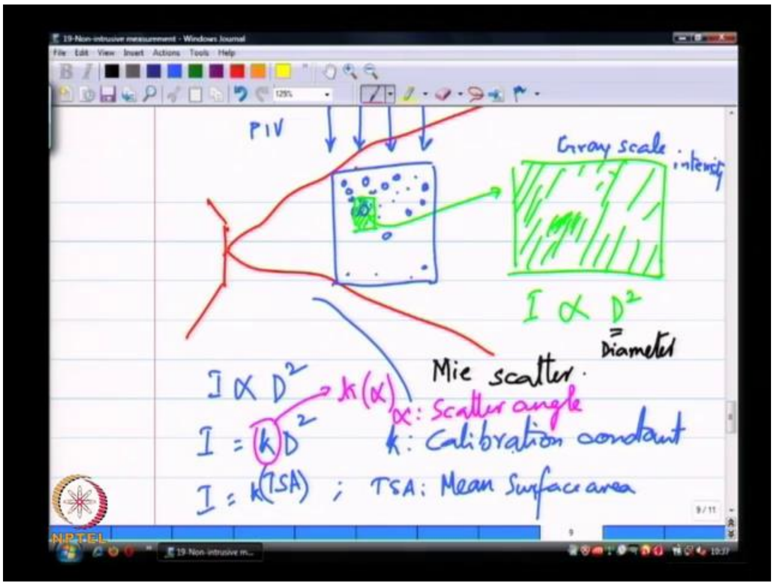

So, one very simple particle sizing algorithm in a PIV system is to use the scatted light intensity. So, think of a spray when I am looking at a certain region in this spray which is my image and in this image, may have some large drops and some really small drops. Now mind you where looking at a PIV. So, we are not at a level where we are able to see individual drops. So, it is sort of a picture that gives us grayscale intensity. And in this grayscale intensity picture if I take a certain region of the spray, I have a certain gray scale distribution of light and this gray scale distribution of light gives me the intensity in an image like this is proportional to D squared, where D is the diameter and this comes from what is called Mie scatter.

So, if I take the simply just to understand Mie scatter. So, I take a spherical drop and subjected to a bunch of light rays, I have the possibility of reflection at this surface followed by a reflection again; sorry I have the possibility of refraction at that surface followed by refraction again as at the second interface. Or I have the possibility of just reflection at this surface or I have the possibility of refraction at this surface or reflection at the second surface following the first fraction. And then I could have another refraction at this surface or depending on the situation here I could have a total internal reflection followed by refraction. There is a whole combination of physical phenomena that come in to play when I have a set of light rays, encountering a spherical, transparent object which is capable of both reflecting and refracting at the interface.

The combination of all of these effects as well as in the gives raise to what is called Mies scatter pattern that is, if I plot the intensity of the light has a function of the 360 degree angle going around the drop its known that there is a lobe at the center, along the axis of the light; we will move this to the next page, so I can.

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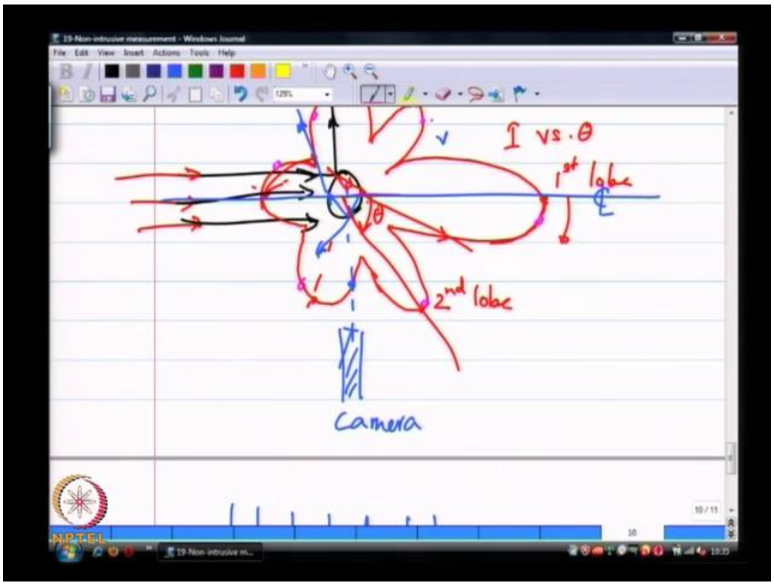

