Principles and Techniques of Modern Radar Systems

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Lecture - 60
GPR Measurement and Microwave Tomography

Key Concepts: Working principle of GPR, basics of microwave imaging, A-scan, B-Scan, C-scan, applications of GPR

Welcome to this NPTEL lecture on Principles and Techniques of Modern Radar Systems. We were discussing ground penetrating radar so and we have seen the theory behind that.

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Electrical Properties of Geological Media

Material	Dielectric constant	Conductivity (mS/m)	Velocity (m/ns)	Attenuation (dB/m)
Air	1	0	0.3	0
Distilled water	80	0.01	0.033	0.002
Fresh water	80	0.5	0.033	0.1
Sea water	80	30,000	0.01	1,000
Dry sand	3-5	0.01	0.15	0.01
Saturated sand	20-30	0.1-1.0	0.06	0.03-0.3
Limestone	4-8	0.5-2	0.12	0.4-1
Shale	5-15	1-100	0.09	1-100
Silt	5-30	1-100	0.07	1-100
Clay	4-40	2-1,000	0.06	1-300
Granite	4-6	0.01-1	0.13	0.01-1
Salt (dry)	5-6	0.01-1	0.13	0.01-1
Ice	3-4	0.01	0.16	0.01

Now, this electrical properties of various geological medium, you can see in the slide. So, here the important thing is you see that the water has a dielectric constant of 80. Now that is very important whereas, dry sand it has a dielectric constant of 3 to 5 and you see that various minerals etcetera. They are from 2 to 6; they vary, but water is present everywhere.

So, if the water gets mixed with any geological material, the dielectric constant increases much and that actually gives a contrast between the ground because sand etcetera. You see is that ground also is 4, 5, 6. This is the ground a thing, but if any water mix thing is there; then the ground penetrating radar can detect it. Well, now conductivity wise you see that water has a very low conductivity, but sea water where lots of mineral salts etcetera are present that has a good conductivity. Now that is why it is very lossy and under water you cannot detect by GPR or other radar techniques etcetera. So, these are the things and this shows that the moment you have some permittivity the velocity of the electromagnetic wave changes in air, it is one dielectric constant one. So, that is why this is the velocity of light. Remember this is meter per nanosecond.

So, it is velocity of light, but the moment you have water of 80 dielectric constant. You have these it has been reduced to almost 100 actually that relationship is mainly root over eighty. So, 81 mean 9 so, basically 9 times almost this is yeah. So, for all others you can see that and also this conductivity. So, it makes the thing lossy and so, there is an attenuation. As the wave propagates 1 meter, how much dB it gets attenuated? You see this so; that means, depending on the medium, you will have to now understand that what type of signal you will receive from the GPR.

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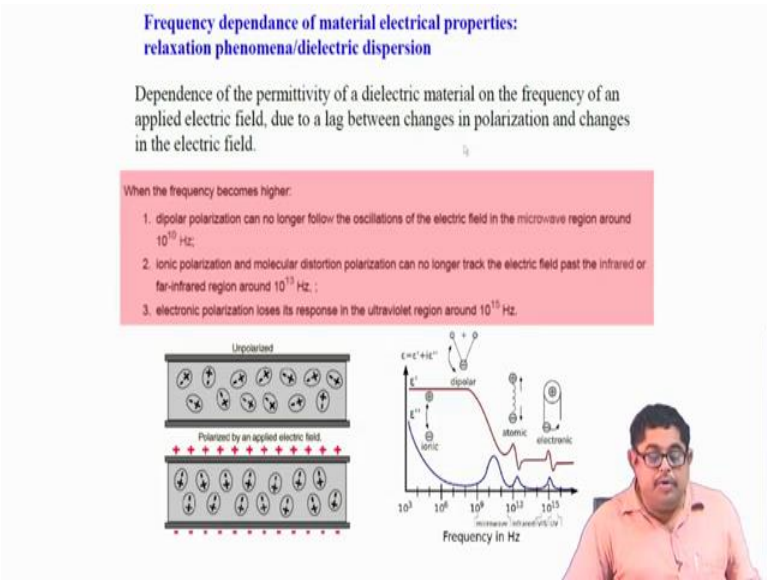

Now, so frequency dependence of material electric properties actually dependence of the permittivity of a dielectric material on the frequency of an applied electric field due to a lag between changes in polarization and changes in the electric field.

So, when the frequency becomes higher dipolar polarization can no longer follow the oscillations of the electric field in the microwave region. Here you can see epsilon prime and epsilon double prime are plotted with frequency. So, you see that roughly upto microwave region, they are constant epsilon prime, but it suddenly if the frequencies increase beyond the microwave region. Then it falls. Again it has an atomic polarization phenomena near about infrared region and finally, the electronic polarization thing that is near the UV spectrum ultraviolet region around 10 to the power 15 Hertz.

Now these slides etcetera, I am using actually there was a course on GPR and one famous person GPR scientist professor Lambot he gave lectures. So, that time this slides are mainly I acknowledge that his material actually that was our course material. So, that we are distributed that time and he really used us for teaching purposes. So, he will be using those slides many slides. I have taken from his thing; I acknowledge professor Lambot for that.

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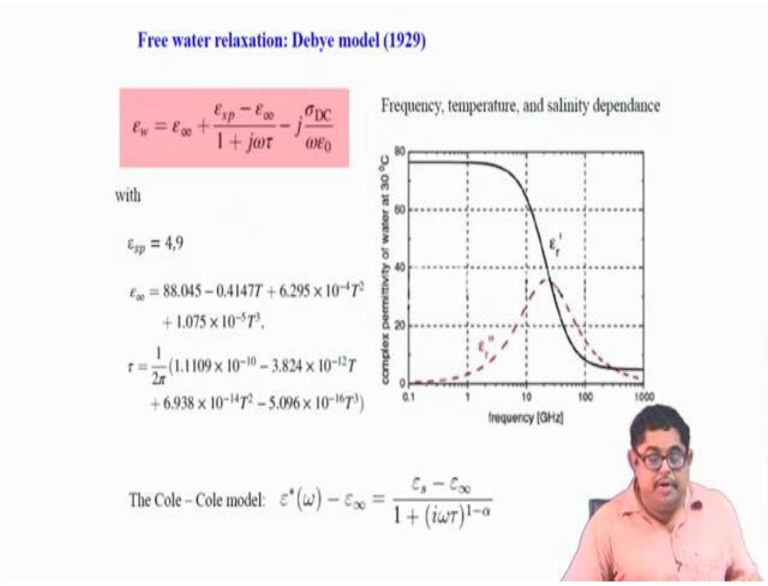

Now, free water relaxation, this is the actually how to calculate the epsilon and actually all these are empirical methods there is a Debye method so, that for water how to calculates its permittivity. So, this is the other thing. So, you can see that water dielectric constant 80 that goes, but after microwave region it again falls etcetera.

So, there is a Cole-Cole model which is from this Debye model. Cole they have deduced this is an easier formula.

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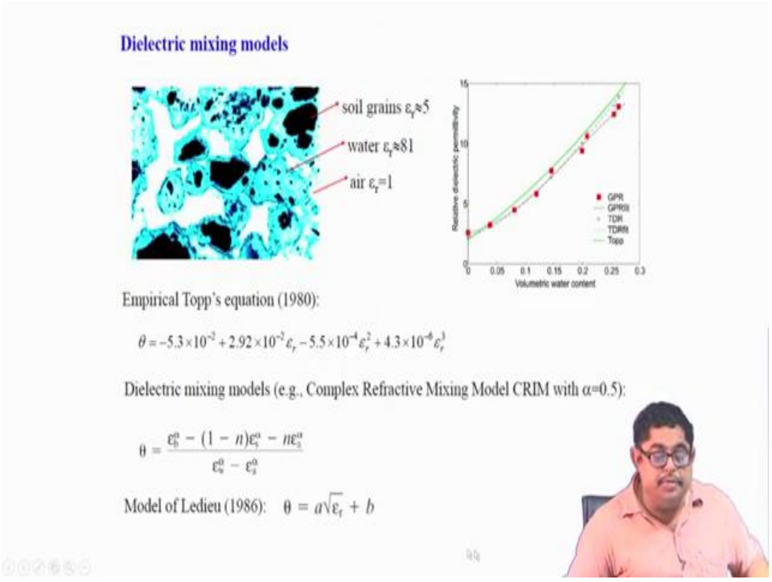

And that then the question is actually as I said that in ground water gets mixed with other materials. So, basically it is a mixture. So, how to find the permittivity of the mixture? So, people have found that in soil the grain size for grains. These are soil grains black ones. So, you see their thing is permittivity where dielectric constant is 5 water molecules are there. They are of 80 81 air is there. So, you need a mixing equation that equation is called tops equation so, relative dielectric constant. So, top has given this formula empirical formula and so, people have found various thing and from that if you plot that permittivity so, depend on water content.

