Introduction to Biomedical Imaging Systems
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Lecture - 39
Beam Steering: Phased Array

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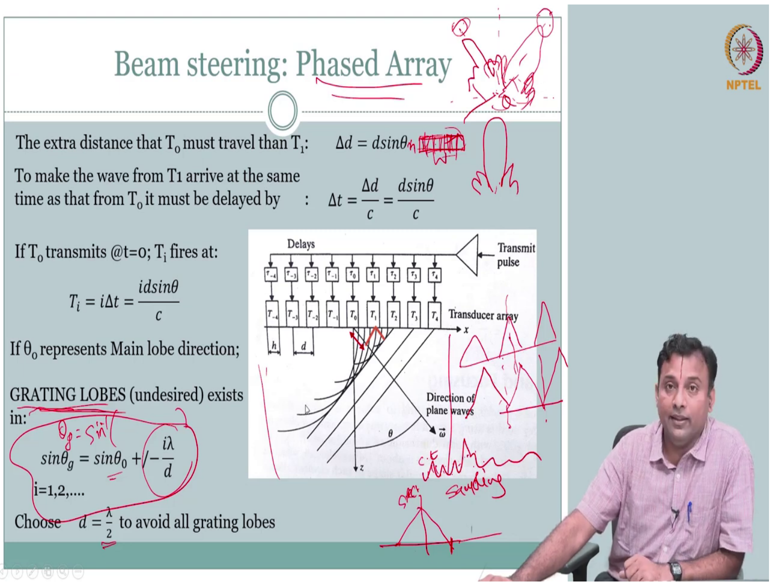

So, Beam Steering in case of a Phased Array. What is our problem? This is the problem proposition. I have an array I call this transducer element 0 just for symmetry purpose right transducer 0 is the centre element; transducer 1, 2, 3 are all on the one side minus 1 minus 2 minus 3 all on the other side ok.

And this is tau I do not know with the resolution you are able to make out this is the tau and not t. Tau is a very generic variable that we always associate with the time delay and therefore. So, from what we saw already? Each of the element can have its own time delay unit right.

So, you could have tau 0, tau 1, tau 2, tau 3 and so, on corresponds to each of the transducer element. The transducer element itself has a dimension. So, you have a h is width of your transducer and d is the distance between centre to centre centre of the element to the centre of the element which is also called as a pitch ok. So, this is an important jargon that you will pitch is an important parameter when you choose a transducer and design of your beam forming ok.

So, pitch is d what else do you have? This is your z direction this is your x that is the length direction of your transducer. So, you could have your transmit pulse can be given to each of the transducer element separately with the its own time delay.

So, if you take a situation here where we are sending this plane wave it a particular direction theta right. So, the plane wave is now travelling at an angle theta. So, we are interested in beam steering. So, we have taken arbitrary angle theta the direction in which you are now wanting to send your waves your plane waves right you want to want it to go in that direction.

So, how do we calculate? So, problem proposition is how do you calculate these tau values such that the waves will go in the direction theta right. So, looking at it what do you see? Let us assume that the speed of sound in the material is c right let us not worry about any other value. So, this is an important aspect.

Most of the scanners are calibrated with c which is the average tissue value of 1540 meters per second ok. If you are not given anything you could assume it is 1540 meters per second.

But the idea is by see in the medium is taken for granted now right ok all I have control over the time because I am exciting it right. So, which crystal what time I am exciting I have a control. So, if I want to do this right what should be the relationship between the delay values of the successive elements or what pattern of excitation should I have for each of the transducer element ok.

So, looking at this if speed is same right you want time, then you know the relationship between speed and time you have to have some distance right. So, look at this. So, if I want to this plane right this plane has to go like this; that means, when I excite transducer T 0, it sends outs a wave if I excite T 1 that sends outs a wave if both of them have to be aligned come along this line the phase fronts I have to form a line right.

Then the idea is what is the distance right? What is the distance that is different or the path length right we do not call it distance usually refer it to path length path is the you know path with the wave is taking, length is the length in that direction path length that a wave takes from T 0 to come here and path length that this T 1 from here it comes here what is the difference right?

So, T 1 this is the distance. So, if you take that you have a T 0 right if you have to T 0 has to come here the wave that is excited at T 0 has to travel this extra path length so, that the wave from T 1 and T 0 fall in the line right they all arrive at the same time to form a line.

So, this is the extra distance extra path that has to be travelled so, that you from T 0. So, if it has to travel this much another way to look at it is; that means, I will have to wait exciting T 1 right I have to transmit use my T 1 delay it until the wave that is excited at T naught comes this distance then I have to excite this correct.

So, let us write it down. So, let us write down the extra distance that T naught must travel than T 1 that is this guy right. This is the extra length this wave has to travel from T naught that is going to be what? You have your theta here right. So, you can quickly and then you know the centre to centre distance which is your d.

So, I know my d, I know my theta. So, I can relate d all I need to do is this extra length what is that right? That extra length delta d is d sin theta ok. So, d sin theta. So, if this is the extra distance that it has to travel what is the time it takes to travel? You know the velocity c. So, it is that to make the wave from T 1 right arrive at the same time as T 0, it must be delayed by the time for this wave to go this much right delta d. So, your delta t the delay should be delta d by c or d sin theta by c ok.

