Transmission Lines and E.M. Waves
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Lecture-1

Welcome to this course on Electromagnetic Waves. The Electromagnetic Waves or Electromagnetics is a subject which has fascinated human beings over many more centuries. In ancient days people used to ask questions like why the stars twinkle and the planets do not twinkle or why there is lightening or if I put a magnetic needle in certain environments why the magnetic needle deflects, how does the light reach from sun to the earth when there is no medium in between. These kinds of questions people try to investigate form many more centuries.

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In the modern days people have questions like how do we have a TV reception, how do we have a Radio station operating, how does the mobile phone works, why the TV reception is good in some part of the house and it is not good in some other part, why we do not have a good Radio reception inside a Railway compartment, why the Radio station

which at medium waves does not show any time fluctuation where as Radio station which is operating at short waves has time fluctuations, why certain things get heated when they are kept inside microwaves and there are numerous phenomena which you see in modern days which fascinate the common man.

All this phenomena either you take ancient phenomena or you take modern phenomena the common thread which runs through all these phenomena is Electromagnetism. In fact in today's world if we look around there is hardly any gadget which does not work on Principles of Electromagnetism.

In this course of Electromagnetic Waves essentially we are going to investigate the high frequency aspects of Electromagnetism. Broadly an electromagnetic phenomenon can be divided into two categories which are low frequency but high power and high frequency but low power.

So the phenomena like electrical machines, electrical power generation transformers and distribution of electrical energy are fall in the category of high power but low frequencies. Where as if you go to the modern systems like Mobile Communications, Radars Satellites, Optical fibers fall in the category of low power but high frequencies.

In this course, essentially we are going to develop the Principles of Electromagnetics at high frequencies. We can ask very basic questions like if the frequencies increases what way the electrical phenomena or the understanding which we have from low frequency circuits get modified and then we can understand the various phenomena which I have mentioned which have a common thread is Electromagnetic Waves.

So electromagnetic waves essentially seek applications in many areas. Firstly, we have applications in Transmission Lines and a High Frequency Circuits like Radars or TV's or Radios.

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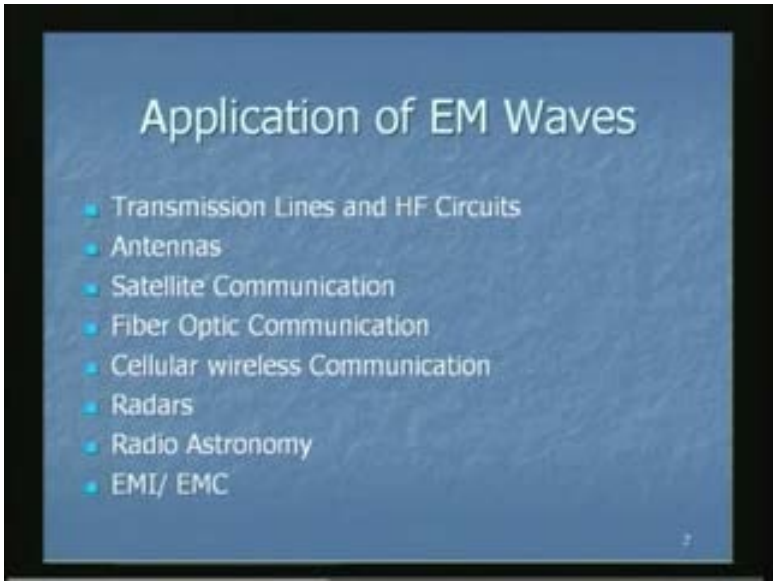

Then we have application of electromagnetic waves in the area of Antennas which can either transmit electromagnetic energy or can receive electromagnetic energy. We require knowledge of electromagnetic waves in a subject called Satellite Communication, we require knowledge of electromagnetic waves in the area of Fiber Optic Communication and we require this knowledge in Cellular wireless Communication and applications in Radars and classical subject like Radio Astronomy and also subjects related to Electromagnetic Interference and Electromagnetic Compatibly.

So in this course essentially we will try to investigate how time varying electric and magnetic fields behave especially when the frequency of operation is large. As we all know that in general the phenomenon of Electromagnetism is governed by the four classical equations called the Maxwell's Equations. The Maxwell's equations represent the phenomena of Electromagnetism in totality. However as we proceed in this course every time it is not required to go to the regress analysis of Maxwell's equations and under certain approximations we can investigate the same phenomena in terms of voltages and currents in terms of electrical circuits, however as we go further we will find

the representation of this in terms of voltages and currents become difficult. then we can move to the general phenomena of electric and magnetic fields.

Let us first look at the Electromagnetic Spectrum.

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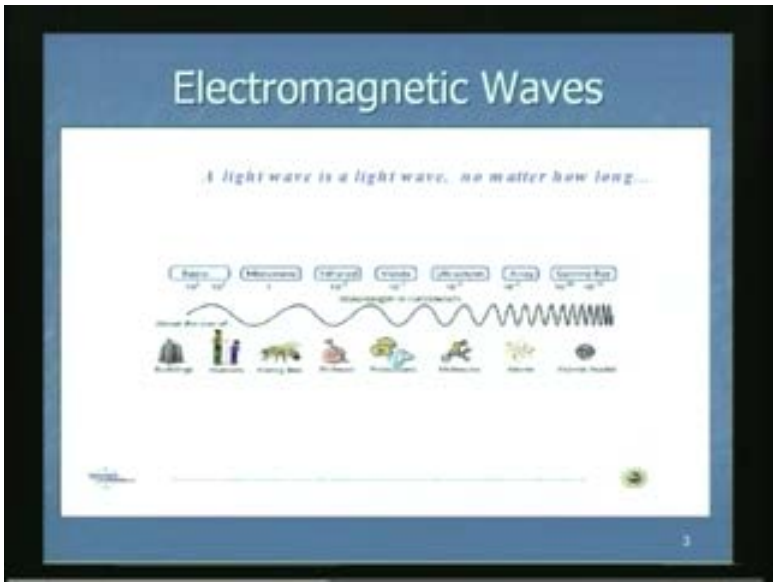

The word the electromagnetic wave corresponds to any phenomena which were related to the time varying signals time varying electric or magnetic fields. So no matter how small the frequency is, any frequency which is not zero can be put in this category of time varying electromagnetic fields.

So what is shown here are the wavelengths and the physical dimensions which normally are corresponding to those wavelengths. So if we go to very low frequencies the Radio frequencies the wavelength is very large and it is comparable to size of a building. When you go to the microwave frequencies the wavelength becomes about a few centimeters which is typically of the side of an insect, as you go further the wavelength reduces then the size becomes tip of the needle. When you go to visible range of the Electromagnetic Spectrum then essentially you are talking about size of the atoms or molecules and when

you go to X-rays and γ-rays the wavelength becomes smaller or comparable to the atoms. So the entire frequency range from very low frequencies to high frequencies can be summarized in one word that is the Radio frequency.

So in this course when we refer to Radio frequency essentially we are referring to any phenomena which is not constant as the function of time but it has a finite frequency. The same thing can be written in more technical terms that here we have got the Electromagnetic Spectrum these are the wavelengths starting from about 10 meters to one meter then ten centimeters to one centimeter and to one millimeter

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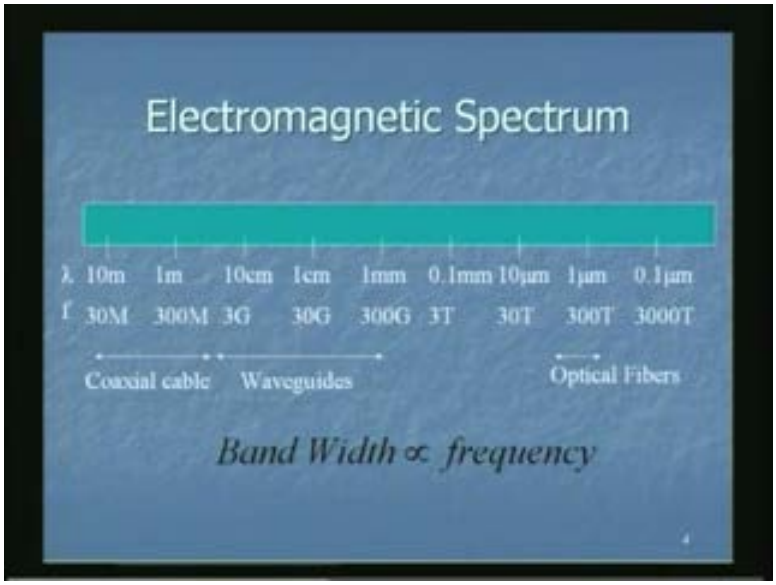

and all the way we go up to about 0.1 micro meters which will be typically in the range of what X-rays and these are the corresponding frequencies. So ten meters would correspond to thirty meters, ten centimeters would correspond to three Giga hertz and like that when we go to this region where the wavelength is typically about order of one micro meter the frequency will be typically of the order of about 300 Tera hertz. Then depending on the frequency of operation we use different media for transmission of these signals so in this region we use the media called the Coaxial cables. Where as when you

go to this range of wavelengths we use structure called the Waveguides and when you go to the very high frequencies in optical domain then the media will be Optical Fibers.