So, as water content increases, you can see the from two three value. You see the dielectric constant of the mixture that goes. So, soil will have these type of things and attenuation loss of a material.

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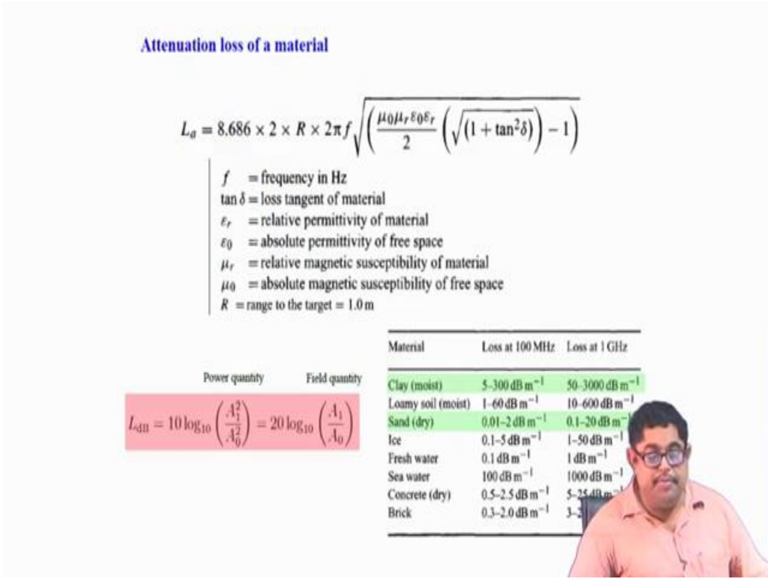

So, you can see that mainly if you look at this loss figure at 100 megahertz and loss figure at 1 gigahertz so; obviously, at higher frequency you have much higher losses as is evident from this presence of the f in the formula. So, that is why from GPR actually the point point from loss point of view. The GPR frequency or the radar the transmitter frequency that should be as lower as possible, but then there are other problems particularly resolution and other things gets affected. So, it is an choice optimum thing that how you choose your frequency that is important because what you want to see that depends on these. Then also the wave needs to penetrate.

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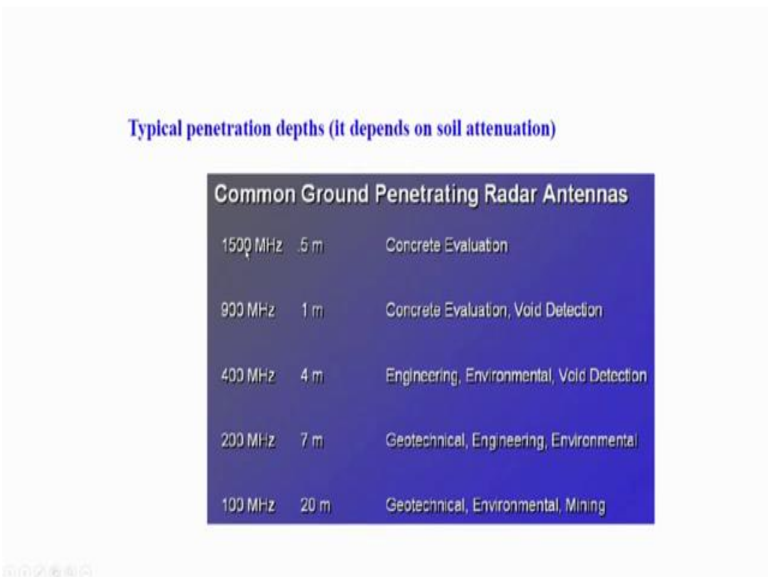

So, at different frequency, you have different penetration depth. So, here is a thing that if you want to have concrete evaluation by GPR, then you choose one 1.5 gigahertz void detection etcetera inside concrete. This is the frequency, then you see that environmental thing mining; then you choose lower frequency etcetera and this is a penetration that this much the wave can penetrate and still give you sufficient returns.

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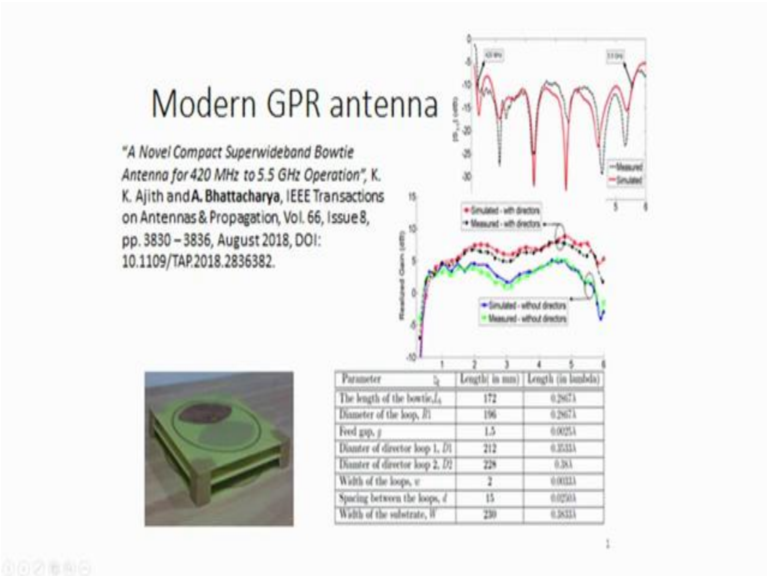

Now, this is the modern GPR antenna and this GPR antenna is very good. It is a very compact size and also its radiation pattern is stable over the whole impedance bandwidth. So, you can see this thing this is a new GPR antenna.

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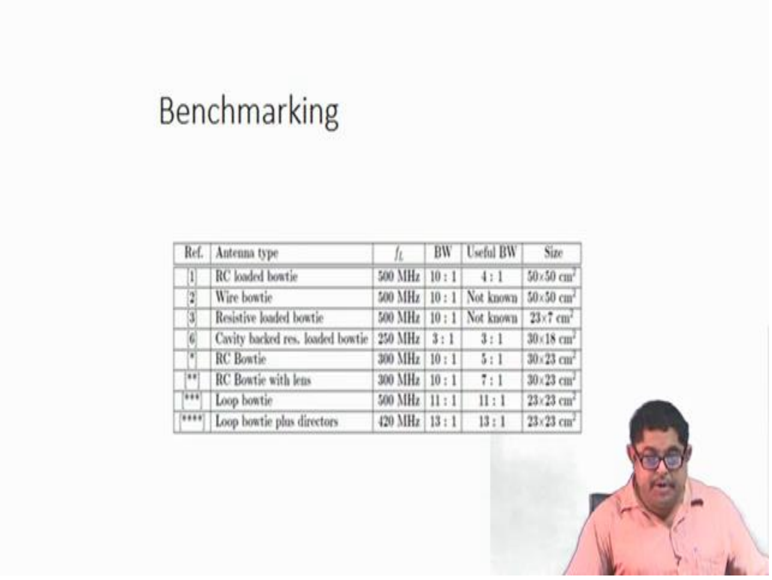

And this is the what I said that useful bandwidth and this is the radio impedance bandwidth. So, but this whole bandwidth you see finally, this last one loop bow tie plus directors. So, that the lower frequency it can operate from 420 megahertz and it can go thirteen times that 420. So, 13 times that 420 means almost up to 5 gigahertz and it is a very compact size.