So, this is for T 1 right, but the same logic I can have for all the others T 1, T 2, T 3 or T minus 1 t minus 2 T minus 3 all of them the logic is same. So, if I if I excite this I have to I have to excite left even further even before T 0. The T minus 2 should be excited even before T minus 1. I have to excite each one of them slightly ahead so, that the angle of steer. So, this it is all steering in this direction correct. A the left guy the left element must be excited first than the second element. If you do the opposite case it will you can steer it the other direction right minus theta.

So, point is ok this is fine what do I do for any. So, if T naught transmits at t equal to 0, T i fires at right we can generalize that T i is i delta t. So, your id sin theta by c clear. So, this is your time delay. So, you could actually think about. So, if this is the main lobe right this you have accomplished you have accomplished steering right. I want to now I can change whichever direction depending on the theta I can manipulate my excitations for each of the crystals right each of this will be a separate channel. So, you could do delay corresponding delay you can code and you can execute this very neat right.

Of course, the only challenge that you need to worry about is when we talk about direction of steering we are always worried about grating lobe. What is grating lobe? Again this is a very tricky concept very powerful important it plays a it kind of dictates some conditions for certain realization of arrays. So, it is very powerful.

But just to give you. So, in a in a full course on ultrasound I would typically go into full detail on this, but just for the purposes of introduction and not letting this word go without some 30 second intro right that will be that will be kind of doing injustice.

So, what I will do is just think you I mean make you think of an analogy right analogous situation maybe then it will be easier for you to appreciate what I mean by grating lobes. You know main lobe right main lobe and side lobe just for the purposes recall your antenna pattern right. We said this is your main lobe and then your side lobes were like this right. So, it has to do with the direction for example.

Now, if I want to steer; that means, at some angle; that means, I am going to have this is rotated right this is going to be rotated let me just draw for the sake of right that is going to be my angle. So, now, that is some theta ok. So, the problem is when you are trying to look at this direction theta and you are trying to send the signal in theta direction whatever you are going to receive right you are going to think that it is coming only from theta direction.

The problem with of course, there is the small side lobes, but then we integrate over the side lobe. So, we you know it is just reducing the signal quality, but it is ok when it is a problem, but side lobe we know how to do apodization to minimize its effect. But grating lobe is a problem because when I am looking at this direction, what if I have another cousin of this main lobe at another angle right.

If I have same pattern side lobe right you have another if I have another main lobe and side lobe, then I am actually thinking I am sending in this direction, but the wave is also going in this direction if that is the case now I am caught I might be completely wrong right I might think.

So, there is some target here for example, I am thinking I am sending it steering by whatever theta and whatever I am receiving I am saying there is a big obstruction at this location. But it turns out that even though I sent my theta this direction there was additional lobe which is called as a grating lobe that actually was in another angle and the object was in that angle.

So, this reflection came I was I have basically coded it wrong right. I am registering this object to be here because of the grating lobe. So, this could be problem, but then you might wonder why did not we cover this in physics right. Why did not we cover this in the physics where is this suddenly coming from? We thought we were very careful in talking about wave equation and we solved example wave I mean example solution using your cosine theta or right a sinusoidal function how did this get through.

So, challenge is here when you do all of signal processing we talk about analog first right. So, we have some signal right some signal what is the frequency spectra of the signal? Ok you get something right this is your frequency spectra ok. And the first lecture that you do in digital signal processing is this is the continuous signal it has its sum spectra first concept that you get to is how do I sample sampling. When you do sampling major concept is your nyquist sampling criteria.

Now I am this is time signal if I sample it I have to sample is how fast? I have to sample is sample it at least twice the highest frequency. If this is the spectra right I have some highest frequency I will have to sample it at least twice that highest frequency then right this is continuous time spectra f of t.

Have you after you do sampling right how do they explain aliasing? You have spectra, but now when you sample the Fourier transform of the frequency domain is going to have copies of this right. So, you want to sample so, that let me just for sake of clarity not draw here another spectra.

Now this is of the discrete samples your spectra is going to be right this is at nyquist, you sample it much higher than the nyquist the there will be separation right you can have one and have. So, essentially you have copies of your spectra right. So, when you under sample when you go below the nyquist you will have overlap and so, your we call high frequency masquerading as low frequency right all these textbook definitions.

Practically what is happening? Practically you have replicas of the replica of the fundamental spectrum. When you sample it you have to sample such that it is not going to overlap ok. So, this is what you know from your basic time based 1 d digital signal processing.

However, here what are we sampling right? In imaging its all about space. Now imagine we have what we covered so, far for main lobe side lobe is just one transducer right we had a width right we had a width and then let us not worry about elevation. So, there was some height. So, do not worry.

So, if you look at the rectangular transducer that we put we put 2 beam pattern. So, let us just take the width which is are in our imaging plane right it is in our imaging plane you take this width. So, this is your element that we had before. Now this single piezoelectric crystal is spatially sampled right; that means, I have different crystals each sampled. So, this is spatially sampled crystal clear.