One can ask a very basic question at this point that why do we have to go to high frequencies? What advantage one gets by increasing the frequency? What one noticed is if you consider a typical electrical system then the bandwidth of the system is more or less proportional to the frequency of operation. If we consider the major application of high frequencies as communication then we require large bandwidth for transmitting more information. So as we can see from here the Band Width is proportional to the frequency, one can get larger bandwidth by increasing the frequency of operation therefore one can transmit more information on a given channel.

So from information transfer point of view, increasing the frequency provides larger bandwidth and it is increasing the capacity of the information transmission.

So the first application which we have for the Electromagnetic Waves is Transmission Lines in which essentially we investigate how the voltages and currents are going to flow in a two conductors system called a Transmission Line.

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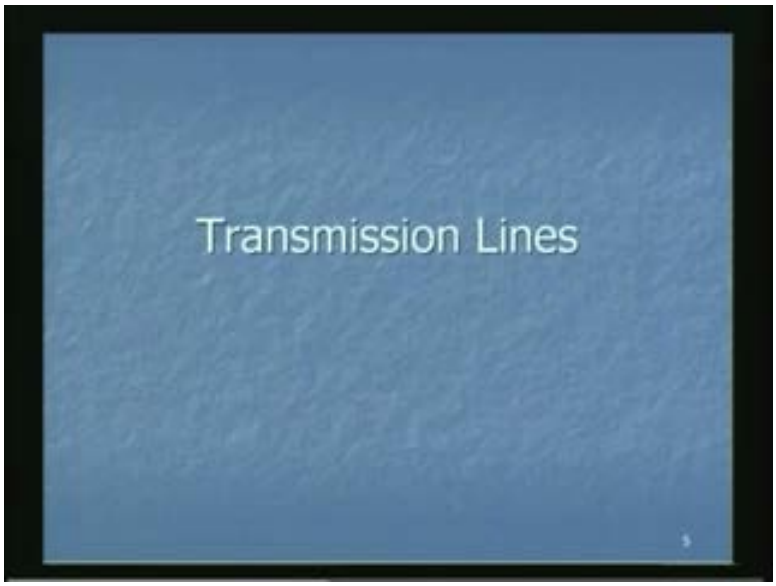

so a simpler system which we see all around for connecting any electrical signal from one point to another we require a pair of wires and these pairs are twisted so this medium is called Twisted Pair.

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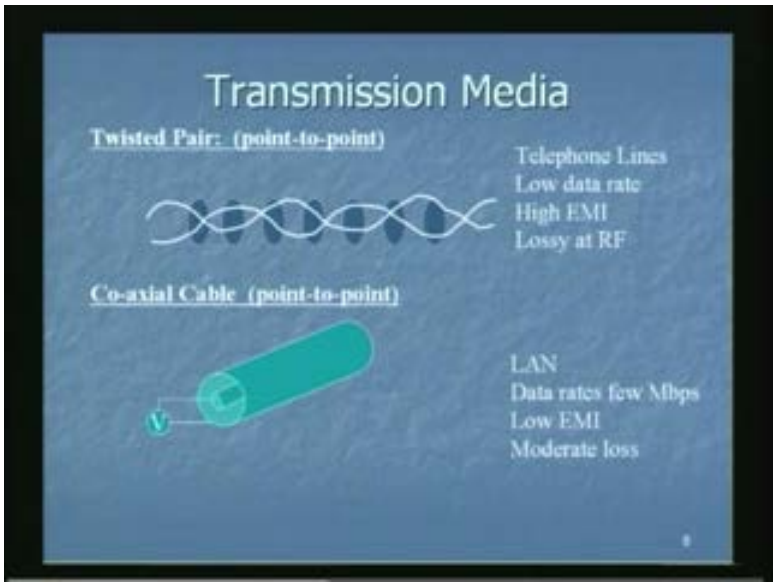

Now we will see this kind of medium is normally used for Telephone Lines and we want to investigate how the electrical signals will propagate on this structure. This media the twisted pair can handle low data rates, has a high Electromagnetic Interference and is very lossy as the frequency increases. So normally this medium is very useful for low frequencies but as the frequency increases the loss increases and that is why this medium became not very attractive.

As the frequency increases we go for a medium called a Co-axial cable where we have a center conductor here and then you have outer conducting shell the high frequency signals are applied between the center conductor and the outer shell and the signal flows inside this empty region here. This cable structure can handle data rates which could be typically about the order of few megabits per second, has low electromagnetic

interference and also has moderate loss. So we require fundamentals of Electromagnetic Waves to investigate propagation of energy on this structure.

As the frequency increases even the center conductor of a Co-axial cable adds to sufficient loss and therefore the surface area of the conductor is minimized.

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And in this process essentially we end up into a hollow pipe of metal inside where the electromagnetic waves can propagate. This structure is called a Waveguide.

If the cross section of this hollow pipe is rectangular then we see that this Waveguide is called the Rectangular Waveguide. On the other hand if the cross section of this pipe is circular then we call this as a Circular Waveguide. So at high frequencies typically at microwaves the hollow pipes made of metal are used for guiding the electromagnetic energy. And again you require a rigorous analysis of electromagnetic wave propagation inside these conducting pipes which helps you in finding out what will be the field distribution inside this structure, how much energy loss will take place when it propagates inside this and so on.

The next application of Electromagnetic Waves is Antennas. The antenna is a device which can transmit electromagnetic energy into the space and also it can receive electromagnetic energy coming from the space.

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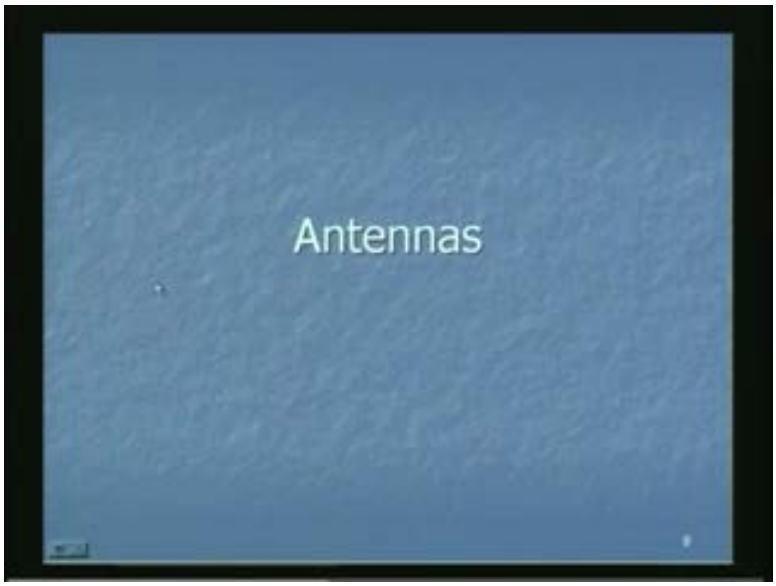

So, many modern types of equipment are using the Antennas. Here you can see an Antenna called a Parabolic Dish in which radiation falls on this dish gets reflected from here and then here there is something called the feed.