There is an intensity lobe at the center line, let me using another color there is 2nd lobe which is smaller in magnitude, but slightly of axis. There is also a third lobe which is more predominant at for the back scatter level.

So, if I plot the intensity versus theta, theta being in some sense this angle, I have the maximum intensity on the center line. As I walk around this center line away along a clock away from theta, the intensity initially decreases which is what looks like a minimum and then increases. So, this is called the 1st lobe and this is 2nd lobe of Mie scatter. This also another lobe that follows from the back scatter mode, so where light; for light to reach this play this point approaching from my left hand side the light essentially we looking at what looks like back scatter, scattered light coming back towards the source, where as the 1st and the 2nd lobe are more scatter lobes.

Now, this pattern would be symmetric, as symmetric as my figure looks and this symmetric distribution about the axis has these distinct lobes, which can be observed. So, if I have a spherical particle suspended let say in a shaft of light, as I walk around I will see the specs of light appear brighter and then dimmer again when I approach one of these minima and then becomes brighter again; this is classical Mie scatter pattern.

So, if I now look at this image, in this case let us say I have this light sheet approaching from the top, this light sheet approaching from the top. And if my camera is placed a vertically where your I is at this moment, when the image found essentially is as though I am looking at this from a 90 degrees scatter point of view. So, this is my camera, I am looking at the spherical entity sitting here, receiving light from the top and scattering light towards your eye and that is in this schematic, it look like a near 90 degree axis. So, the intensity of the lights scatter at the 90 degree position, without if I do not change the angle the intensity of the light scatter at that position varies with D squared; varies as the diameter of the drop squared.

So, it is essentially of phenomena where the intensity is proportional to the surface area of the drop. And if I receive different amounts of light from different points in this image, I can now knowing the intensity of the light coming in and through some calibration process. So, let us say at before I came to this experiment, I went through a calibration process where I put drops of a known diameter in to the same light sheet and then measured the intensity of the scattered light coming towards the camera. So, from that, if I take this I proportionate to D squared, I can now convert this to I being of the form K times D squared. So, K is a calibration constant, that I can calculate or that I can measured from my calibration process where I set up an experiment and have drops of a none size in the light sheet and knowing the intensity of the light that the camera sees, I am able to measure I am able to obtain a value of K, during the calibration process. And I can use that same value of K in my real experiment where I am dealing now with and drop of unknown size, but I know the intensity.

This is in some sense the basic principle by which I can add a particle sizing algorithm to a standard PIV set up. Where I take any one of the two images remember PIV deals with pairs of images, I can take any one of the two images. Get the grayscale intensity of the light that the camera sees. And knowing this calibration constant K, I am able to calculate a distribution of surface area; I do not get individual particle sizes. Look at this way this green image here is a gray scale intensity that is all what you have to deal with. This gray scale intensity at any point is proportional to the surface area the total surface area of the drops present in their per unit volumes.

So, if I have mono disperse drops, then I know that I is exactly equal to K times D square, if I have a whole distribution of drops like a in a real spray, will still say that this I is equal to K times the total surface area per unit volume. So, TSA or in some sense instead of saying total you might say this is the mean surface area; like an average surface area in this little green rectangle and that surface area liquid vapor surface area that is present in this green rectangle, is responsible for the gray scale intensity like an average gray scale intensity at that point.