So, instead of one crystal for which I know you get a pattern like main lobe and side lobe, now I have sampled it I have picked right different spatial locations. So, I have one crystal here another crystal here another crystal here. So, I have samples I have different crystals at different locations right. So, I have made it from one continuous piece of crystal to multiple discrete crystals each spatially at some spatial sampling each located at some spatial location right. So, what would you expect? If that is the case I would expect I will have copies of my Fourier transform.

Remember the far field of your the beam pattern that we talked about the far field was your Fourier transform of your aperture. So, now, if I sample my aperture what should I get in my beam pattern? Copies right. So, if I sample very well that is greater than your nyquist I should have this not overlap right I should have multiple copies, but the other copy should be small right.

So, in order to avoid this grating lobe there is going to be a constraint on how will you sample the sampling here the parameter is d right how close the two elements are how close the two elements are is going to dictate whether you are going to have copies of your main load and side lobe. This copy of main lobe and side lobe is called as your grating lobe ok. So, I will just leave it at that you can have your own imaginations of what it is, but that is the very powerful design constraint ok.

So, you can have your grating lobe sin of grating lobe to be sin of theta plus or minus, d is not a surprise because it is the spatial sampling parameter right. So, it has to come somewhere note. So, i is your element location notice it is in terms of lambda. So, lambda by d.

Why is this important? Because if this if this gives your grating lobe. So, this is i equal to 1 or 2 is your first grating lobe or second grating lobe ok. So, ideally what do you want? I do not want any grating lobe at least I do not want any grating lobe in the imaging direction. If I have my transducer here right if I have my transducer this way, this is my imaging direction.

So, I do not want this is my body my transducer is at the surface of the skin. So, at the least I do not want any grating lobe within the imaging region or at the forward region correct. So, if that is the case I can eliminate grating lobe how can I eliminate grating lobe? Because this is sin theta. So, grating lobe will occur at theta g will be occurring at sin inverse of this quantity.

So, you would want this quantity if it is greater than 1 right. You do not have grating lobe how do you make that? Look at this guy. So, sin theta 0 is sin theta 0, but look at this guy. If I choose my d to be lambda by 2 then I can avoid all grating lobes now you understand why this array is called phased array. So, it turns out phased arrays are arrays such that the d is lambda by 2.

Now, you see the problem higher the frequency I get better resolution lower the lambda. So, you need to have spacing to be lambda by 2. So, you see the intricacy in if you having a high frequency high sampled aperture right. Then you have to have the corresponding electronic so, that each one can do. So, it quickly becomes very sophisticated. Nevertheless, this is invoke this is very popular right. So, it has certain applications where you need to have no grating lobe clear.

So, we will stop the idea of grating lobe here, I guess you get the feel. So, you should be able to calculate one from the other, you should be able to calculate grating lobe angle if the position is not d, if the separation is not d what happens, what when you change lambda what happens right all this can be worked out ok.

So, this is for beam steering. We need to also do focusing right that is our other big objective.

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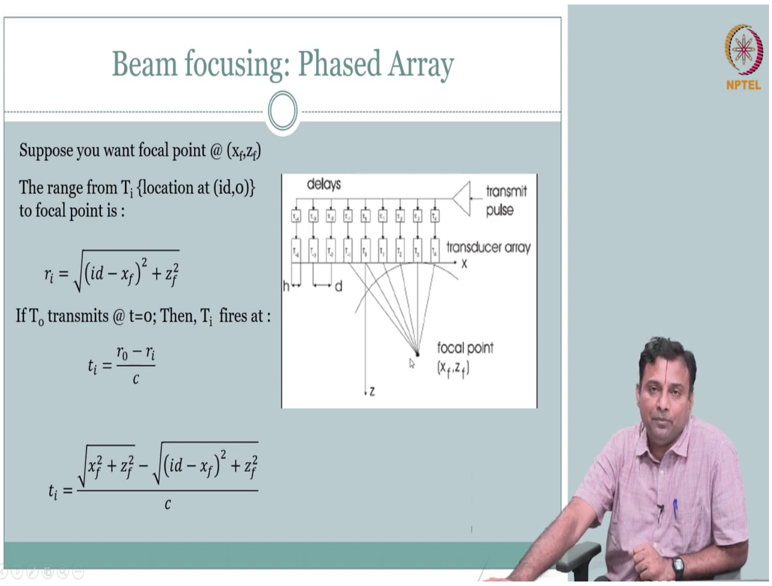

So, how do we do focus? Take a point where you want to focus arbitrary some x f comma y f. This is your imaging plane x x z is your imaging plane you have your point. So, now, the objective of focus is I want all the waves to come at the same time coherently at this location right. So, same logic you have different crystals each one has its own time delay that you can control when you can excite them.

So, now the calculation has to be again what is the extra path length that each one has to travel right. So, clearly if you have to arrive at this point the closest needs to travel the shortest the farthest need to travel the largest distance right and so, the range from T i any location here id is any location T 1 T 2 T 3 T 4 T minus 1 minus 2 any location id is here 0 is it is at the 0 z is its at the surface to the focal point is what? You can calculate r i as square root of id minus x f square plus z f square clear.

So, this is the path length if you will right r i from each of the transducer element to the focal point; however, what are we interested? We are interested in time delay between T 1 and T 2 T 2 and T 3 and so on and so forth right when should you excite each of the crystals.