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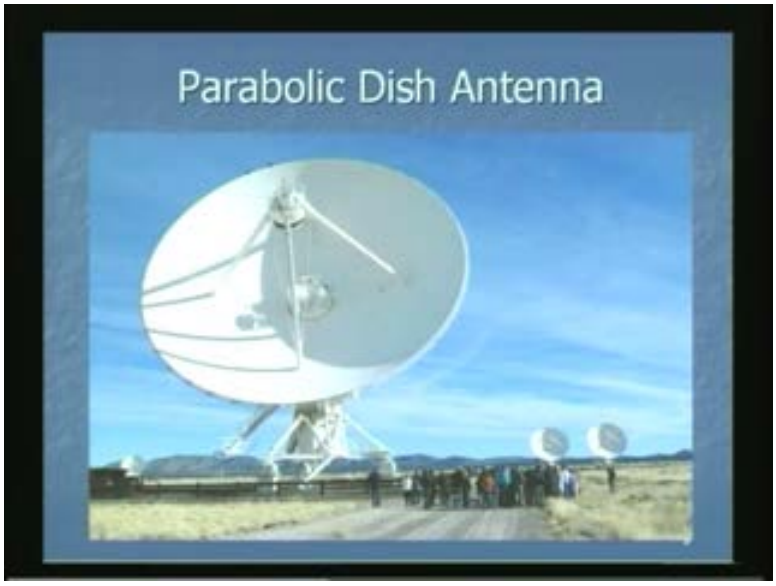

The Electromagnetic Waves get focused on to this point and then it gets converted into electrical signal and that electrical signal is processed further. The same dish will generate electromagnetic wave if the electrical system is supplied to the feed, which will get reflected from this and it will get into the Space.

So Antenna is a device which selectively puts the radiation in the desired direction. In fact a simple Antenna structure may not really provide the directional characteristics of radiation.

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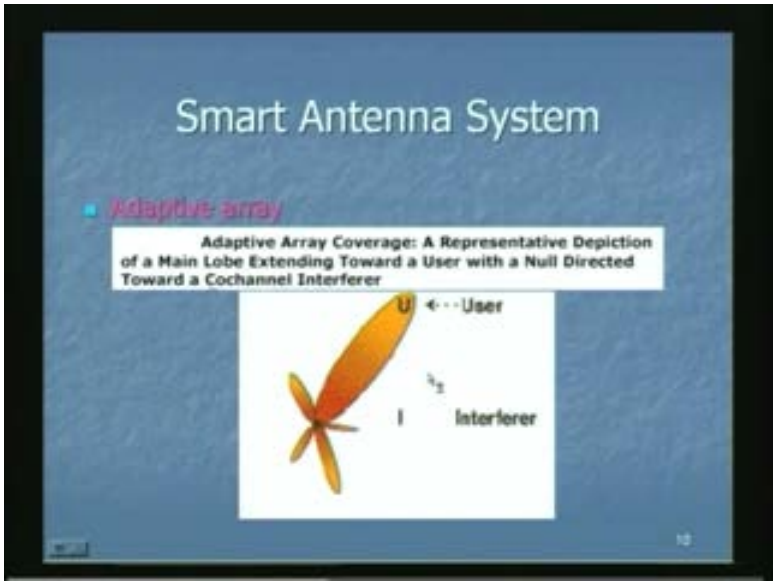

Also in modern days we have got the Smart Antenna Systems where the radiation characteristics of the Antenna are automatically changed to maximize the reception of the signal. So we require a thorough knowledge of electromagnetic wave propagation in the analysis of Antenna or the Smart Antennas.

Here is another Smart Antenna System which has not one beam but have multiple beams and these beams can be switched or they can be placed inside this space on permanent basis.

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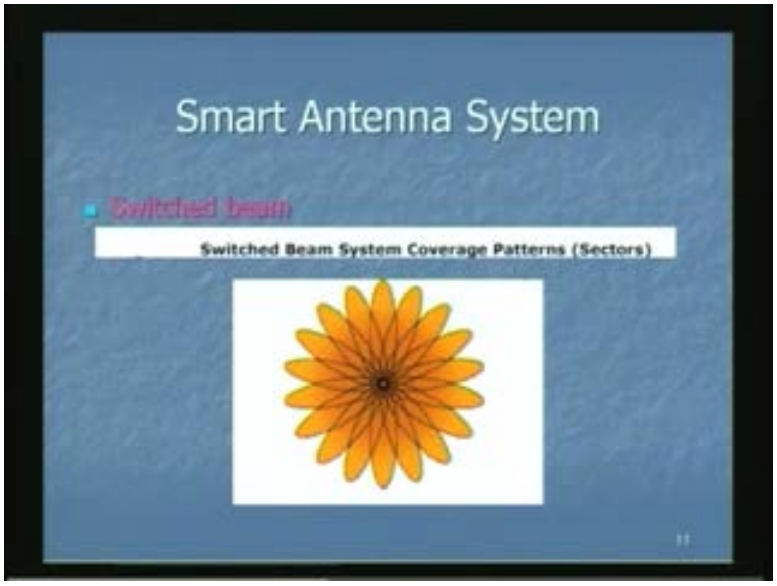

And one can transmit the signal or can receive the signal from that zone depending upon which area the observer is. So controlling the radiation characteristics is one of the important aspects of Antennas.

The next area where you require a thorough knowledge of Electromagnetic Waves is the Satellite Communication. The Satellite is an object which is placed above the earth's surface.

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So here you can see the Satellite picture. This is the earth and this is the Satellite where this picture is taken from the Satellite towards the earth.

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And this is the station called a Earth Station. The transmitted signals from the earth to the Satellite and from the Satellite to the earth are received by this station.

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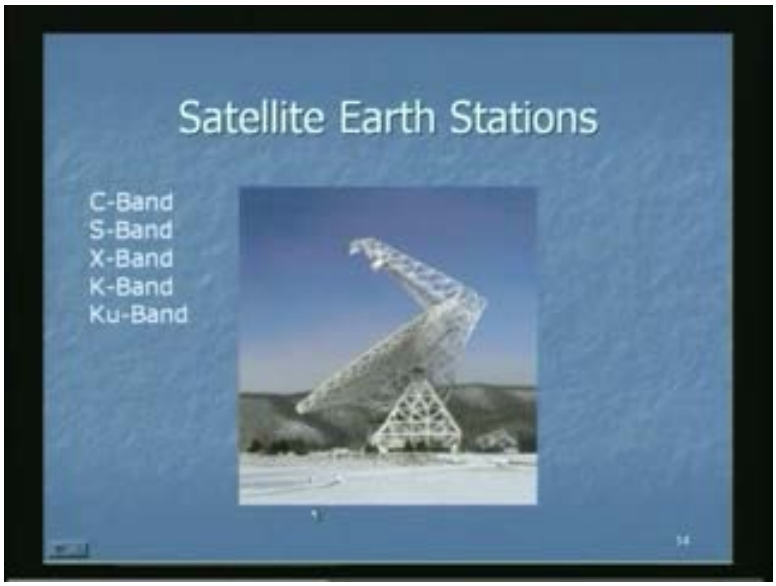

There are certain frequency bands assigned for Satellite communication called C-Band, S-Band, X-Band, K-Band and Ku-Band.

So in this mode essentially we have electronic systems here with an Antenna and we are having our station here, the signal is transmitted from the Earth towards the Satellite.

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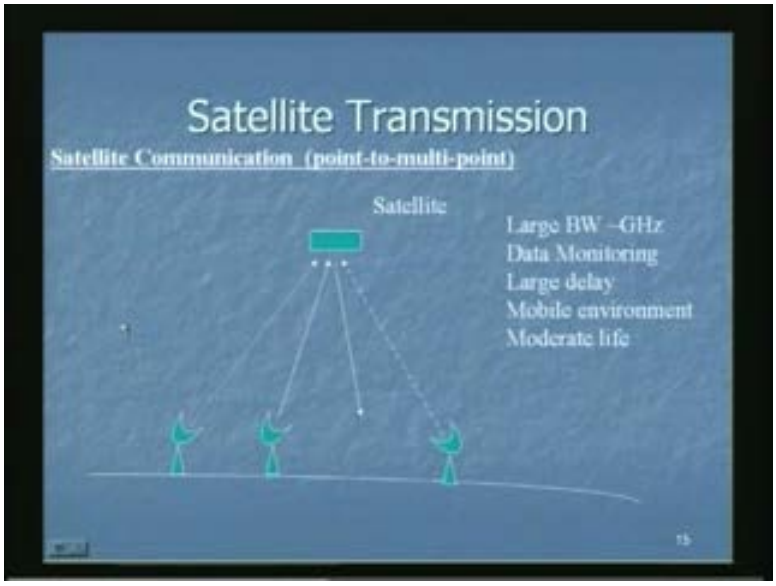

The satellite receives this signal converts its frequency and then sends it down towards the earth and this signal which is coming towards the earth can be received by the receiving stations on the earth. So one can establish a communication between one point on earth to any other point on earth. This whole propagation of electromagnetic radiation and proper placing of radiation in a direction towards the earth is controlled by the electromagnetic wave phenomena.