So, I can look at the entire image, look at where the images bright and assume that there is a higher surface area of the drops. I could get this surface area in one of many ways could have a few drops that are large in surface area locally concentrated there; I could have a large number of very small drop. So, all I know is some sense the total surface area that is available for scattering the light.

So, I have now a developed methodology by which we can take the gray scale image and convert it to a surface area distribution, spatial distribution of surface area that is essentially what you get from processing a single image. There is a problem with this approach, though and it goes back to this Mies scattered pattern. Now if I have a drop exactly at 90 degrees, this dot here indicates there sort of level of intensity I might expect that to be seen by the camera.

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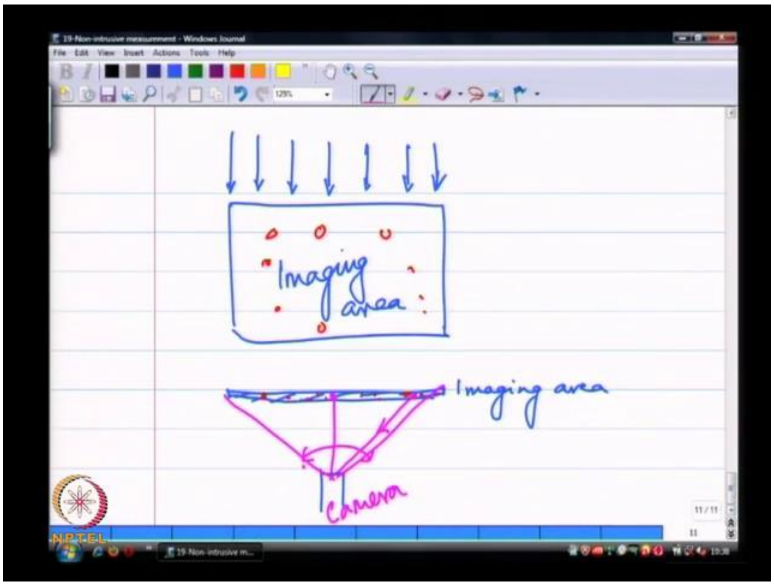

So, if I take an image like this, like I will take this blue image and typically and I am draw this out separately this so we know what we dealing with, if this is my imaging area and if this is a camera that I have, now really speaking the camera is where your eye is. So, I am going to draw a projection of this, this is my imaging area say thin light sheet and I have lots of drops inside this light sheet that is the whole idea just like these drops when projected look like this. Now drops in this edge of the image sub tend a different angle, now mind you that we are like coming in from here just like in the image I showed before.

So, if I have light coming in from your eye towards the spray in the second in the bottom image the scattered light makes an angle different from different at different points in this spray. So, the angle made by the scattered light coming towards this camera from one of the edges of the spray is different from the angle made by the scattered light coming in from the middle of the spray. So, if my field of view is much larger than the camera aperture, which is always the case it is very rare that your imaging at 1 to 1 or less than 1 to 1 magnification in a typical PIV application.

So, you are really looking at a fairly broad region in the spray and so this typical angle may not be as large as this schematic indicates, but it is surely not small it surely not zeros degrees. If the angle is nearly 0 degrees which is the case like in a microscope, you are essentially looking at this scatter from all the drops being very close to that 90 degree. So, light coming in from the top and scattering light towards the observer, where as if the light coming in from the top and there region of interest is much larger than the camera, then I have light being scattered towards the observer from different angles from at from different angles in different parts of this rectangular image.

And if you go back to this Mies scatter pattern, the in the intensity of the light observed is different when observed from different angles. So, the same size drop present in different corners of this image or in a middle of the image, would appear brighter or dimmer this is a challenge because this K the calibration constant K now becomes a function of the scatter angle alpha. So, far different points in this image, I have to know what we angle over which light a scattered towards the camera. So, I know the angle of the incident ray in some frame of reference and I know the angle subtended by the scattered ray towards the camera, I mean I am using ray tracing arguments but for now this is sufficient at least get a qualitative picture of what is happening here.