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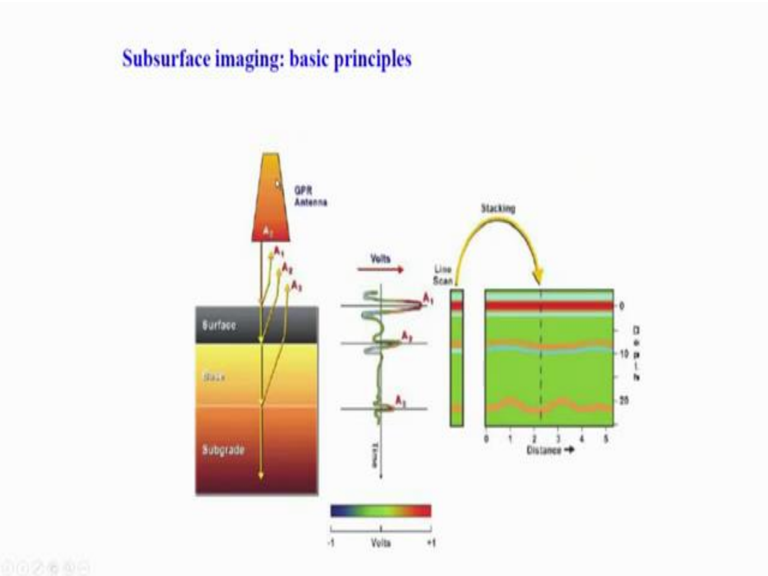

So, now basic principles of GPR that subsurface imaging what happens at GPR antenna. It is sending the signal now, the moment from antenna to air the thing goes there is a return which you are calling A0, then when the wave is falling on the ground top layer. There is a return that is called A 1, then again the first surface that because we are assuming that the air as ground has been divided into surface base upgrade etcetera.

So, these are soil people, they do it like that. So, from every interface; that means, whenever there is a discontinuity in the epsilon and sigma the there is a return. So, if you see with time because the lower one that will take much more time to go. So, that is we will see that with time it will come later so; that means, A1 will come faster A 0 is before that then A 2 will come A 3 will come etcetera. So, this thing this if you this is in radar terminology; this is called A scan; that means, the waveform as you obtain the voltage versus time that is called A scan.

Now you can stack it because this antenna, you can move along the horizontal direction and then this is scan will be distributed in the along this moving zone of the moving line of the antenna. So, that you can think of this line scan is getting stacked then it looks like this is called a B scan.

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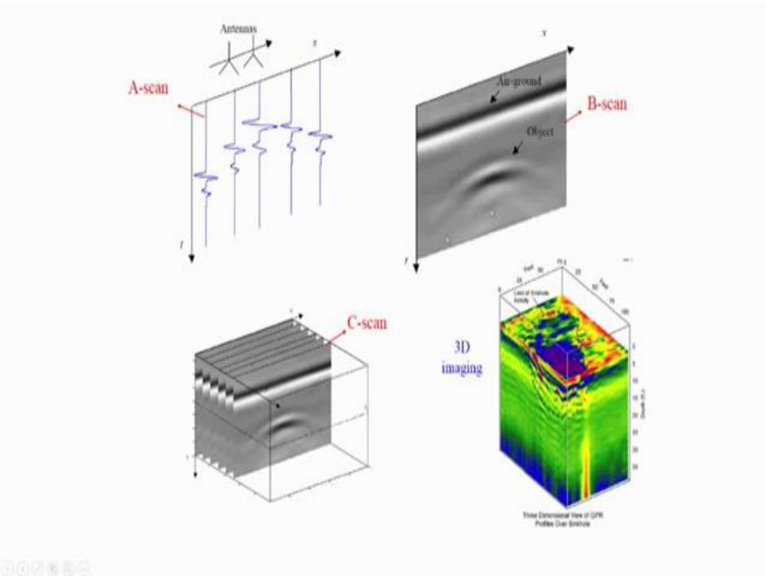

So, here is that terminology that you see this is an A scan this is an A scan etcetera then this becomes a B scan. So, here you see that air ground that has a very strong reflection, but that is not of your interest your interest is you see something is here. So, that is your object. So, in the B scan you get that now these B scan again antenna if it with this after that if it moves in another horizon perpendicular direction sorry, then you get C scan and from this C scan, if you have imaging so, that is called an image. So, three dimensional view of GPR profiles over sink hole. So, this is this becomes an image this is called 3D imaging.

So, otherwise GPRs give you these type of scans, these are called radar grams and from radar grams by proper pixel wise distribution of epsilon mu that you will get the image.

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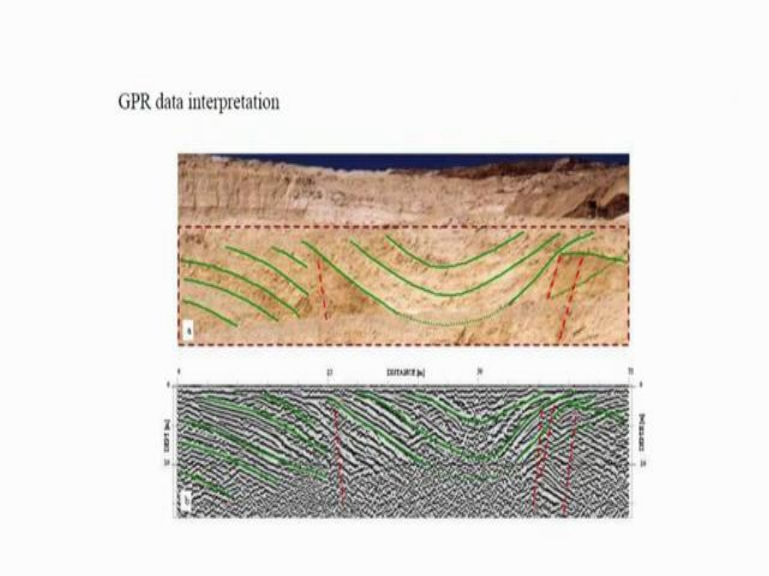

So, this is a example of a GPR data.

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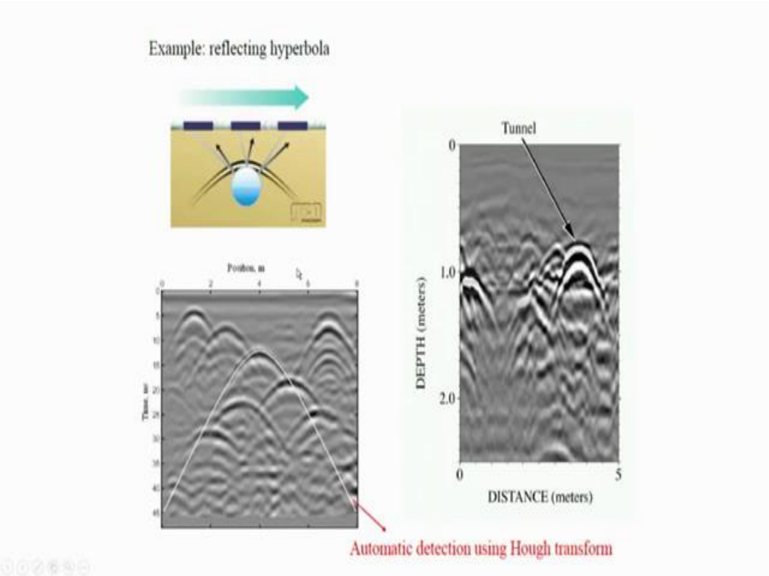

Now, this is important you see that suppose I have a point object may be distributed, but the antenna first is in the left side, then comes to the centre then comes to this right side. Let us assume that these are the three positions. So, in this position, it will get some return in this position; it will get some return in this position. It will get some return now; obviously, the time to travel of the wave the return wave that will be lowest when the antenna is in the mid position and these two are more. So, from the return from any object that its locus in the B scan that becomes an hyperbola.

So, you see any hyperbola means there is an object so; that means, there here is an object, here is an object, here is an object etcetera. These you need to understand. Now the question is that by looking at this thing, I can find it. Now there are techniques by which automatically given a radar gram by there are various transforms Hough transform is one of that by that it is an example that automatic detection using Hough transform. You can find that whether there is anything, this is basically a tunnel is present here. So, GPR is detecting that.

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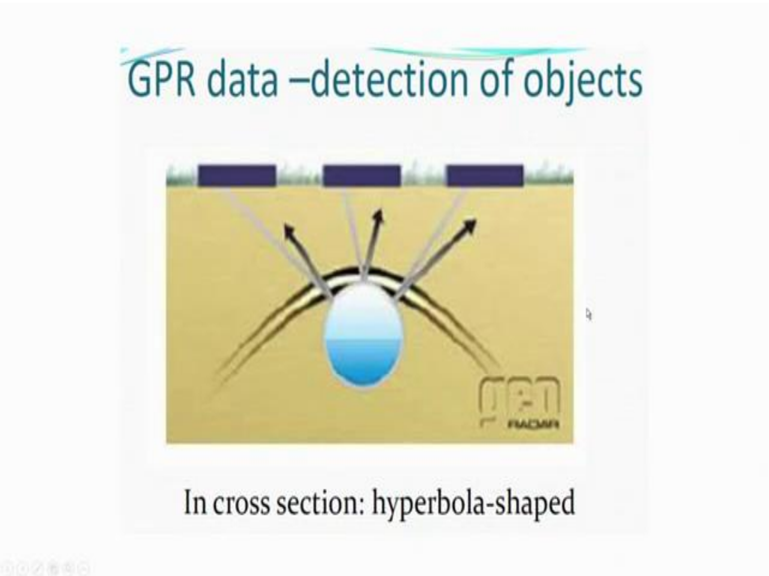

Now, I will just make that this thing; if there is there in cross section hyperbola shaped a thing what are the basic formulas by which our epsilon gets detected.