So, essentially again we require a good understanding of the propagation of Electromagnetic Waves in investigating of propagation of energy from ground to Satellite and from Satellite to ground. The Satellite is one of the modern communication transmission devices which have a relatively large bandwidth, it can transmit the data which can be itself monitored and it provides you a mobile environment. So in fact Satellite was one of the modes of transmission with a large bandwidth before the Optical Fiber came.

Later as the time progress the Fiber Optic Communication came.

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Then the knowledge of Electromagnetic Waves is required for investigating the propagation of light inside the Optical Fiber.

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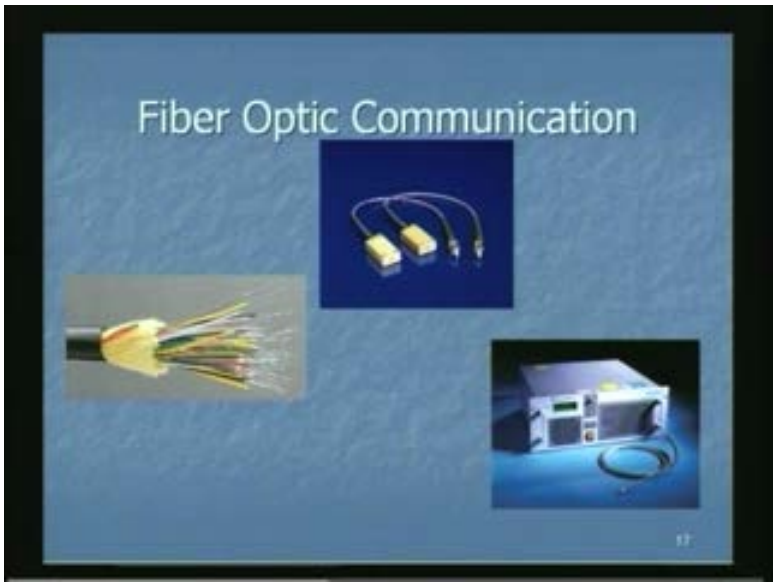

Here you can see a set of optical fibers having a very thin structure which is made of glass through the light is propagated. And we require a good theoretical understanding of propagation of light inside this because the signal gets distorted as the light propagates inside the Optical Fiber. Unless we understand fully how the signal get distorted one will not be able to tell how efficiently or properly the data can be transferred on this medium which is Optical Fiber.

Similarly the devices which are used for optical communication which are lasers again require a good knowledge of electromagnetic waves. Then when we come to the Wireless Communication which is the most modern mode of communication, again you require various aspects of electromagnetic waves.

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Here you can see father of Radio Communication is Hertz, he is doing some measurement on radiation. This is an environment where there are lot of gadgets which all works on electromagnetic wave principle, this is a mobile phone

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So all this together we will see today in a mobile environment all these devices are working on principles of Electromagnetic Waves.

In this modern communication called a Cellular Communication we have the base stations from where the signals are transmitted and then you arrange users which are located inside a cell.

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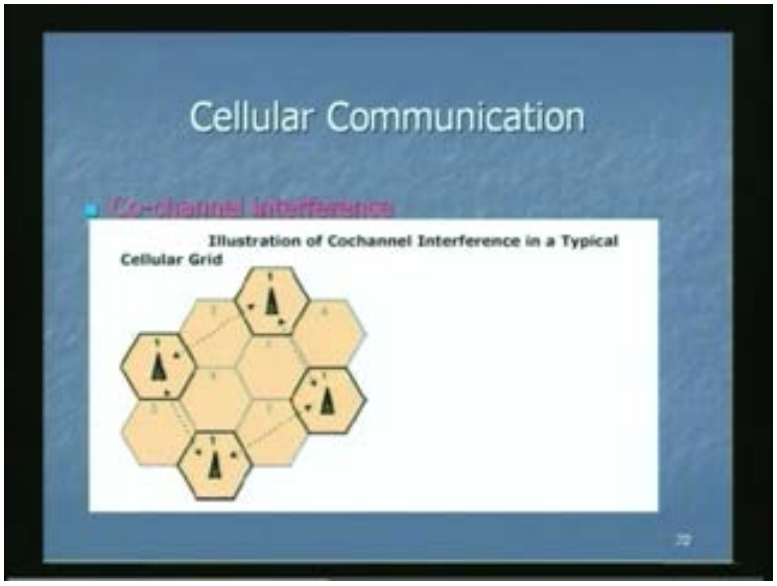

So any mobile call which we make goes from handset towards base station and then the call is diverted to the appropriate user so we have a constant communication between a mobile handset and our base station. So again you require a good propagation model in this environment especially when we are talking about this environment in cities where we are having large buildings and structures which are having lot of reflections and refractions of electromagnetic waves we essentially have a very complex electromagnetic environment. So as the object moves inside this structure from the base station towards the receiver one not only gets the signal which is coming directly from base station to the user

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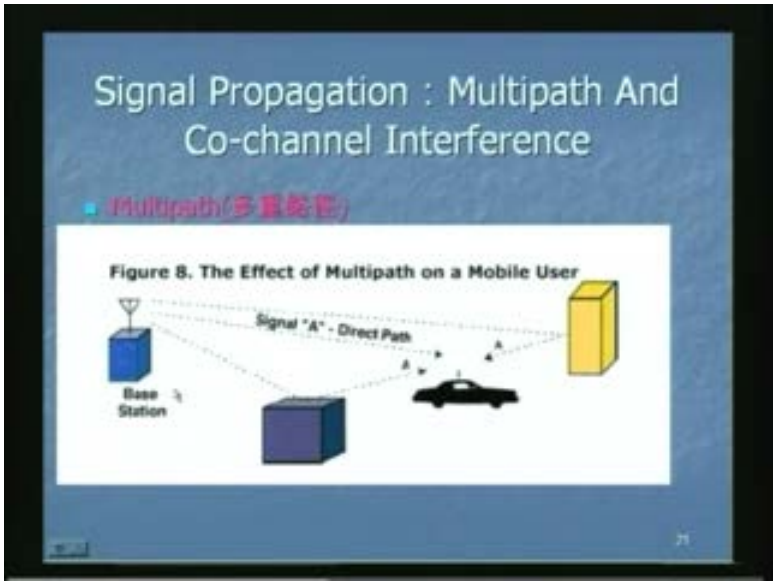

but you also get the signals which are coming after reflections from this objects so what one receives at this location is a combination of the signal which is coming by the direct path as well as the signals which are deflected from the buildings and other objects which are in the vicinity.

Now as the object moves the total signal which you receive here is essentially an interference of all those signals which leave from multiple paths. So as this vehicle moves the lengths over which the signal travel they change and as a result you get a phenomena of interference which could be either constructive or destructive. Whenever we have a constructive phenomenon you can have a strong signal where as if you have the destructive phenomena then you gets very low signal otherwise there is cancellation of signal.

So one notes that as the vehicle moves the signal varies as the function of time and those phenomena essentially is called the fading phenomena. And to understand properly this fading phenomena one requires a good modeling of propagation of these electromagnetic waves in this complex reflecting and refracting environment.

To avoid this fading phenomena one can create systems where the reflected and refracted signals are not received by this objects.