So, the angle subtended by the scattered ray coming towards the imaging frame imaging plane, the angle between these two is essentially what we saw here as this theta; this is the scatter angle. So, if I take an imaging frame like this, I need to know the scatter angle for all the points in this imaging plane. So, for example, if my camera is right about the imaging plane, the lights scattered from the top right corner of the image versus the middle of the image versus the bottom right corner of the image would be different. And I need this k at different points in order to get a quantitative picture of the total surface area distribution.

This is a challenge and can only be addressed through proper calibration. So, I populate this light sheet with drops of a given size none size and get the entire image over the frame, take the entire frame and knowing that I am suppose to get the same gray scale intensity at all points, as though I was looking at the entire image from the same scatter angle that is where the calibration constant K has to be derived. Now some of it disputes geometry where you get the scatter angle and estimate the value of K given I and d squared at that point.

There are other sort more optical effects which aberrations that have to be accounted for when you are doing light sheet imaging like this, but we want go in to that at the moment because we are only focus on sizing and velocity measurements for now. So, give if I was able to get K as a function of alpha, I have a way of taking one of the frames in a PIV imaging system and get an estimate of the total surface area in different points of the image and this I will take this surface area as indicative of this size at that point.

That is method by which we can get some size related information in a PIV.

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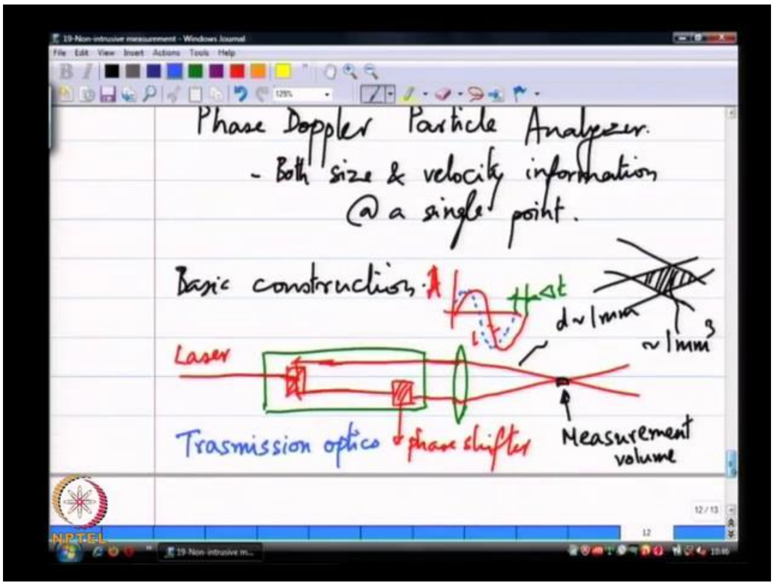

We will move on and talk about another instrument that is very widely used in particle sizing called Phase Doppler Particle Analyzer. A Phase Doppler Particle Analyzer is an instrument that measures both size and velocity information at a single point, basic construction is as follows take a light beam a laser you do require a laser here.

For PIV really you do not require a laser they have been some studies where people are used reasonably high intensity LED sources to get PIV because all I am doing is imaging I am getting two snap shots of a moving set of particles and I am not taking advantage of coherence in the light source, to in a typical PIV system the one big advantage that a laser has still is its intensity because it is a collimated and coherent light source it remains it is a very high intensity light source and intensity matters in a PIV because the if I go back for a moment, this I is a scattered light intensity really speaking I should strictly write this as I by I 0, where I 0 is the source light intensity.

So, for the same I naught if I increase I naught for the same D, I am likely to get a higher intensity of the scattered light back towards the camera, which also means that if I take a certain I naught intensity of my source light and if my camera has a thresh hold of detection, that is it is unable to sense intensity levels below a certain lumens or whatever unit you are comfortable dealing with, then that intensity level determines the size of the drop I am able to detect.