So; that means, you have to have path length is one criteria. So, if you assume T naught transmits at t equal to 0, then T i should fire when should it fire? It should fire to compensate for this r 0 minus r i by c the path length the extra path length right that is your and path length by c distance by velocity is your time clear. So, if I do. So, I can generalize this. So, I can generalize t i is equal to r naught is x f square plus square you have your r i by c clear.

So, so far so good. So, this is what you need to do intuitively we know that the shortest distance will be delayed most the one the element that has to that is farthest away should probably be excited earlier right that way they all can come at particular location at the same time ok.

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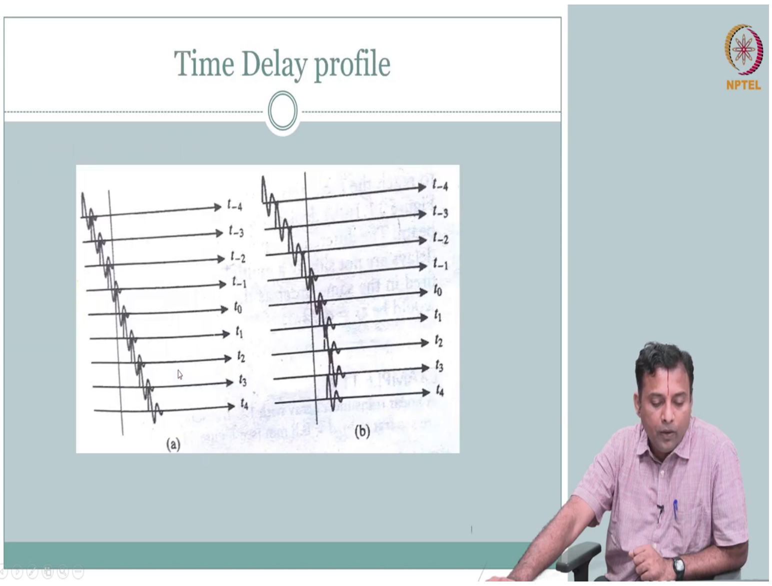

So, if you were to plot the time delay profiles, this is how it will be for steering it was a linear whereas, you see when it is focusing it is a parabola ok you had a x square term right. So, the parabola. So, clearly you can do combine steering and the focusing which is how. So, we can do whichever.

So, your time delay that you are doing, the only thing you have to take care is negative time delays are not realizable. So, you can always have a say you cannot t equal to 0 we said, you cannot physically realize you have to have everything in positive delay. So, the most negative delay that you calculate, you have to give that as a bias to every term then you can get a physically realizable relative type delays ok.

So, you can see that you can realize both steering and focusing by combining the time delays right. Steering alone is only linear the distance right linear with respect to each of the element the time delays are just multiplied right delayed whereas, here that is not the case ok. So, this is for transmit.

So, I know I have sent the wave in a direction I want with a focal with a specific focus, I have sent it now what do you do? So, this is your transmit beam forming if you will what do I do now? Now I need to do the same thing with respect to receiver ok. So, here I delayed and then transmitted now I am going to get the echoes once I get the echoes I should probably do similar thing right.

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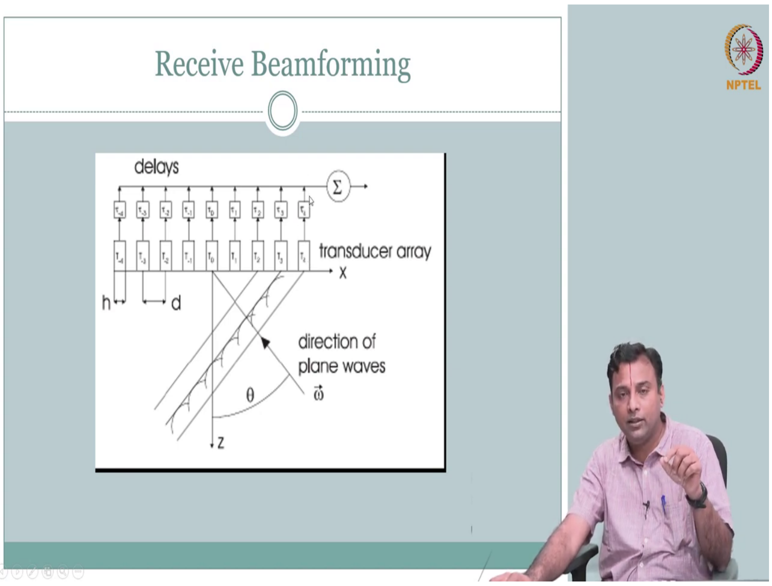

So, what we call as receive beam forming. So, you have the echoes are coming back right if you send the plane wave the echoes are going to come back and you could do this reverse of what you did already. So, here this is what is going to go to your ADC. So, each channel will have a corresponding analog to digital converter. So, you have this tress transducer.

So, one has one signal right transducer 2. So, each one is receiving the signal straightforward apply the delay, the earlier one this you got you have to delay more until you get the last one right same profile that you got for transmit inverse of that which one was delayed there most will be least delay here you can get the thing right get your receive data. So, we will just do it for focusing as well. So, dynamic focusing.