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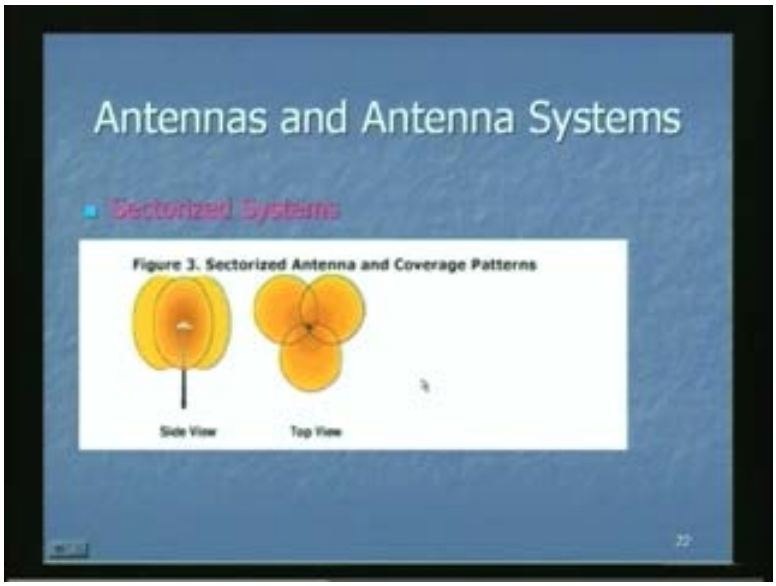

So if you make the receiving antenna's not omni directional or suppose they are directional and if they can receive signal only coming from this direction then the deflected signal contribution can be reduced, as a result the effect of fading can be reduced.

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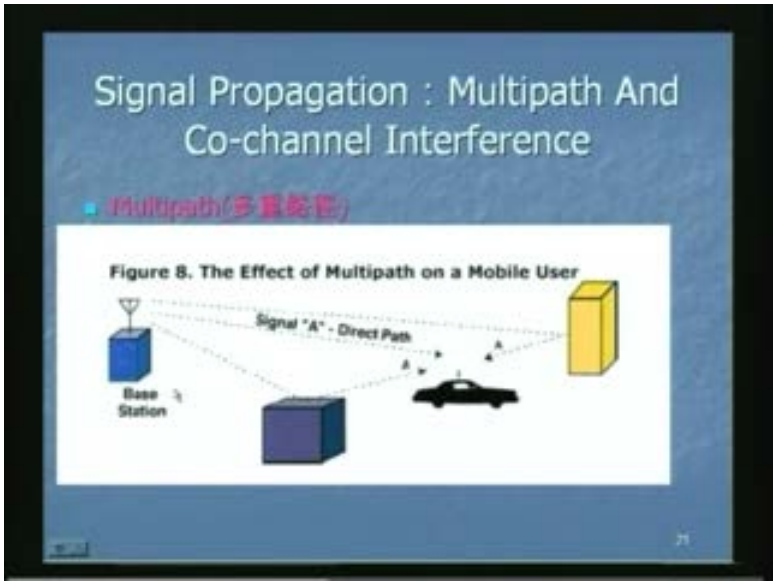

So again you require good design of the antenna systems which again require a good knowledge of electromagnetic waves so that the multi path interference in a mobile communication can be reduced.

Again we can use the Adaptive Antenna System essentially to reduce the interference and especially if you are having the environment which is mobile then one has to keep changing the direction of reception as the vehicle moves. So you require some kind of a Smart Antenna or Adaptive Antenna.

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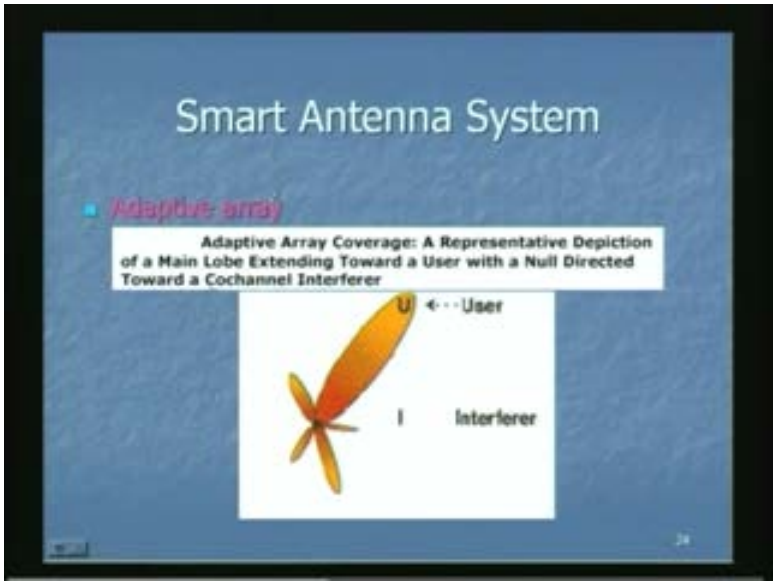

Another application of Electromagnetic Waves is Radar and Remote Sensing.

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As we know Radar is a device which is used for finding the distance of an object. The principle of Radar is as follows: we are having an antenna here which is excited with an electromagnetic pulse.

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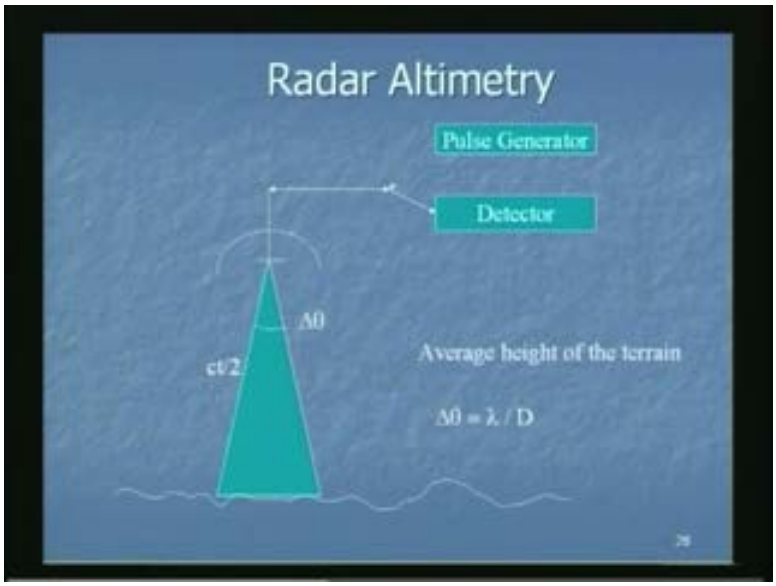

This pulse is radiated by this antenna into the space the pulse goes and hits the object and part of the energy is reflected from the object which again is picked by this antenna and is processed in the detector. Then by knowing the time delay of this pulse one can estimate the distance of the objects and also if the object is moving in the radial direction then one can measure the change in frequency of a signal what is called the Doppler Shift and from that one can estimate the velocity of the object.

So the radar essentially uses the electromagnetic pulse to find the distance and the velocity of an object. Again since we are transmitting a very high frequency electromagnetic energy here we require very special designs for these antennas and also we require certain techniques by which the resolution of this device can be improved so there could be either signal processing techniques or there could be even electromagnetic techniques which an can be used to enhance the resolution of the Radar.

In general, essentially we have the antenna called a Monostatic Radar so the signal goes from the Radar Antenna to an object, they are deflected from here again received from here and one can calculate received power

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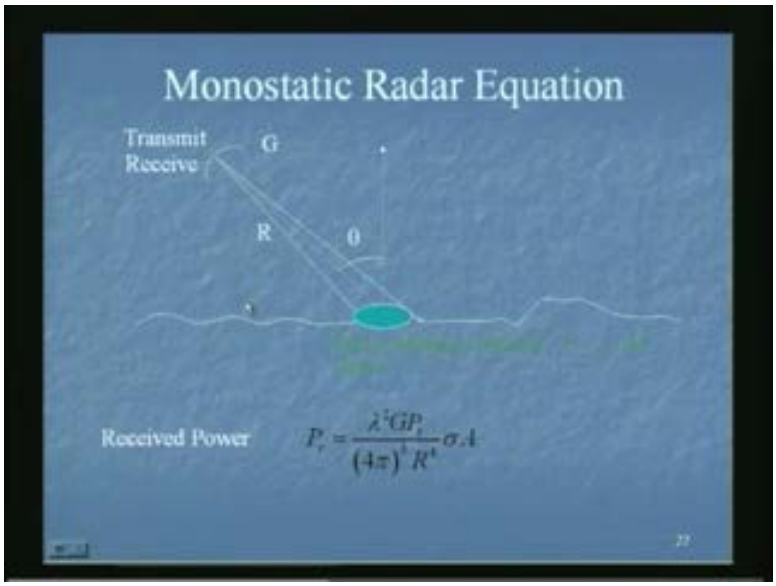

So firstly you require a good modeling of the propagating medium and also a good modeling of the scatterer or the object form which energy is going to be reflected. So in fact a parameter called the effective cross section of an object requires a very good modeling of electromagnetic waves. In fact there is significant work has been done in modeling different objects and finding the radar cross sections of objects which are made from different materials and which are of different shapes and sizes. The Radar is also used for remote sensing that is if you have a vehicle here which can send the radar pulses down towards the earth and the reflected energy is measured by the Radar.