So, if I want to detect very small drops I do require a high value of I naught because I by I naught is the ratio that scales with D squared, surface area. This same applies to P D P I here. So, I take a laser of a certain intensity, these a mechanism involving some this a construction involving beam splitters and mirrors inside here, which I mean it is not really important, but essentially I create two laser beams.

And in the path of one of the beams there is a phase shifter, it is in often called a Brag cell, it is a small it is like a piece of glass if you want to imagine it in very simple terms, if I put a small piece of glass in the path of one of the two beams versus the other, I am going to shift the phase because the optical path length is proportional to the refractive index times the physical length, that the refractive index of air is one the refractive index of glass is higher in relation to the one. So, I am going to create a higher path length for one for this bottom beam in relation to the top beam.

So, that is the simplest way to think of this. So, if I take the light here, if I plot the wave intensity or wave amplitude as a function of time, if the top beam has an intensity that is look like that, on the same plot the bottom beam may be slightly shifted in intensity as shifted in phase. So, this phase shift you can call it a phase shift in time or a phase shift in phase angle, this phase shift is important we will see later. So, the moment I take two light beams that are of the same wave length and potentially even of the same intensity will come to that in just a moment, but a one phase shifted in relation to the other.

You see some very interesting thing. So, the next part of the construction is that there is a convex length that you used to focus these beams down to a single point. This forms my measurement volume. So we said a point, but it is a linear measurement volume because each beam is approximately about 1 mm in diameter, slightly less than 1 mm typically 1 mm. Now if I take two beams that are approximately 1 mm in diameter and form an intersection you are essentially looking at the intersection of two cylinders that have 1 mm in diameter.

So, this is your measurement volume and it is typically about1 mm cube. So, we this is a point measurement instrument, point that average is information over this scale of length about 1 mm. Now this part is called the Transmission optics. So, this is called a transmitter in the Phase Doppler Particle Analyzer construction. So, you are essentially consisting of a transmitter a receiver and a signal conditioning system.

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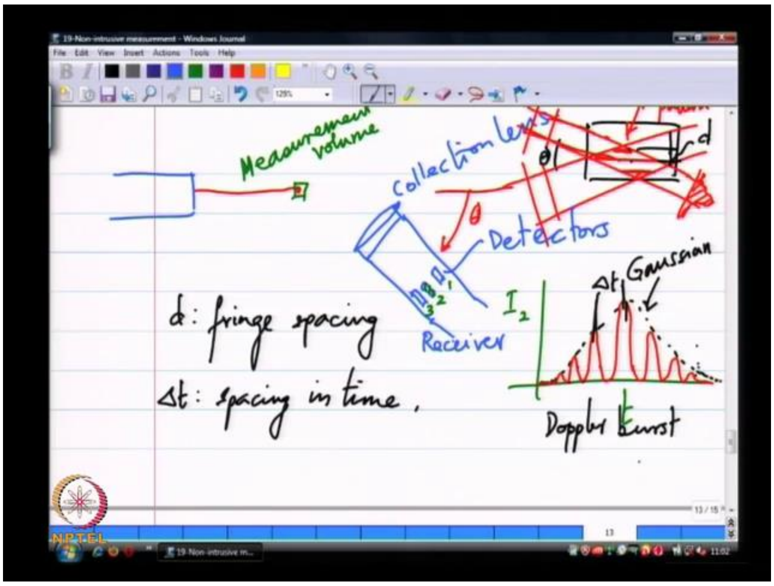

So, these are the three big building blocks, this is the transmitter and the receiver construction involves 3 detectors, that are separated physically in space.

So, I these are 3 detectors with in appropriate lens in the front, this is called a collection lens. So, in relation to this I may place the transmitter over here, now I am only going to draw one laser beam here, but should have imagine that the plane of the beam is perpendicular to the plane of this sheet of paper. So, I do have two beams that are intersecting in this way and the receiver is paced where my right hand is. So, I have two beams coming in this way and the receiver is place my hand is and so in the plane looking at from the top where I can draw the receiver.