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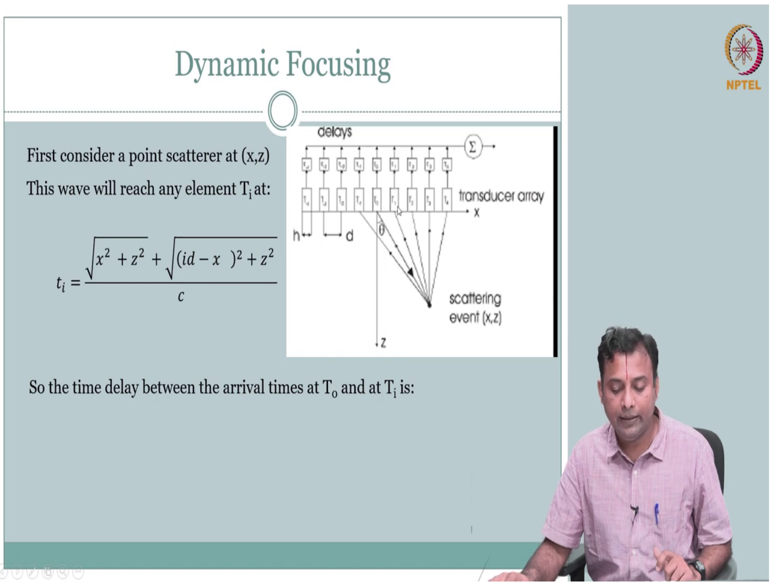

So, dynamic focusing one another same thing take that same x of f now only thing is now the arrows are point at the other direction. So, if you pretend now after the transmit beam came it hit this point object right at the focus and it is now sending the waves back right. So, there is going to be a wave component that is going to hit this transducer, it is going to hit this element, this element each one at different times because the path length is different.

So, straightforward we write similar to what we did first consider a point x comma f, this wave will reach any element t i at t i your x square plus z square plus the extra path length right divided by c. So, if you if you care this is very similar this is actually same as your transmit with only thing is here we put a plus there it was a minus ok or the same two components are there right.

So, you have your t i then what is the point? I know my time arrival what is of interest time delay is of interest right. So, I can time delay between the arrivals at T 0 and at T i right T 0 and T i any location.

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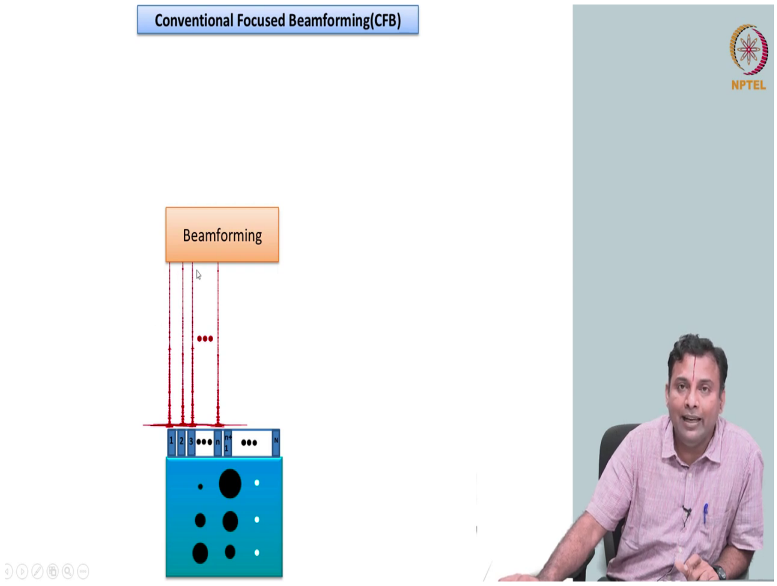

So, we call this as focused beam forming conventional because most of the scanners employ this methodology. So, here is a linear transducer array elements labeled 1, 2, 3 up to n this is your image this is the ideal object that you want to image. What do we do here? We excite few crystals I know how to do this right focus elements are exactly the time delay calculation that you did for your phased array. Just that the theta is 0 here right.

So, you can excite with the delay value that is computed so, that you get focusing at the centre of this aperture what we call as active aperture. What happens when you send it like this, you get echoes back. Once you get echoes back all the echoes are hitting all of the active transducer elements you get time trace right this is what this is the a signal that we got amo amplitude. So, each crystal now peaks.

So, the advantage of using array transducer is, I have each of these as a separate channel. So, now, what can I do? I will go do my beam forming what do I mean by beam forming? I will employ the time delay I just calculated the time delay for right receive beam forming same thing I can apply here. So, each one will be right delayed depending on which location they are, I will do beam forming delay essentially delay compensation.