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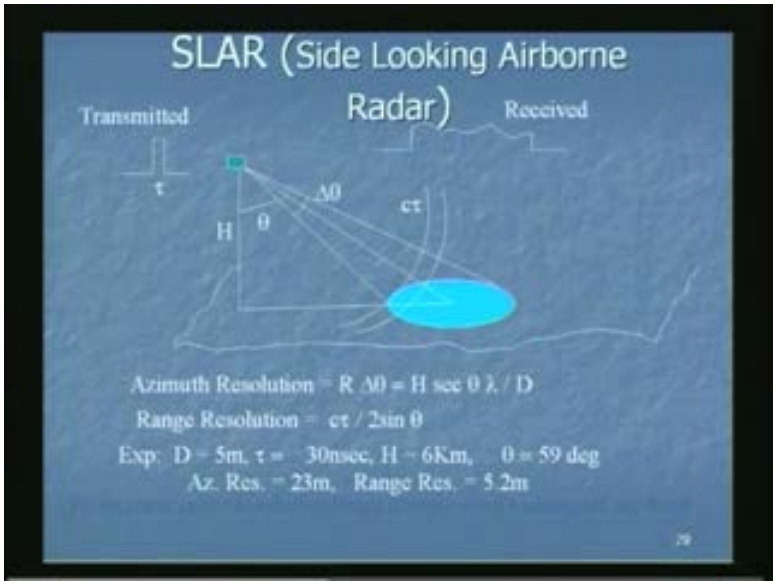

As the vehicle moves essentially we can get the reflectivity of the terrain at different locations. Then by combining this information which is coming from different locations on the earth essentially one can create a map of reflectivity of the earth surface and since the reflectivity depends upon various parameters like what is the vegetation, what is the conductivity of the earth surface, whether this is a water body. One can essentially do some kind of a mapping from reflectivity measurement to the actual objects on the earth surface. So Remote Sensing is one of the very important field where modeling or knowledge of Electromagnetic Waves play the important role.

To improve the resolution of radar in remote sensing one uses a technique called a Synthetic Aperture Radar.

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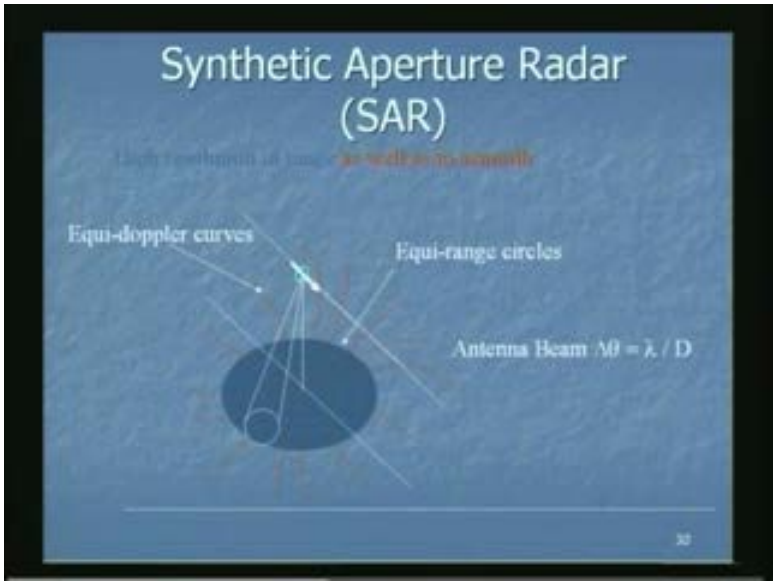

For an Antenna like parabolic dish the angular resolution is approximately given by the wavelength of operation divided by the size or the diameter of the Antenna. So one can see that to get a very fine resolution in an image which we have got from remote sensing we require a very large aperture. These kinds of large apertures cannot be very easily created especially on the vehicles which are moving like aero planes or Satellites. So a very clever technique called a Synthetic Aperture Radar Technique has been developed where the antenna size is small but the vehicle moves and the reflection information is stored as the vehicle moves. After all the reflection information is collected from the different locations then a data processing can be done to get an angular resolution which will correspond to the total distance traveled by this vehicle. This technique is extremely powerful technique because without having a physical aperture or a physical antenna one can effectively realize an aperture size which could be of the order of tens of kilometers.

Therefore one can improve the angular resolutions substantially. So again you require good analysis of electromagnetic waves. And if you go to the Synthetic Aperture Radars then you get very nice characteristics.

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Firstly, you get a very high linear resolution from this Radar which is independent of the range though it requires very large atom processing. So electromagnetic waves find very active application in investigation of Synthetic Aperture Radars.

The same techniques is used very actively in a branch of Physics called Radio Astronomy where the signals are coming from the sky are measured.

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So a typical Radio Telescope would look something like this, the signals are coming from sky what you have is a very passive receiver nothing is transmitted in this case like radar so we have an Antenna where the signals are received.

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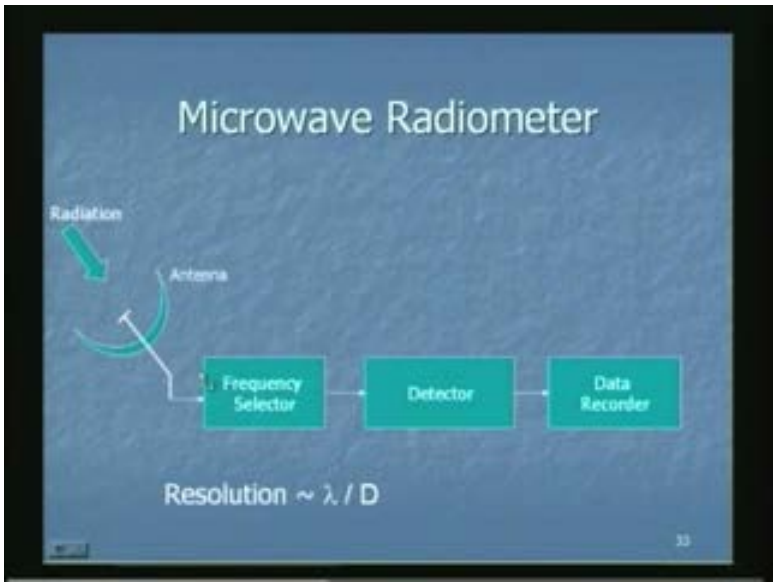

They are frequency converted, detected and processed. And again we would like to know precisely from which direction a radiation is coming or in other words by a Radio Telescope one would like to get an image of a sky with as larger resolution as possible. So again this resolution limit λ/d comes into picture and one requires very large telescopes to get a very fine resolution of the image of the sky.

Again since realization of very large telescope is very difficult and again falls back on the technique called the Aperture Sensor Technique as we saw in case of Radar.

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But in this case we have a set of Antenna which are located on the earth, each Antenna might look like that or could be some other shape. Then by collecting the information from these entire Antennas one can actually have a effective dish which is of this size. so one sees that each dish here which is a primary antenna which could be of the order of about tens of meters but by using this technique one can create an aperture which is typically of the order of about tens of kilometers. Therefore one can get an angular resolution which is far better than what one can get from a single dish.

So Radio Astronomy is one of the areas where again the knowledge of electromagnetic waves plays a very important role. It helps you in designing very effective Antennas and thereby giving you a very high quality map of the radio sky.

This is the same picture of an array which synthesizes an aperture which is of this size.

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This dish is of the diameter 25 meters but the total spread of the antenna is of the order of 21 kilometer and therefore we get an effective aperture which has a radius of 21 kilometer though each antenna has a diameter of only 25 meters.

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This is the image which you get from the sky and you can get very high angular resolution.