If the receiver is as you can see slightly of angle and that angle in the plane that I can draw this receiver the two beams of light are coming in and intersecting at this measurement point here. Now if I look at the measurement volume, let me first draw a zoomed out picture of the measurement volume, I have two beams coming in and these are in essence plane waves that are shifted in phase slightly.

So, where the phase they are some parts where the phase add up, where the amplitudes add and other parts where the amplitudes are opposite in phase. So, you get essentially dark and bright bands. So, this is an interference pattern that is created due to the phase shift. So In fact, you can see this if you take a Phase Doppler Particle Analyzer and you just spay missed in to the spray in to the measurement volume, where the missed is much smaller in size than the fringe spacing or you just spray missed and look at the measurement volume where the microscope, you can see this dark and bright. So, my finger I am imagining to be the bright band followed by a dark, bright dark, bright dark etcetera that is at a fixed spacing.

The brightness of the bright band in relation to the dark band, so ideally my dark band should be exactly black should be pitch black if the two intensities are exactly equal, the 2 in the intensities of the 2 beams are exactly equal I will get the dark band to be nearly perfectly dark, the bright band to be bright. This is important because this contrast is what I am going to use for particle velocimetry and sizing.

So, if I come back to the construction, this is the part, this is my measurement volume and in the measurement volume I have fringes, in the fringes in the plane of paper here, the fringes are in an orientation perpendicular to my plane of the paper and the spray typically is coming in from the top. So, the drops are moving through these fringes and I am only going to focus on the motion of the drops perpendicular to the fringes, the component of the velocity perpendicular to these fringes. So, we will first look at velocity measurement and then coming to the sizing part.

As far as a velocity measurement is concerned, if I have a particle going through these fringes and imagine I have one detector here, sensing the light scattered from the motion of this one particle. If I plot the intensity measure by one of these detectors I will call is 1 2 3, I 2 the intensity measured by 2 as a function of time goes as I will see the drop or the drop scatters light or the detector sees the drop when it is in the bright part, when it is in the dark spot you do not see the drop.

Then again you see it is like a little spec that appears and disappears that is sort of a simple mental image that you can carry with you and in this process there is another effect that you have to understand that lasers have an intensity distribution. So, if I take one of these beams, the beam itself has a Gaussian intensity distribution. That is a middle of the beam is much brighter than the edges of the beam, this is characteristic of any laser source. Now if I take this Gaussian beam and create these fringes, the fringes that are formed at the top and bottom are going to be less bright in comparison to the fringes in the middle.

As a result the intensity pattern that we see, takes on a shape that looks like this. So, this is the intensity measured by the detector to as a function of time and this intensity profile falls in this envelop which is due to the Gaussian intensity distribution. So, every time one of these particles passes through the measurement volume, I am going to see this I 2 as a function of time this is called a Doppler burst. I am going to see every time a single particle passes through the measurement volume, I will get one of these Doppler bursts and if I know the fringe spacing which is this part in space.

So, these are perfectly equally spaced interference fringes, where the fringe spacing only depends on wave length of the light and this angle of incidents; so this theta and lambda the wave length of the light, something to that effect. So, if I take this fringe spacing and place it, if I know the fringe spacing and if I know the time separation delta t between one peak in the Doppler burst and another peak in the Doppler burst, we are able to then calculate the velocity.

So, if I know the fringe spacing d and spacing between the peaks in time we are able to estimate the velocity of that particle, but in reality the way this is done is one of these Doppler burst is sampled at some fairly high frequency. So, I have the intensity measured by this detector to at various instance of time. If I do a fast fully transform of this Doppler burst, there is a particular frequency in time that shows up as a peak frequency and that peak frequency before we do that, In fact, the before you do any sort of a fast Fourier transform.