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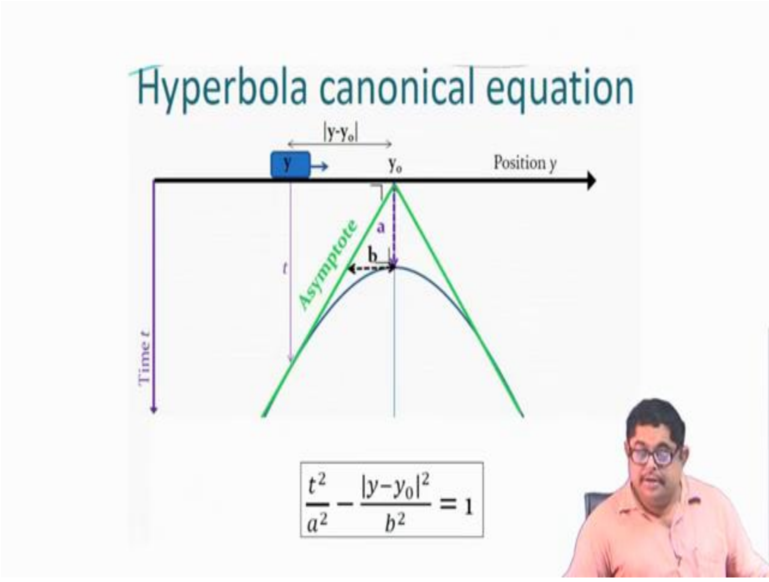

So, hyperbola, this is the equation we are assuming an hyperbola and basically this hyperbola. I can always measure from the ground this apex of the hyperbola that if I call a and the any hyperbola has an two asymptotes. So, from this apex the distance of the asymptotes; if it is b then the hyperbola canonical equation can be written like this. This you can easily check, you know all hyperbolas equation.

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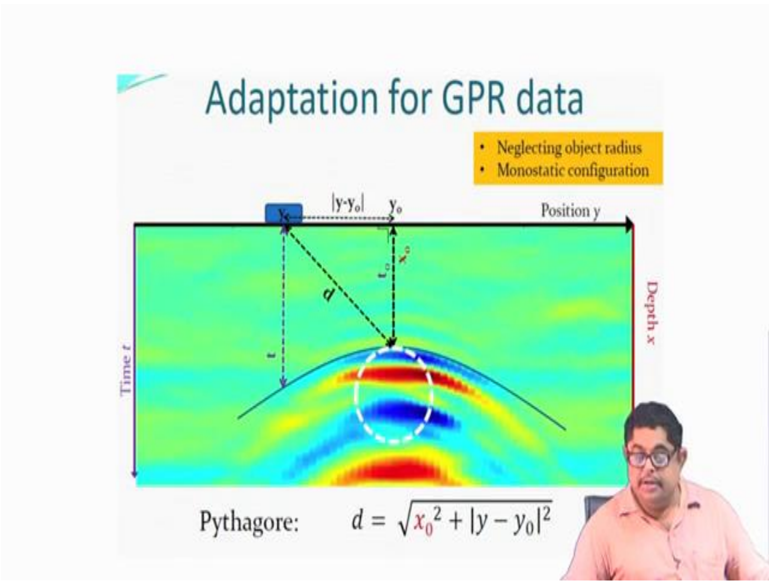

So, you can put it now a and b are measurable and we will show that we will assume this for a simple model that object is a point object and mono static configuration is assumed.

Then by Pythagoras theorem, you can write that the distance d that can be written like this x naught and y naught. These are the two coordinates of this point.

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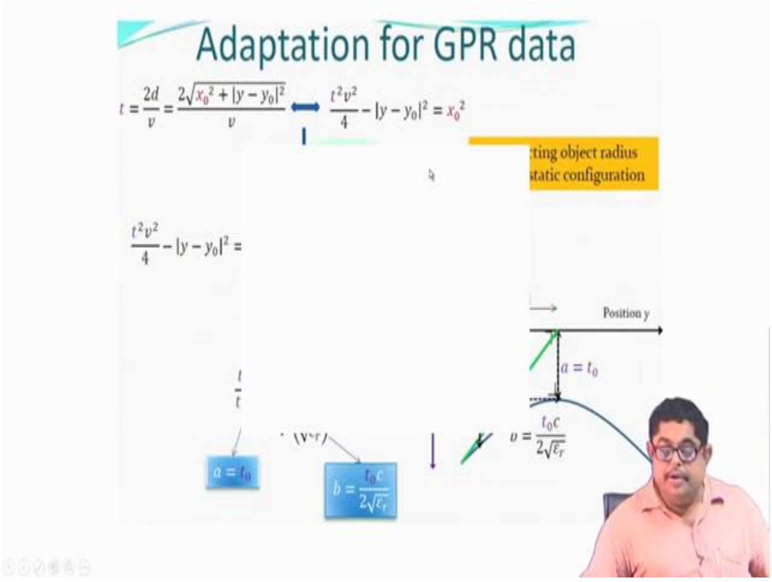

So, then you can follow it here that time for travel is two d by velocity.

$$t = \frac{2d}{v} = \frac{2\sqrt{x_0^2 + |y - y_0|^2}}{v} \Longleftrightarrow \frac{t^2v^2}{4} - |y - y_0|^2 = x_0^2$$

So, put it here and that gives you finally, solving you see that you have got this equation that time you can always measure and also by measuring it basically this a gives you t 0; that means, a and t 0 are same. So, t 0 is measured and then a is obtained and b actually if you measure b, then b will give you basically c we know t 0 we know. So, epsilon r can be found. So, if you get an hyperbola in the radar gram by measuring a and b we can easily detect these.

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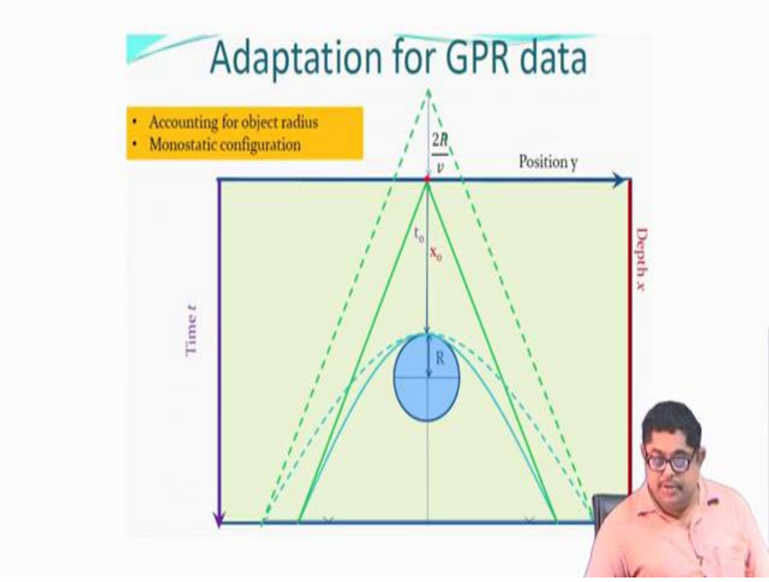

So, these are then the relaxing those earlier things and accounting for object radius and monostatic configuration, you can refine those formulas.