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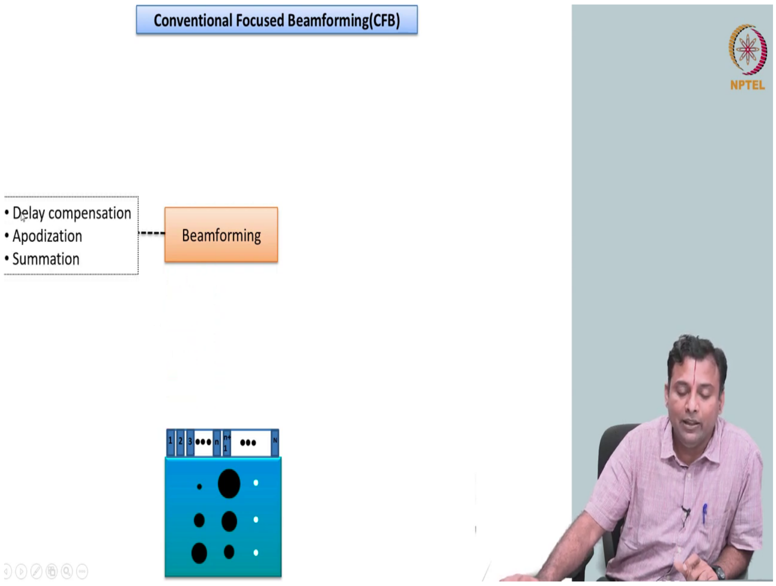

Delay compensation apodization right I can do my apodization just waiting each of it is a window function right. So, I can do apodization and then sum them. So, this is a typical D A S is a typical beam former that is there in majority 90 95 percent of your scanners ultrasound scanners employ D A S beam former delay compensation apodization summation.

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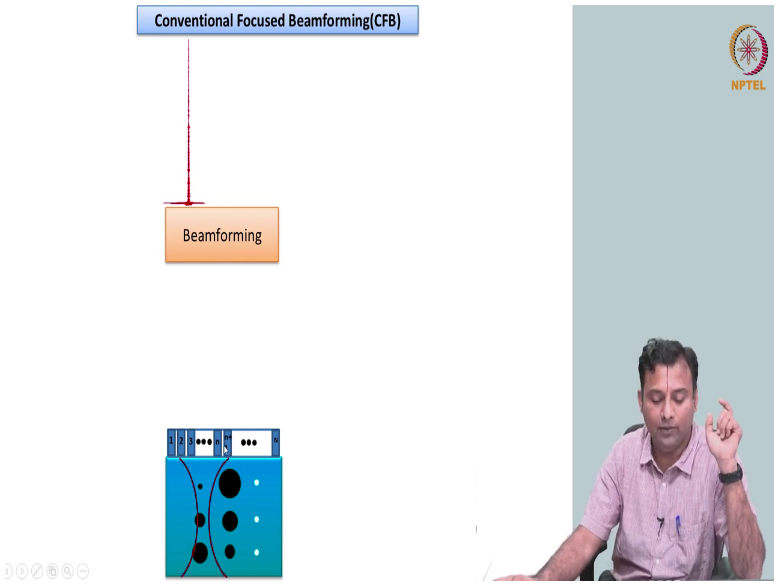

Do that you get one line now which is aligned to the centre of the active aperture. Now what do I do? I need to scan from this is just one a line. If you had a single transducer element this is exactly what we got these all happened we did not have control anything that falls on the surface were summed and what you received was only one line.

Here we have we are doing it explicitly only thing is we are able to compensate for the time delay because each one has a control separate control. I have one a line trace this is called as post beam formed a line ok. So, I have only one line how do you how do I get an image? I do repeat the process now I will translate right 2 to n plus 1.

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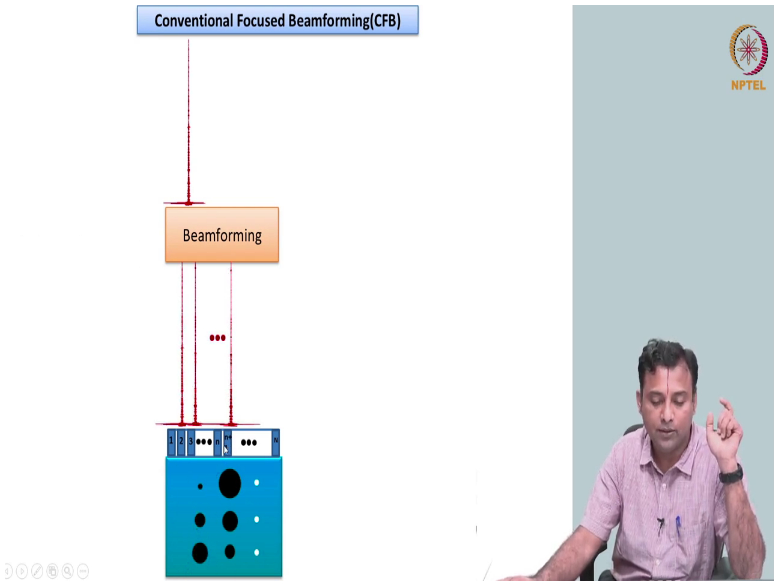

Do the same process get the next line.