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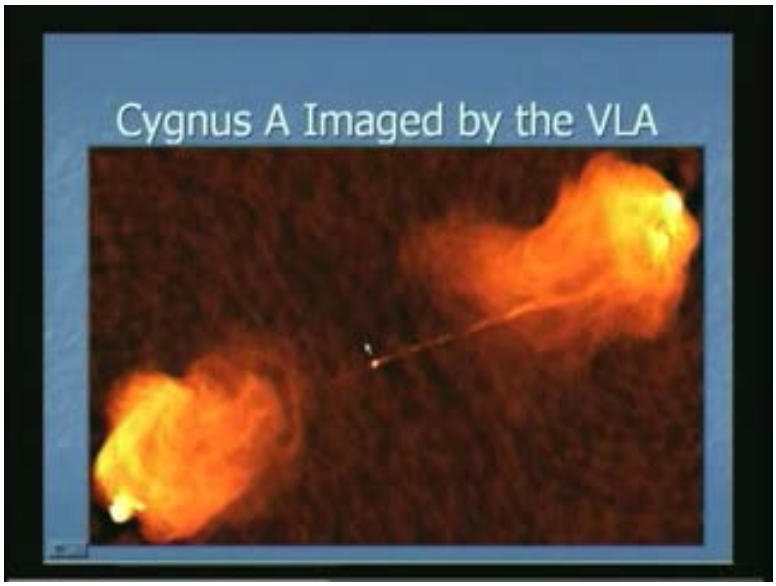

This is another object you can get in the sky.

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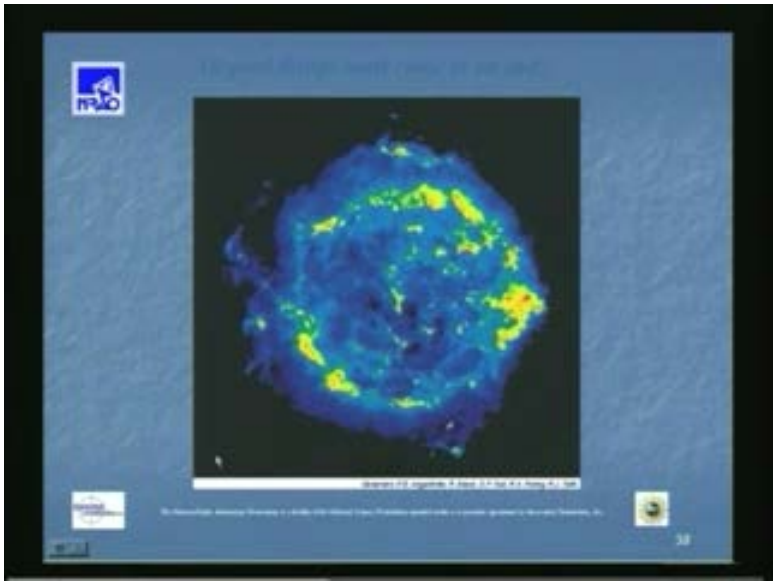

So these are the areas in which essentially have very active applications of Electromagnetic Waves. so though the phenomena is very basic phenomena and as I said this phenomena has been under investigation for many more centuries the focus or the emphasis is changed depending upon the applications.

So in today's scenario when we are having the communication dominance we see a variety of phenomena which are related to high frequencies and which have direct application in the areas of communication.

This course essentially deals with the subjects which are the high frequency phenomena.

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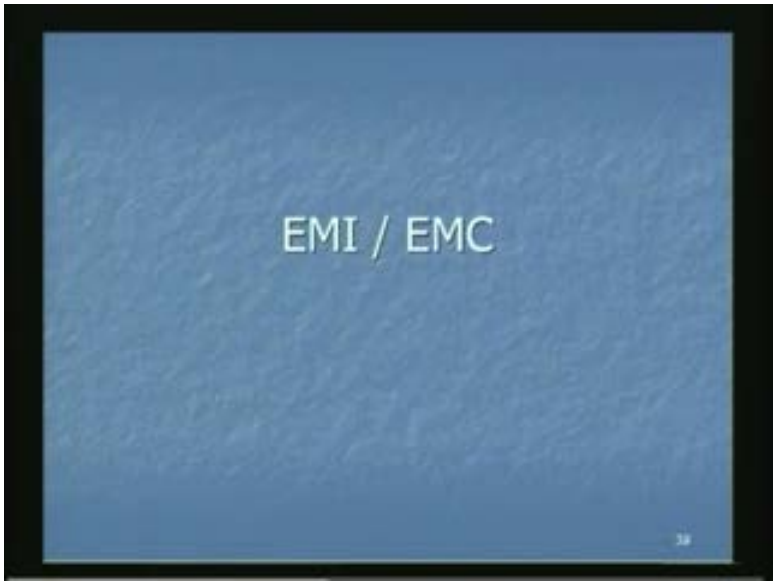

When you are having so many signals which are at high frequencies present in the environment then it is natural to have the interference created by one system to the other. So we require techniques to mitigate the electromagnetic interference and that is what essentially is done in this branch called EMI and EMC.

The EMI is the Electro Magnetic Interference. So first we study how a high frequency device would create interfering signals and then what are the ways by which this interference can be reduced. In fact any time varying signal and if it is varying at very high frequency then it will create lot of interference.

Take a simple device like an in inside a computer a switch more power supplies where the current is switched at a very high rate it creates lot of electromagnetic interference. So if you are having any other instrument in the vicinity one sees interference created because of this high switching current. Also one would remember that we may get interference on our radios whenever somebody starts a car or a scooter in the vicinity because whenever we start a scooter there is a sparking and because of that spark you get

electromagnetic interference which is picked up by the radios and then you get disturbance on your radio.

So as you are having more and more devices which are operating at high frequencies the environment now is having lot more interfering devices. Therefore it is essential to investigate the techniques by which the interference can be reduced or one has to find the mechanism by which the devices can be isolated called shielding. One can shield the devices from one another or the devices become more and more electromagnetic compatibly.

So today whenever we design electromagnetic gadget or an electrical device it is mandatory to make it electromagnetic compliant so that it does not create additional electromagnetic interference which will affect the other systems.

In this subject, essentially we are going to discuss the high frequency aspects of electromagnetics is the electromagnetic waves.

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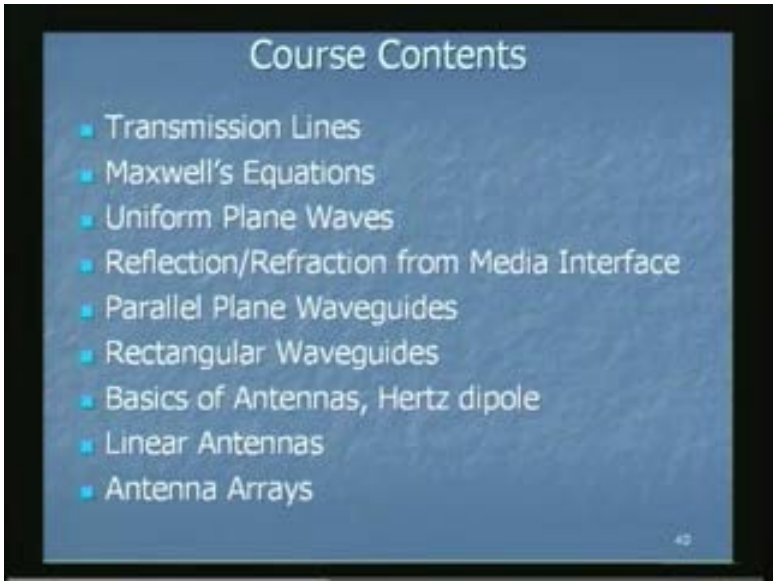

So first we talk about the Transmission Lines where we still deal with voltage and current. Till now we have developed our understanding of the circuit in terms of voltages and currents, suddenly if we start talking about electric and magnetic fields it might appear that we are talking about totally different subject. So in Transmission Line essentially we make a slow departure from our low frequency circuit analysis to the high frequencies. So what we try to do is we still retain the terminology of circuit that is we talk about voltages and currents circuit parameters like inductance, capacitance and assistance but we introduce the concept of space and then naturally we get the solutions for voltages and currents which are waves as soon as concept of space is introduced in the circuit analysis.