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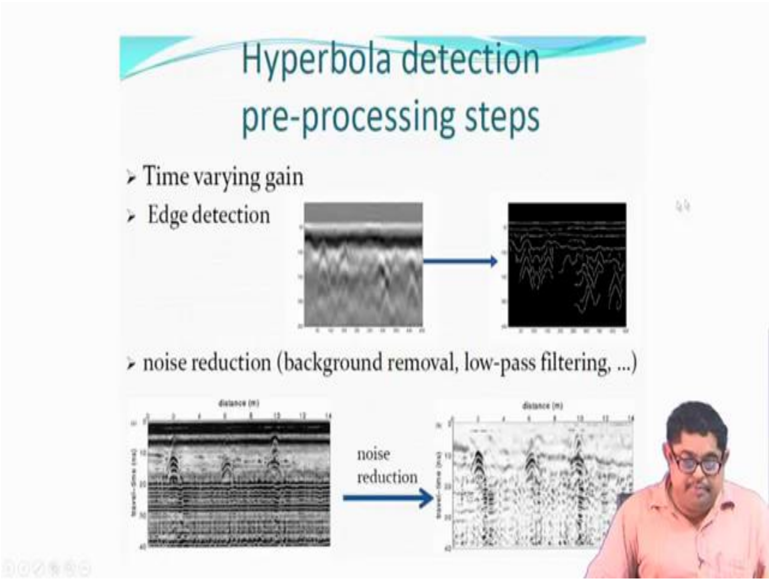

Those are hyperbola detection various pre-processing steps are necessary, but as I said that by Hough transform, you can do the Radon transform Hough transform. Those are various transform the by which people can detect. So, these are everything now another thing is that soil water content determination. So, this is already we have discussed these things.

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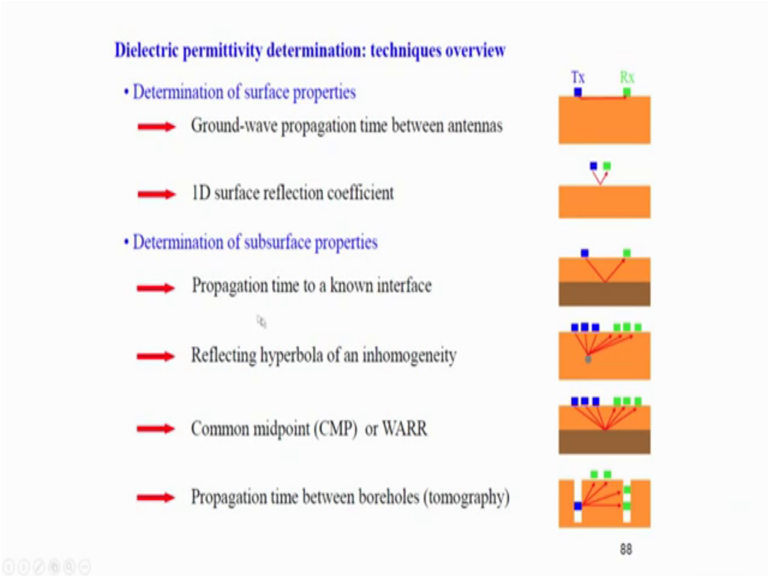

So, in various ways determination of surface properties determination of subsurface properties, you can see these. So, these are still various models are being proposed and active research is going on.

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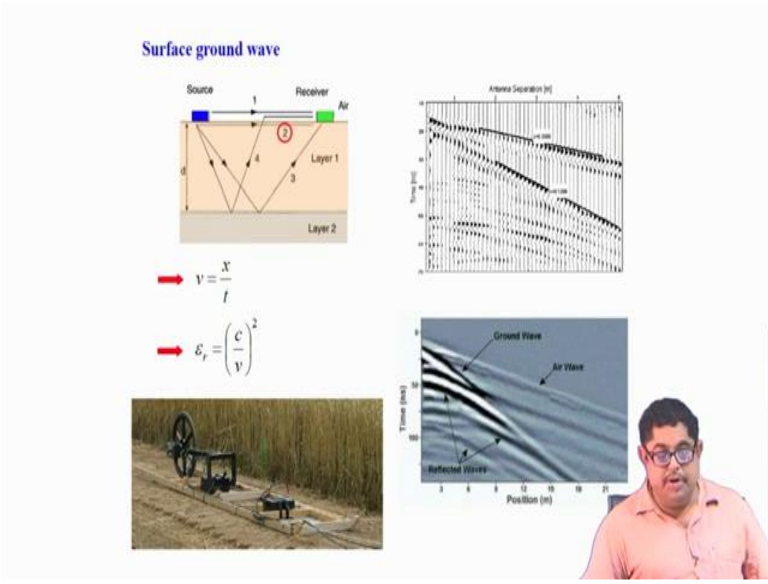

Then these are the basic formulas that v the velocity is x by t the total travel time and epsilon r is given by this.

$$v = \frac{x}{t}$$

$$\varepsilon_r = \left(\frac{c}{v}\right)^2$$

So, you see this is a typical examples of radar and these are the various wave reflected waves air waves ground waves.

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So, now you see where GPR is used. Now let me give you some example suppose road the road has a internally, it has a crack underground pipes. They are leaking there is a statistics that in many modern cities old cities European cities; 30 percent of this water supply that gets lost because of these cracks etcetera.

So, you need to detect that now without disturbing anything on the road, you can find out underground pipes cables buried tanks whether they are leaking bridge decks.

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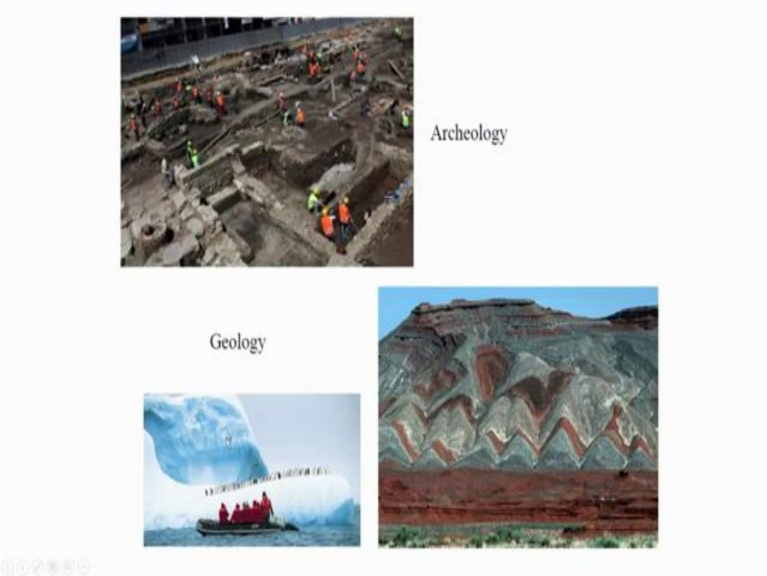

You see tunnels inside that if there are archaeology various heights are you will have to excavate, but then where exactly we will do that where exactly you can find something that archaeology people use GPRs. Then in geology, you want to find out what is the whether the polar ice melting etcetera what is there inside a new planet. So, that is geology people do.

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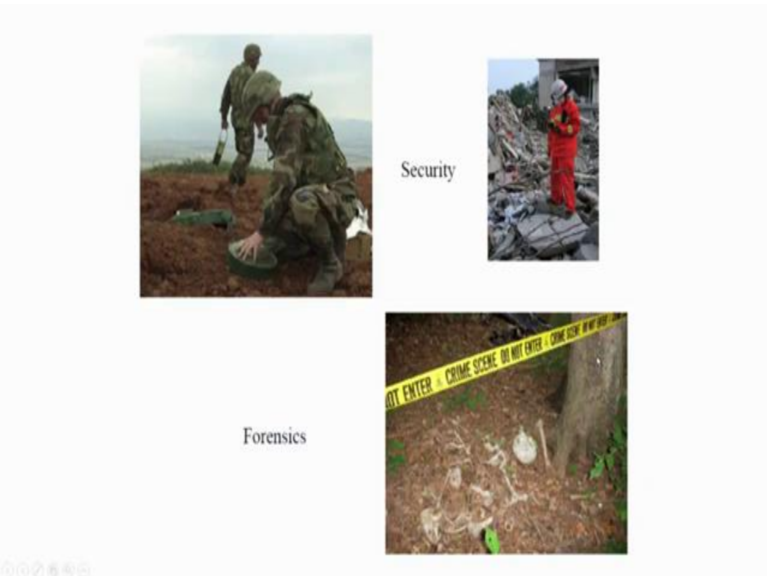

Then security people see whether there are any mines land mines under the thing, then you see whether something has been hidden here crime scene. So, some human skeleton is there, you want to detect someone is inside debris because of some building collapse etcetera whether that person is living that also people are now trying to find out that whether the person is dead or alive because if he is alive, then only there is a point to rescue him.