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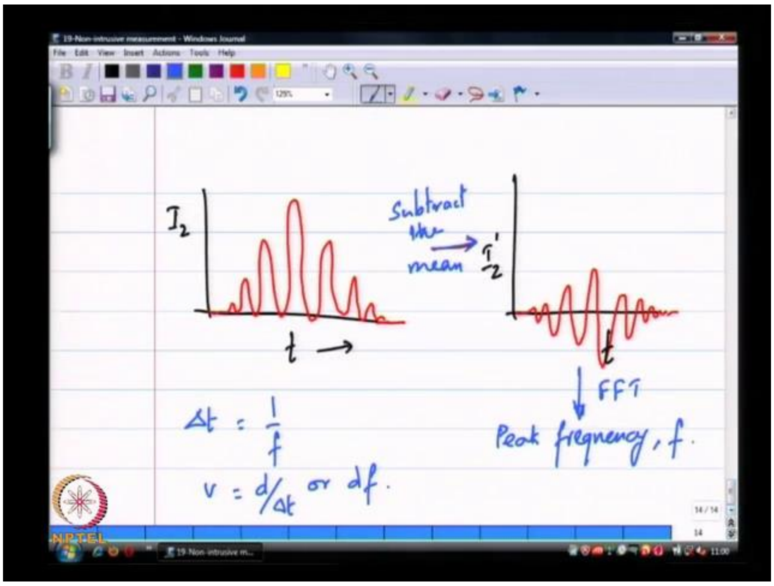

This intensity I two versus time is converted in to a profile where the mean is subtracted. So, you get something that looks like this.

If I subtract the mean intensity over this entire data set I will get something that looks like this and now. So, this is let me write down the different steps, so the first part is really subtract the mean, the second part is where you do an a FFT of it and in the FFT you get the peak frequency and from the frequency, let us say this I call this f delta t then is simple 1 over f, forget the peak frequency that frequency 1 over that frequency gives me delta t, in the velocity of that particle is this d over delta t or d times f, d b reference spacing.

So, this is a point wise particle wise measurement system. So, I get a velocity measurement of every particle passing through the probe volume and if I by chance have more than one particle passing through the probe volume at the same. So, if the over lapping time in terms of their residence inside the probe volume I will not get this clean sort of a Doppler burst, I will get some image that does not have these clear peaks because I may get a peak from a particle up near the first fringe, while the previous particle is still inside the probe volume and that causes a problem to the instrument.

So, typically it looks for a certain feudality in the Doppler burst before it does the FFT. So, the peak in the frequency should be a very clear peak in relation to everything else. So, these are all part of the signal conditioning and signal processing algorithms in the instrument, but essentially it can only measure it is hard wired to measure the velocity of one particle at a time. So, there in lice a very simple limitation that I cannot take this instrument very close to the spray nozzle, where I am increasing the probability of multiple particles deciding inside this 1 mm cubed volume, at the same instant of time I can only use this instrument sufficiently far away where the particle density is about one particle per mm cube that is the density at level at which particle number density level, at which we can safely operate this instrument.

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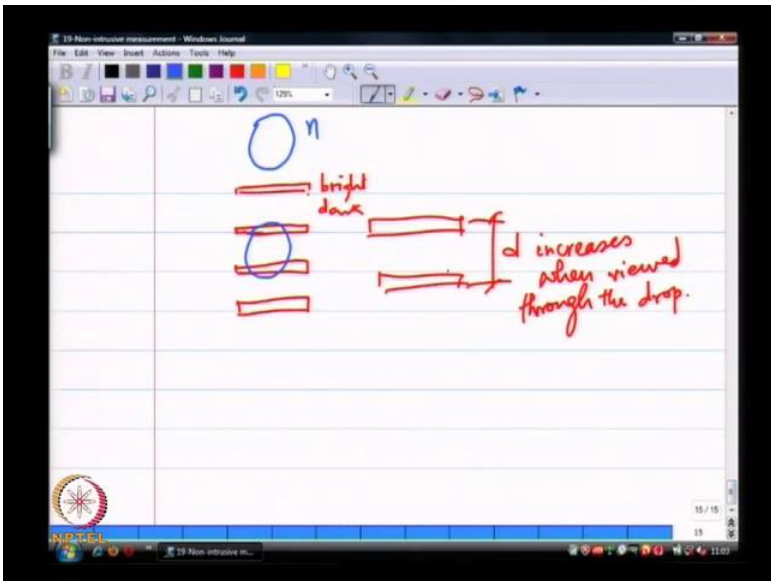