So we get a phenomenon of electromagnetic wave though in the form of voltage and current but that gives at least the foundation of a wave phenomenon. Though this is going to be related to voltages and currents we are talking about only scalar quantities but that provides at least some field for the electromagnetic waves. Once that concept is understood we go to next topic in this course which is Maxwell Equations which are the foundation of the Electromagnetics.

We starting from the basic laws of Physics establish the Mathematical equations which are called the Maxwell's Equations.

Then we ask that what is the solution of the Maxwell's equation in a medium, how the electric and magnetic fields exist inside a medium and then we start with a very simple case that is a medium which is unbound and then we find that the solution we get for Maxwell equations in that medium is the uniform plane waves. Then we go further and try to investigate how this uniform plane waves would behave when there is a medium discontinuity.

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So how the energy transfer takes place from one medium to another medium if there is a sudden change in the medium properties. This comes under this topic of Reflection and Refraction from media interface. Then we make the medium which is a special medium is the conducting medium so then we take the reflection of the electromagnetic waves from the conductors and naturally we migrate into a structure called Parallel Plane Waveguide. The Parallel Plane Waveguide is a structure which is essentially two conducting sheets parallel to each other and the electromagnetic energy propagates between these two sheets.

And later on we modify this device to Rectangular Waveguide where we put two more parallel planes perpendicular to the earlier planes so that you create a pipe in which the electromagnetic energy is trapped.

So if you see the journey of this course from here to here is essentially to capture the electromagnetic waves into more and more bound region. In this case we start with the unbound medium then we go to this one where we just try to put a boundary so that the wave is confined in half of the space then we try to capture the waves between two boundaries finally we try to capture the wave inside a pipe which is called a Rectangular Waveguide.

Then later on in this course we discuss the basics of radiation that is under what condition the radiation will take place. And the very basic device or the very basic element which can give radiation is called the Hertz dipole is investigated and then by using this knowledge one can go to more practical antennas called the Linear Antenna.

Following these we will go to more complex systems called Antenna Arrays and that will give us the knowledge of how to manipulate the directional characteristics of radiation from the Antennas.

So these are the topics which will be covered essentially in this course. Now let us look at the some of the devices which work on the principles of electromagnetic waves before we close this.

The simplest one is this Co-axial cable you can see here. This is basically a Transmission Line. you can see there is outer conductor here and there is a center conductor here.

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So electromagnetic energy propagates inside this and as I mentioned earlier these kinds of structures Transmission Lines are used at frequencies up to few Giga hertz.

Then the devices which are based on electromagnetic waves are this structure called an Horn Antenna. This is in the shape of a horn. There is a connector here which is of Co-axial type.

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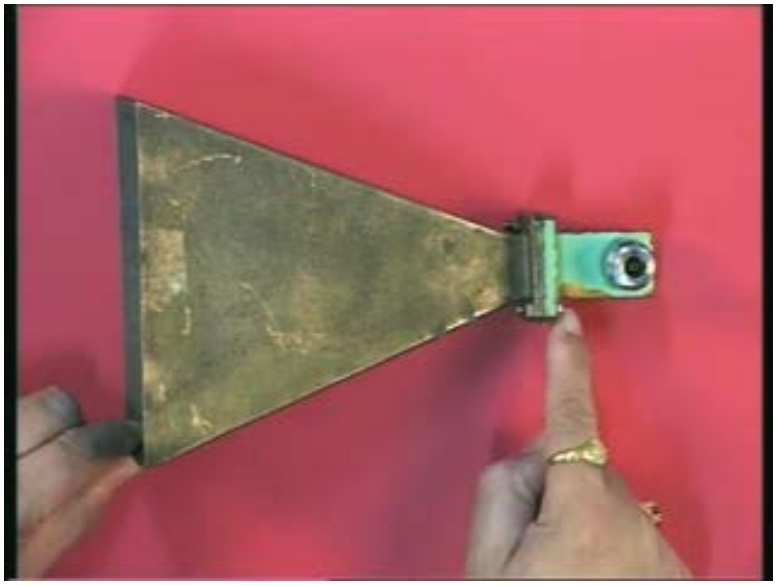

So electromagnetic energy is connected at this point, these are sides this structure which is the wave guiding structure and then my flaring this wave guide in this shape essentially the radiation goes into the space. So this device is an antenna which is normally used at microwave frequencies.

Then we are having guiding structures optical fibers and this is a optical fiber which is made of plastic. One can see here that there is a inner portion here through which the light is guided.

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and the light can now go through this structure can emerge very efficiently from the other end of the fiber. So the electromagnetic wave in the form of light can be sent over very long distances by using optical fibers.

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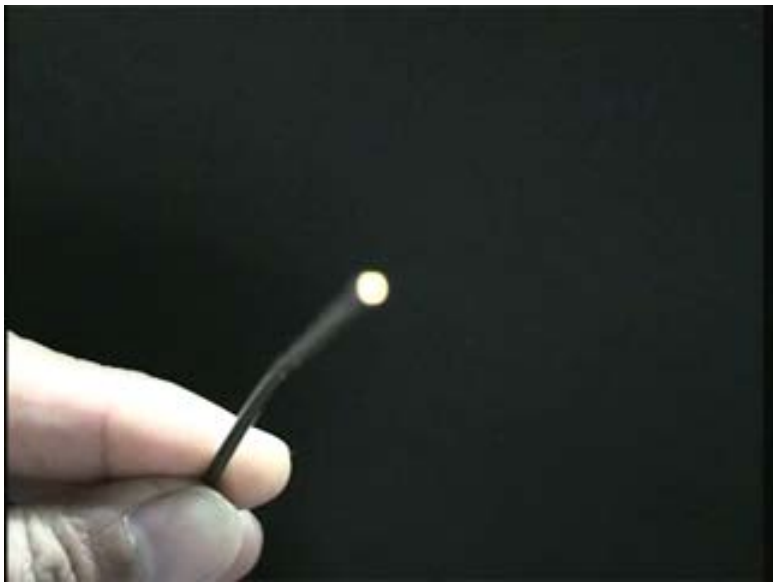

This is another optical fiber which we have here, this is very thin typically of the order of about 125 micron so the thickness is little thicker than hair.

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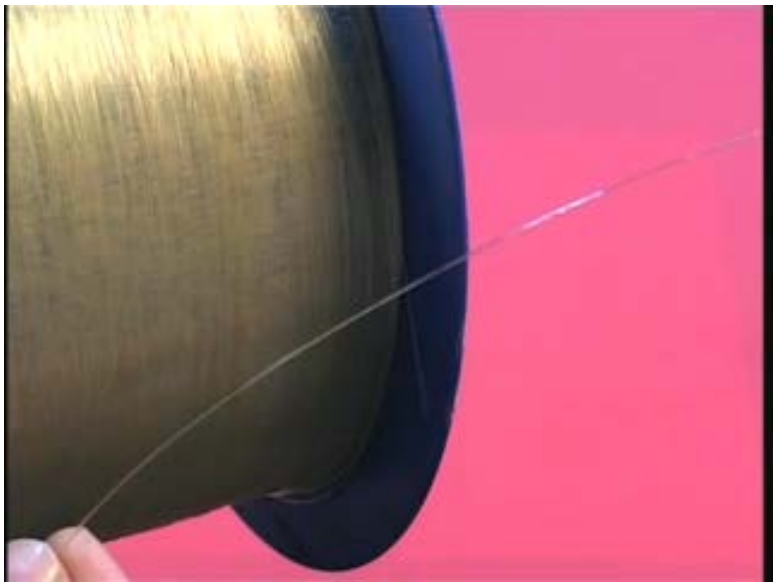

And this is the fiber actually is used in practice for sending the information over very long distances.

So you see all this devices which we are seeing here either Co-axial Cable or the Horn Antenna or an Optical Fiber all of this require a thorough knowledge of Electromagnetic Waves.

So basically this course on Electromagnetic Waves is the foundation course for time varying electric and magnetic fields and predominantly its application is towards communication but there are many other applications also which are not communication related for example microwave oven in which the things can be heated by using the microwaves work on the principles of electromagnetic waves.

So in this course we are going to build the concepts of high frequency circuits and the basic phenomena of time varying electric and magnetic fields which are Electromagnetic Waves.

Thank you.