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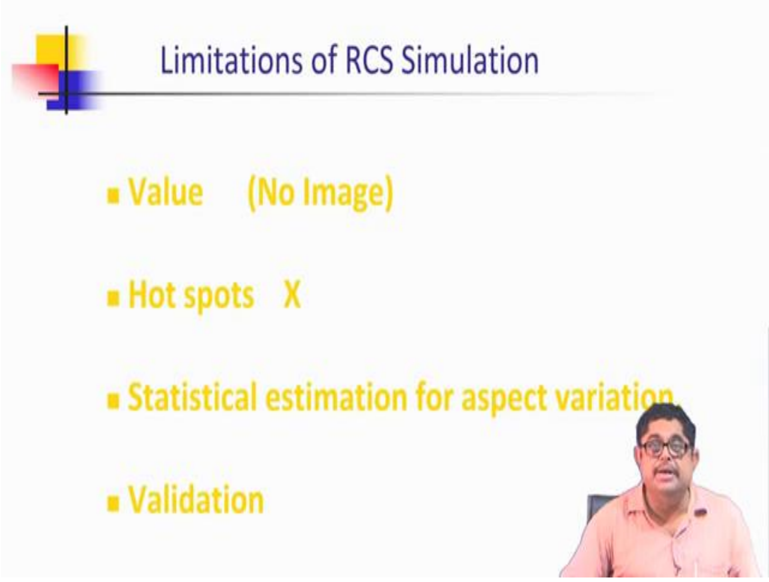

You see that we have discussed about RCS. Now RCS, Radar Cross Section of a large body. Now suppose for a plane for stealth application suppose I want to see the RCS, but there are some limitations of this concept of RCS actually RCS gives you a value because from the whole body various form scattering points the total vector addition of all that gives us the RCS.

So, I can find out okay that this body has more RCS than the other body or less RCS than the other body, but suppose a plane has been designed and I want to now find out that what are the main scattering centres. So, that I can apply some material on that etcetera some radar coating RAM (Radar Absorbing Material) etcetera or coating now for that RCS does not help. So, I need to image the whole thing. So, that is one thing. So, radar people call it that hotspots are not found from RCS study simulations or studies, then for every aspect you need to find the RCS.

So, you will have to have a statistical estimation for that and what is the validation of what you are suppose someone is telling you that RCS of these plane is so and so, but how do validate for that measurement etcetera will be necessary.

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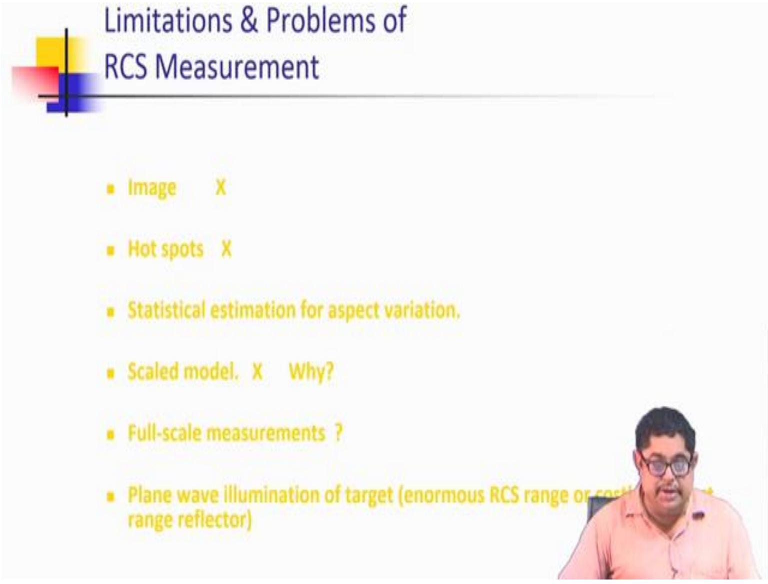

Now, measurement also the problem is that as I said that RCS measurement also will not give you the image also. Also it will not give you the hotspots the same problems that were getting another problem is I think we discussed that you cannot have for measurement scaled model. So, that huge structure, you will have to do you will have to have huge structure for measurement of RCS. So, those are problematic things. So, that is why full scale measurements always is not cost permitted etcetera. So, plane wave illumination of target, you require enormous RCS range or costly compact range reflectors etcetera.

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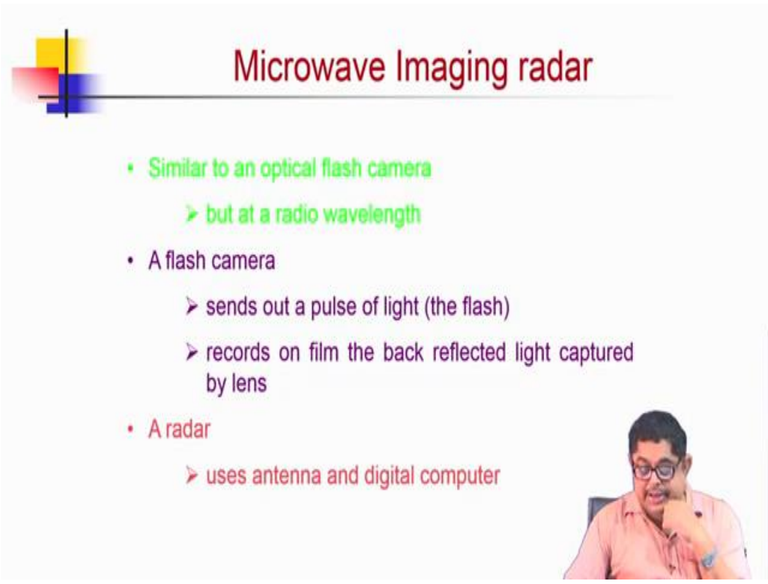

So, a solution is imaging radar. It is similar to an optical flash camera, but at a radio wave length a flash camera; that means, what you use every day that is an optical camera sends out a pulse of light records on film the back reflected light captured by lens a radar is similar. It uses antenna, it requires an antenna at microwave frequency. You cannot send like the light because light due to its very high frequency compared to microwave. It almost goes in a straight line and it is easy to send light, but for sending a microwave signal, you require an antenna and recording etcetera. In this case for radar cities done on digital computer.

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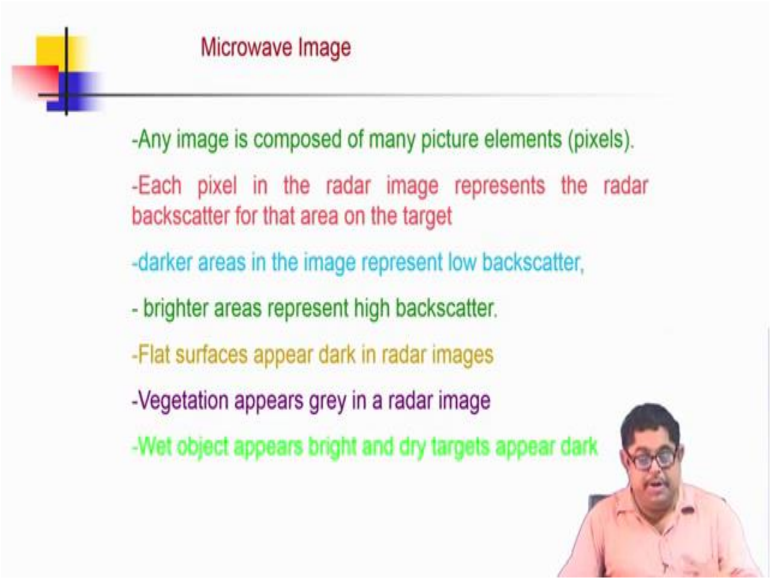

Now, what is an image? Any image is composed of many picture elements that you know each pixel in the radar image represents the radar backscatter for that area on the target; darker areas in the image represent low back scatter, brighter areas represent high back scatter flat surfaces appear dark in radar images. Vegetation appears grey in radar image wet object appears bright why because wet means the dielectric constant high because water is there. So, that is wet appears bright and dry targets appear dark.

Now these are peculiarities which normally for light we do not have. So, light image or a light induced image or optical image and microwave image. They are the these are some fundamental differences.