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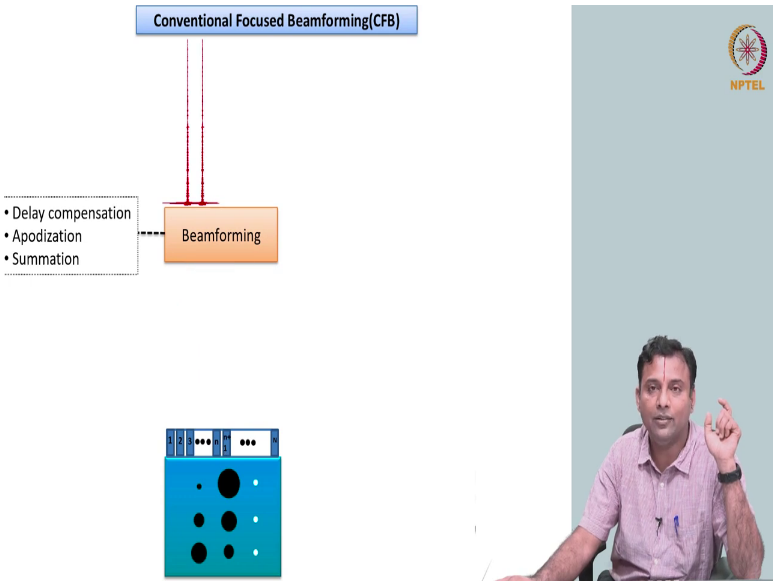

So, this is my scanning I am not moving physically right, but my electronics is translating the active aperture. So, this is electronic translation. So, electronic steering if you want to call it right mechanically we are not doing it.

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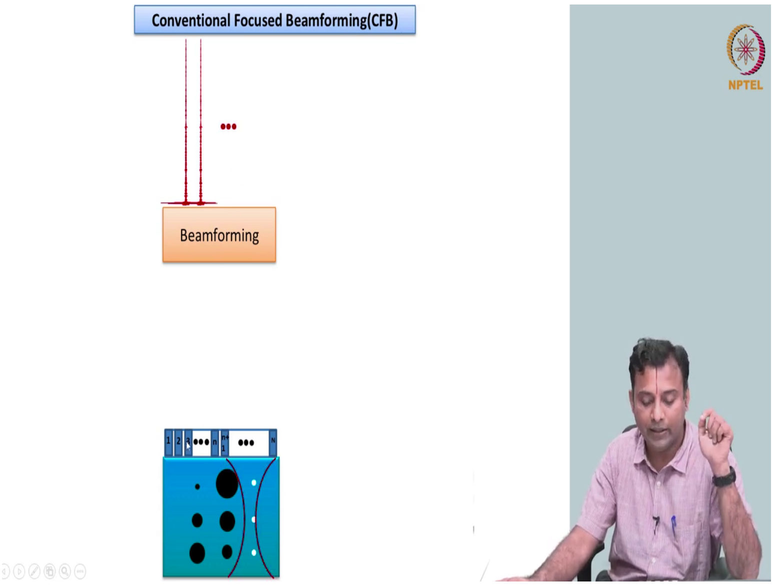

So, you can do this so, on and so, forth till you reach the end.

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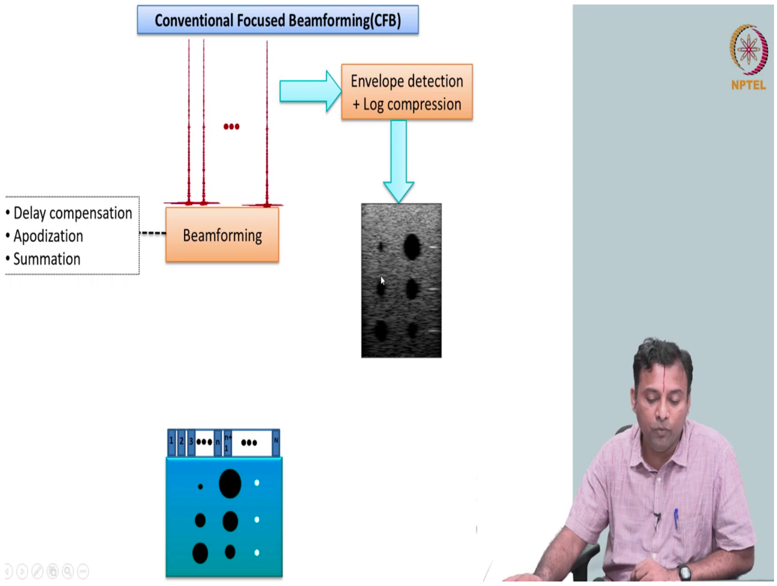

So, now, you get the image data beam formed image data this is the depth direction this is your width direction what do I do? This is raw data. What am I interested in image? Its a brightness image. So, I need envelop and then color code right. So, I will do envelope detection.

Log compression just so, that you can see you know few strong points not saturate the image. So, we do log compression envelope detection log compression if you do magic this is the image that you get just by this operation right. So, this is the ground truth image, this is your ultrasound image b mode image brightness sonogram whichever you have heard it.

So, notice more or less the structure is there, but it has its own. So, the resolution you can see that its becoming difficult to see here this round is now not really round because deliberately it was stopped in the end ok. So, if you use a much more sophisticated signal processing do other things, we could improve the image quality further. But the idea is you know now you are visualizing hopefully, how we start with the physics have instrumentation, how do we manipulate the instrumentation in the digital beam former case to get a image ok.