So, that is the basic method by which one can estimate the particle velocity. Now far the particle size the way this is done is if I now draw out the different fringes, I have these bright and dark spots. So, this is the bright and this is the dark fringe, if I take a drop you are say a drop that passes through these drop of a certain refractive index, pass through these fringes. So, I just quickly super pose the drop on here. Now if I was still look at these bright and dark fringes through a glass sphere.

So, I am going to just to understand what it looks like, if I look at this static bright and dark fringes through a glass sphere, the spacing between the fringes would appear different. That spacing would essentially so if I look at it from through a glass sphere, this placing would increase through the drop. So, if I now go back to my transmission optics or receiving optics sorry this is my receiver, if I go back to the receiving optics I have these fringes as the drop goes through this fringes, the receiver is seeing scattered light coming in the refraction mode or the forward scatter mode, coming towards the receiver and the fringe spacing that the receiver sees.

Increases based on both the volume both the size of the drop and the refractive index. So, if I know the refractive index of the liquid being spread, I can get the size of the drop. You can do all you can do this increase in fringe spacing also through sort of rate race optics, we needs to just to get a feel for it, but essentially one can understand that the fringe spacing is now higher, when viewed through the drop. So, the previous argument that we looked at where I took I 2 the intensity observed by 1 of the 3 detectors and from just that one detector I am able to get the velocity information, but I need to know the fringe spacing. If I now have this transparent drop, I do not know the size of the drop, but I do know the initial fringe spacing without the drop, that is from the geometry of the intersecting beams.

So, if I take the fringe spacing to be a function of the refractive index and the drop size and I have multiple detectors. So, really speaking I only need one more detector, if I know the intensity versus time Doppler burst pattern on intense on detector 1 and then detector 2, I can saw I have two different Doppler bursts from that I can get both the size which is the fringe spacing as well as the peak in a frequency which is related to the velocity; so really speaking, if I have 2 detectors that give me enough information to calculate both the fringe spacing and the velocity independently knowing essentially the phase shift in this Doppler burst.

In other words when a particle passes through the probe volume, detector 1 which is spatially separated from detector 2 inside the receiving optics, sees the Doppler burst at a slightly difference phase, the 2 detectors see this at a slightly difference phase from that phase difference between I 1 and I 2 as well as the peak in a frequency from any one of the 2 detectors, we can get both the fringe spacing related to the size and the droplet velocity related to the peak frequency.

In a really PDPA; however there is a third detector that usually incorporated to get what is called a validation procedure. So, we look in to that at the beginning of next lecture, where we look at why the third detector is needed is this essentially needed to make sure that you are seen light only in the refraction scatter mode and not any part in the reflection scatter mode..

So this is important, and the third detector is there to ensure that among other things. Now this is the basic principle of operation of a Phase Doppler Particle Analyzer, if you remove the sizing part, this is also the basic principle of operation of a laser Doppler velocimater LDV the basic and of a 1 component LDV. So, we are only measuring the component of velocity perpendicular to the fringes and any velocity in the in a plane that is not perpendicular to the fringes either this way or this way is ignored.

So, if I now create fringes in the other two planes, we can get three components of velocity independently. We look at that in the validation algorithm with the beginning of the next lecture.

Thank you.