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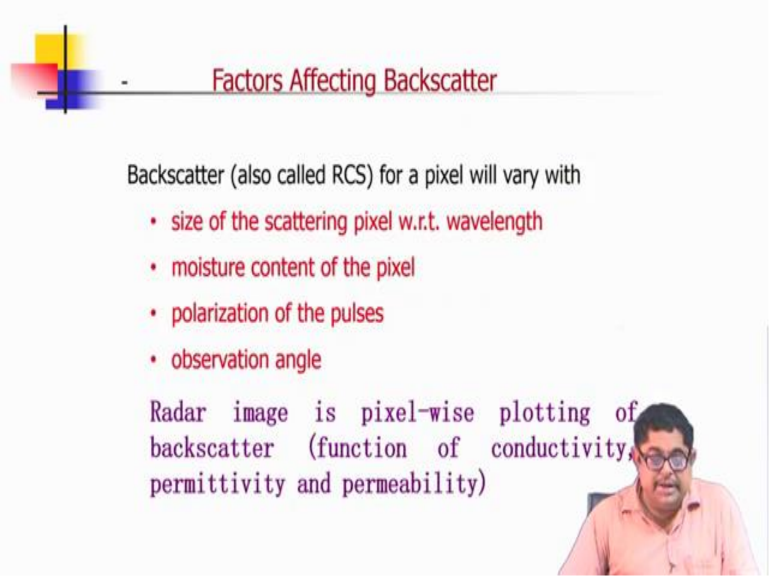

So, back scatter or for a pixel will vary with size of the scattering pixel with respect to wavelength moisture content of the pixel polarization of the pulse observation angle. Radar image is pixel wise plotting of back scatter function of our those old conductivity permittivity and permeability.

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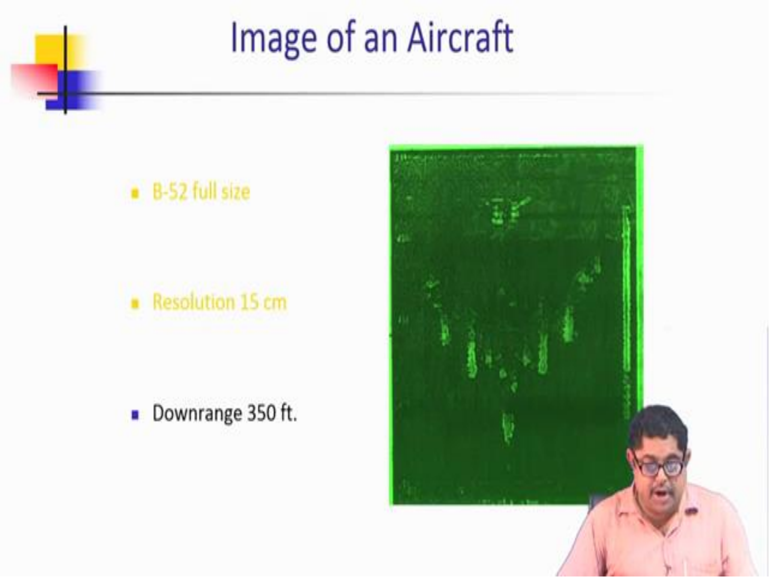

So, this is a typical image of a fighter aircraft B-52 full size; you see it is not like optical image, but experienced people can find out various things resolution in this of this image is 15 centimetre down ranges 350 feet.

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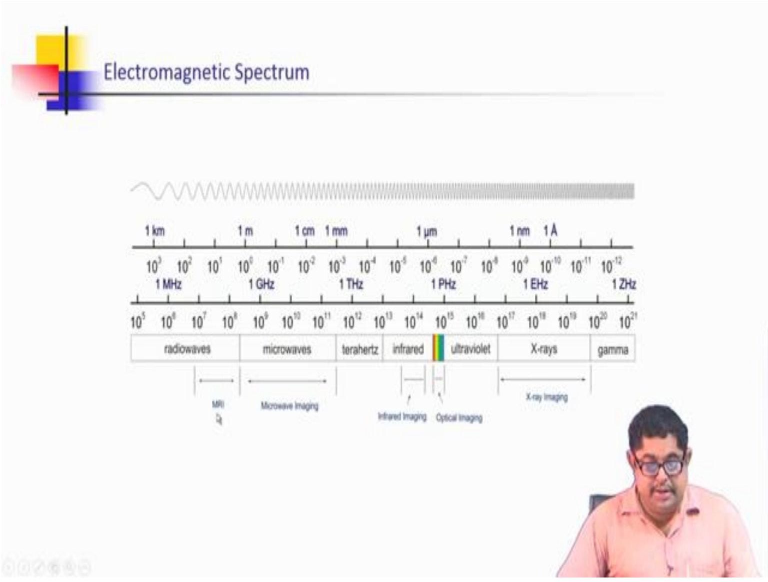

Now, in electromagnetic spectrum, you see that for imaging there are various methods; one is MRI, another is microwave imaging, then you have heard of infrared imaging optical imaging X-rays imaging.

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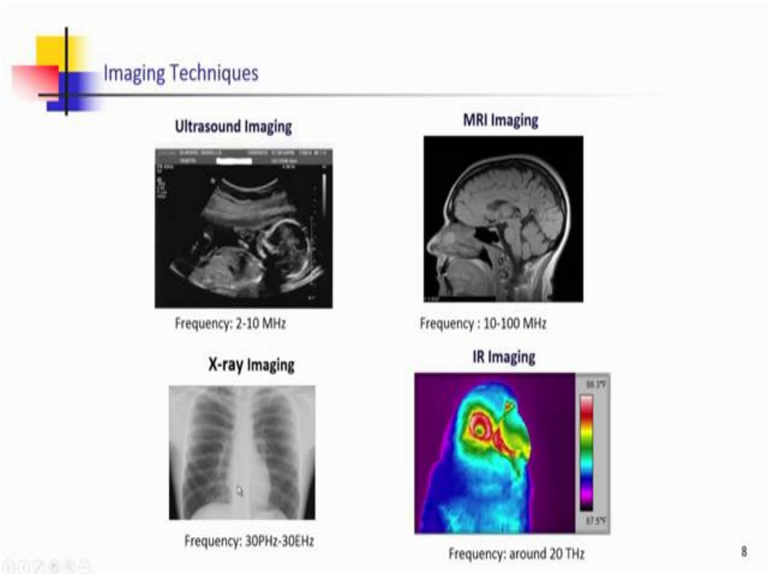

So, where microwave imaging stands. Let us see that ultrasound imaging is frequencies 2 to 10 megahertz. It is a low frequency thing and if you go to frequency 10 to 100 megahertz. You have MRI imaging; you have microwave imaging, then IR imaging frequencies around 20 terahertz and X-ray imaging. You have 30 peta Hertz to 30 exa Hertz.

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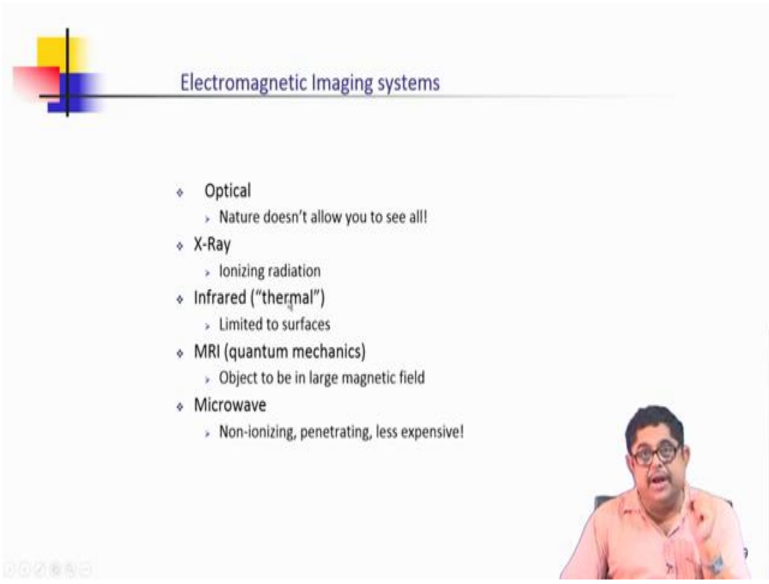

Now, optical what is the problem with optical thing nature does not allow you to see all means that without light; that means, in suppose the there is when the sun is not there that is the in dark optical camera does not work in rain, in snow or those things it does not work.

Now for X-ray imaging problem is that it gives you a good image, but it is an ionizing radiation because X-ray particles they have or X-ray that wave that has a huge energy. So, they ionize the thing. So, human body etcetera that have that ionization and its permanent, it is cumulative so, that is why we are not X-ray only for very required cases we do X-ray imaging infrared the problem is infrared cannot penetrate the surface. So, you get only the impression of the surface. It does not have any penetration MRI the problem is the object to be image that should be in large magnetic field.