So, we will I hope this gives you kind of a good picture of what you know the big overview. A lot of details it is a separate course in itself I do not want to drag this further, but I think we have covered enough that you get if you look at this particular value, I hope you will be able to know this is the reflectivity that he was talking inside here there is no scatterers.

So, there is no reflection that is coming. So, that is this point, here you have high scattering region. So, that comes as white. So, the impedance mismatch right that is distributed there is no scatterers here. So, there is no impedance mismatch here. So, there is no echo coming from here. Here is a huge impedance mismatch and therefore, strong echoes come from here.

So, you can now and then look at this black and white texture that you see that is your speckle ok. So, I think you get hopefully get a hang of how this is. Now this is straightforward this you can now do it at steering angle you can curvilinear you can excite do the same methodology right you can get the image.

So, all other things if you understand this idea of how to calculate the time delay profile and keep in mind the wave propagation how it is happening, then you can actually you know jump into putting all the pieces together and form an image ok. So, last part that just for the sake of completion I want to highlight is the Doppler principle.

So, from the image point of view we covered what we wanted to cover, but the extra functionality we talked about Doppler, we are not going to cover Doppler signal processing itself is a whole chapter in itself here we will not do it. So, we covered the physics.

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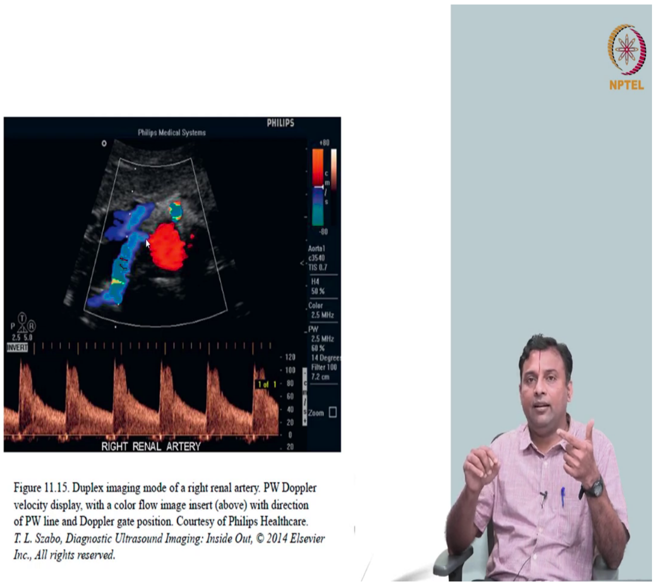

So, I will just show you the output how it is typically use. So, you know how this gray image is formed right your B mode image. So, after you see a B mode image you know where all right some flow is going to be. So, what you see here is what is the duplex image wherever there is velocity the velocity using Doppler principle is calculated color coded and it is overlaid on the B mode.

So, you can see the color bar is centimeters per second again like I said if it is flowing towards the transducer it is one color flowing away from the transducer is another color. So, what you also see is there is a that is called as range ranges right ranges distance, gate means range gate. So, within this range gate that whatever is the FD remember we calculated FD frequency shift Doppler shifted frequency.

So, your Doppler frequency right this is plotted here FD within this small window in this range gate because there is flow if you take the data r the radio frequency data right that we call the echo data only from this region and see how with the time the frequency is shifting right the Doppler shifted frequency if you plot that this is what it is ok.

So, this is the velocity from your Doppler shift. So, what we use here is your pulse wave Doppler because we are using pulse echo. So, its pulse wave Doppler velocity display with a color flow image insert. So, this is usually the color flow image they call.

So, the concept of Doppler is there you fuse that with the challenges of scanning right and registering it with B mode you can in principle get this color flow imaging. So, you can see where is the flow, how much is the flow, which direction is the flow pretty neat right so, but we will not cover I mean that is going far beyond the scope of this introductory material.

So, we will stop here I think we did justice to the modality because this is just touching giving trying to give you a big picture over you at the same time make sure some elementary concepts you are aware of. So, physics we covered, reflection coefficient right your medium snells law those things should come to your mind speed of sound, material is needed for sound to propagate unlike your electromagnetic waves right. So, your lambda is an important parameter, the length wave number.

So, these are some physics that we covered. And then we talked about instrumentation, but primarily we focus on the transducer right transducer backing material, but predominantly it was going to be with the resident frequency, crystal size and shape and beam pattern. So, beam pattern transducer shaping right that is something that we covered.

And then we came up with imaging we covered four different modes A mode B mode M mode and we covered three; there is there are other modes as well C mode like how you did compute computed tomography same thing can be done with ultrasound right you can have one transducer on one side you can have another transducer on the other side through transmission we have not covered that. But most popular among them is your B mode and combination with your M mode and Doppler ok.

So, that is what we covered. So, take home message for the last part is your beam forming time delay profile, how do you derive design the time delay to accomplish focusing and steering and the idea of apodization incorporating apodization and doing this focusing also dynamic receive focusing.

I think if you get a hang of this; this is the good point to stop the introductory material, if you are really excited if you are happening to work in the area of ultrasound perhaps, you will find the future course in ultrasound dedicated to ultrasound you know ultrasound imaging alone. I I recommend you to read that further or take that course in the future. So, for now for the purposes of medical imaging system we complete this module of ultrasound right here.

Thank you.