Now that one thing is its creating a large magnetic field requires huge heavy infrastructure and also that has its own problems also for human body etcetera. Now microwave usage does not suffer from anything microwave can see in night microwave is non-ionizing microwave penetrates the surface and microwave is do not require that high magnetic field etcetera; less expensive.

So, it is a very good choice, but the technology needs to be developed. So, that microwave image comes resolution wise closer to optical image.

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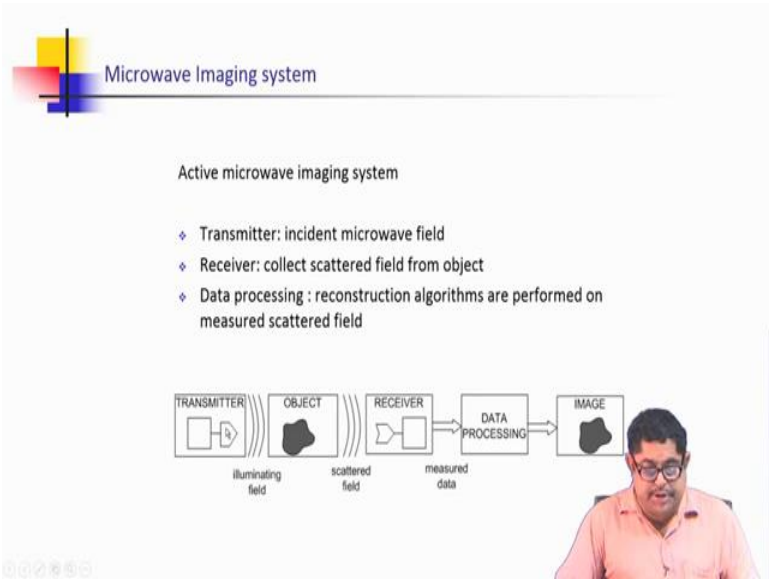

So, this is a block diagram of an imaging system transmitter is there object is getting hit, then there are scattered things receiver is receiving that processing the data you are giving the image.

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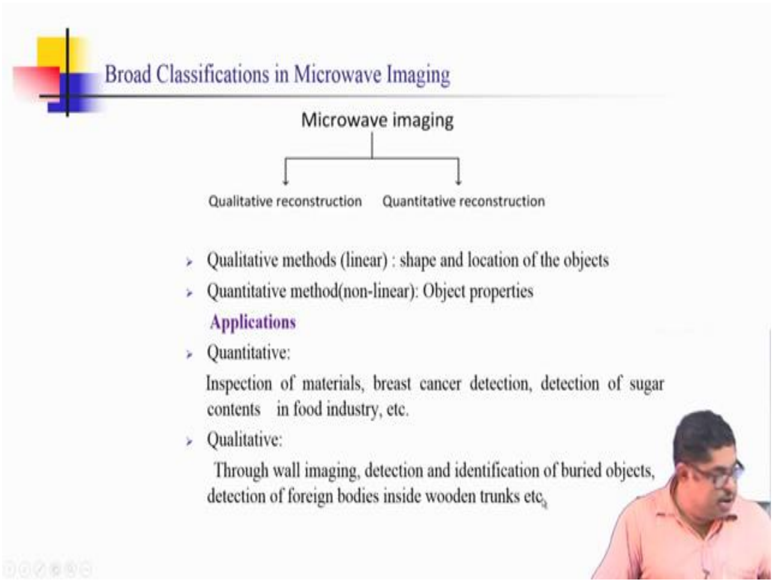

Now, microwave imaging is broadly, the it is can be divided into qualitative reconstruction of the image quantitative. Qualitative method means you get the shape and location of the object nor the inside the inside the object pixel wise epsilon mu and sigma's distribution it does not give. Whereas in quantitative method gives you the exact of object properties, but quantitative methods are non-linear. So, forming an image by quantitative method is much more tougher qualitative methods.

They try to give the shape and location and actually then the quantitative methods search domain gets reduced and it then gives you an image now application wise a listed that quantitative methods are inspection of materials breast cancer detection of sugar contains in food industry etcetera. The examples for qualitative methods through wall imaging detection and identification of buried objects detection of foreign bodies inside wooden trunks, etcetera.

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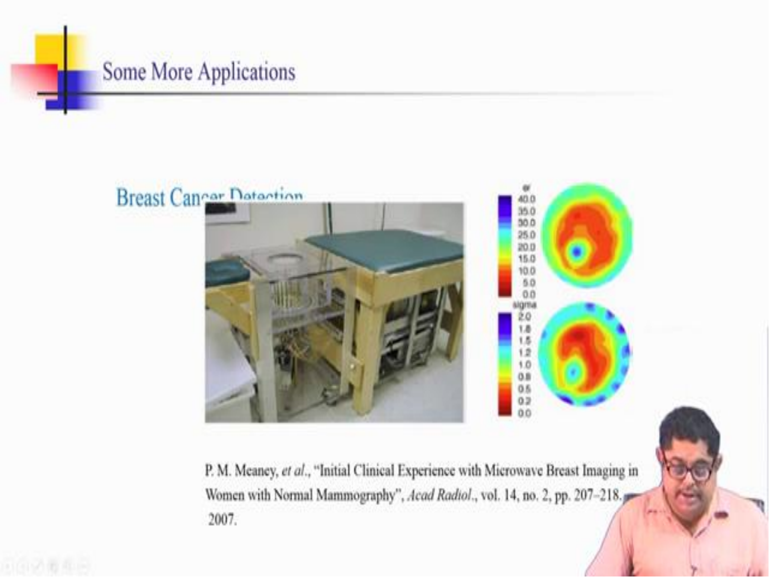

Then this is a breast cancer detection thing actually in USA; in many was some of the advanced hospitals. These things are already operational; it is a very good breast for breast cancer actually since breast is protruding out of the body detection by microwave breast cancer detection is much more healthy and error free compared to X ray mammography and other techniques.

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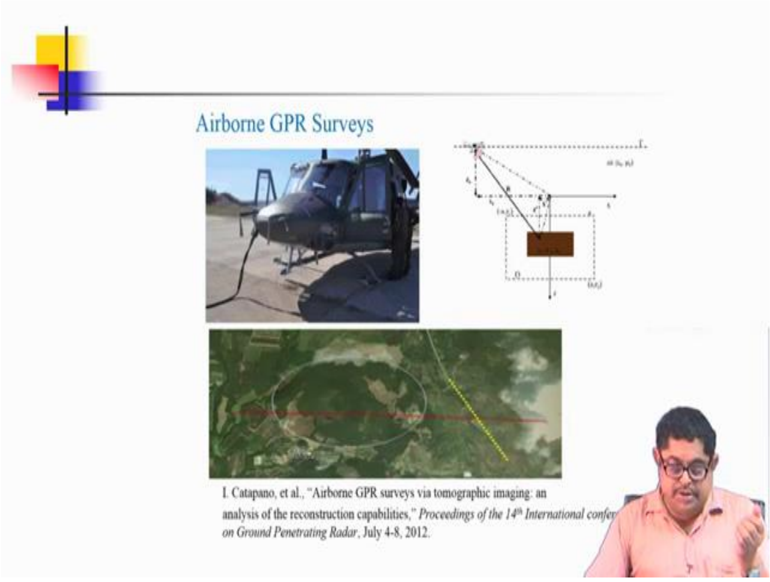

Then airborne GPR surveys where you can find out whether there is any buried tunnel in two countries. Suppose between them there is a border, but generally people infiltrate through tunnels etcetera. So, detection of that or is there any underground activity going on.

So, for that this tomographic image helps to find out what is there inside this. So, thank you. So, by that we close this course on principles and techniques of modern radar systems actually you see we have tried to give you the basic ideas the concepts of radar and finally, we have indicated that actually radar though it came from the womb of the war industry. But recently for last 20 30 decades the various scientific applications and now various humanitarian applications civilian applications are taking this using this technology.

And actually the GPR is one such example that it has taken shape that to solve various civilian problems actually various scientific problems. These ground penetrating radar is a very good example of review the technology war technology getting transformed to civilian technology or humanitarian technology. And I hope that those students who are attending this course in your professional life, you will see the GPR is will be. There are various challenges to find GPR. In this imaging and I hope that the background you learnt in these courses that will help you to solve those problems solve those challenges and you will enjoy your journey with this radar GPR which is a future of the radar industry.

Thank you.