

## **Radio Astronomy**

**Prof. Abhirup Datta**

**Department of Astronomy, Astrophysics, and Space Engineering**

**Indian Institute of Technology Indore**

**Lec-32**

### **Lecture 1 - Revision**

Hello everyone, I am Harsha Avinash Tanti and I am your TA for this course. So let us revise from the starting. So how this radio astronomy came into picture. Okay. So from the earlier, means like from the earlier times, what we used to see is some stars and all by naked eyes, so which is in visible range. Okay, this band.

Also, we used to see something called twinkling of stars. We see in radio astronomer terms, it's also called scintillations. Okay, twinkling or scintillation. Scintillation is just a, it's like a scientific term, term, which means if your wave is passing through some media, it goes under a scatter means diffraction, which causes twinkling.

It can be atmospheric reason also due to ionosphere. So, so with this and in late 1900s, we know, we came to know that besides visible range, there is huge amount of means very broad electromagnetic spectrum. And also it was discovered that in radio frequency range and up to this is I think around 16 megahertz. Okay. To a few, few gigahertz.

Okay. About X band till about X band, which is, which is eight to 12 gigahertz around. Okay. For this, the atmosphere is kind of transparent. Everything can pass through and there is no, nothing at such much of a loss while transmission.

So for, for that reason, people started being at this, this band and above six below 16 megahertz band, ionosphere blocks everything. Okay. So we will also see why it does later on, but just here. And also with the kind of, also with the knowledge of the radio astronomy and all, we also came to know about something called cosmic wave background and sky temperature, means the flux density and all for which we tried to build telescopes to see whether all those theories are correct or not.

Okay. Now the base root of this means the basic theory on which this entire radio astronomy is dependent upon is what is called the electromagnetics. Okay. So electromagnetics or electrodynamics or EMT means electromagnetic theory. It, it is made up of two things, electric and magnetic field theories.

Okay. And which, which is nothing but, but kind of front and back of the same point face and head and tail of the same point. Okay. Because, and which was explained by Maxwell's equation also. So we had first what electrostatics, something called electrostatics, where we have electric

charge, electric charge, which follows conservation of charge. Then there is something, if we go deep into atomic theories and all, then there is quantization of charge, quantization of charge.

Why? Because we have, we can have this smallest negative charge as electron, electronic charge. Okay. And then uh, with this games, Coulomb's experiment, which gave us Coulomb's law, which is very similar to the gravitational law, which was, um, explained by a means, which was put forward by Newton, but for electric charges. And here the constant  $K$  is nothing but one by four by epsilon naught, where epsilon naught is permittivity of free space. Say if there is two charge in a media rather than in a free space is then there is another term which will come into picture, which is epsilon r, which is also called as relative permittivity, relative permittivity.

That means the permittivity of the media to the permittivity of the free space. Okay. This is what relativity, relative permittivity is defined as. Okay. And from electric charges, comes electric field, then electric field intensities, field lines.

There is general rule that electric field lines never cross each other. Okay. And also a different concepts like potential. One of the main, uh, means, uh, main concept, which led to, uh, explanation of your plane wave.

Okay. Now, potential, what is potential, uh, potential in general sense means, uh, say, uh, in literally literally, uh, in terms of literature, literature, potential is ability to do something. Okay. So here also the potential is defined such that the, if you are doing some amount of work, how much, uh, energy will be consumed per minute, I mean, energy will be consumed kind of thing. So that's how potential is also defined. And after this, this came electrostatics, which was similar, uh, to it, uh, magnetos, I mean, after a little, several teams, magnetostatics, which was similar to electrostatics, but this was due to current carrying conductor.

Okay. So current carrying conductor will create a magnetic field around it, which will be, which will, which will encircle it. And the magnetic field will be directly proportional to the amount of the current, in the current element for the small, uh, infinitesimal part over the  $RQ$  means the, at the distance, which you are measuring. Okay. And with this, there is a constant term comes  $K$ , which is mu not by four pi.

Okay. So with all this is we moved on to something called electrodynamics where electric and magnetic field coupled. And we saw what is plane wave and that, that whole things was governed by something called Maxwell's equation or the Maxwell's theory put forward by, uh, Maxwell J Maxwell. Okay. So the, there were kind of four laws to it. First law was Gauss's law of electricity, Gauss's law of magnetism.

Actually, this has, uh, most of, uh, most of the scientists consider no name, but, uh, still with some, uh, some of them says that this is Gauss's law of magnetism. Okay. So the first, this is the integral form. There is also differential form. The official form is nothing, but they'll dot B.

So nabla dot B is equals to row where D is nothing but Epsilon not E okay. Now Gauss's law of

magnetism can also be written in differential form, which is  $\nabla \cdot \mathbf{B}$  and this is divergence, divergence of  $\mathbf{B}$ . So it is zero. So no divergence of  $\mathbf{B}$  is equal to zero suggests that there is no diverging magnetic field. What is divergence means going out of a point.

Okay. Say something is here and if it is going out, then it's divergence. And if it's going out and then, uh, again, coming when this is curling, curling of a field. Okay. So if we see electric field, when it was introduced, you see that there is a charge here and the fields are going outside if the charge is positive.

Okay. So this is kind of diverging out. So then, then there must exist divergence of a electric field. And when we started viewing the magnetic field, we always talked about curling of the, uh, field means there is a circular magnetic field here. Okay. So with this, you see, there is no divergence divergence.

That means no magnetic monopole exists. This is how the interpretation of no magnetic monopole came into picture. Okay. After that Faraday's law of induction came before that Ampere's circuit law came Ampere's law, which was modified by, uh, Maxwell James Clark Maxwell.

And the addition was this term. Okay.  $\nabla \times \mathbf{B}$  by  $\nabla \times \mathbf{D}$ . Okay. Now here, uh, in Ampere's law, Ampere's law, what it suggests is if, if we see it's differential form and it's very easy to interpret both of the forms forms, but it's very much easier to, uh, kind of, um, very much easier to, uh, explain the differential form or, or understand it different differential form. So we, if we have curl of edge means of a magnetic field strength is curling around a point, then that will be because of the current density flowing from the center.

Okay. Means if, if the, if you say there is a curling of a magnetic field, that means from here, there is a electric field. There is a current going in this direction. This was, was this was what was suggested by Ampere. No means Ampere by Ampere's law. But Maxwell saw that when, if you say, if you have a capacitor in between, okay.

And you connected to a kind of AC source. Okay. So we all might, we've all have learned in class 11 and 12 that capacitor passes AC blocks DC. How is that? See capacitor has empty space in between. So what is current is movement of electron.

Okay. Movement of electron through a conducting wire. Now what, what happens in DC current is you have one side positive charge and another side has negative charge. So, so what will happen? A negative charge will have most of the electronic accumulation. So all the electrons will move from here to here.

Okay. Now, if there is a, there is a capacitor over here, what will happen? This circuit will be, this circuit will be broken and the charge will accumulate. Negative charge will accumulate over here and positive will accumulate over here. So virtually you will see no current here. You will see only field lines from top to bottom electric field lines.

Okay. But when AC current is there, so what happens one times electron goes like this and the, for the other cycle, electron goes like this means there is alternating cycle of electron flow. So it seems like current is passing through, I mean, current is flowing through the circuit, right? But actually no electron is passing from this plate to this plate from crossing the empty space or the media. What is happening? This is getting charged and discharged again and again. Okay. But, but what the conservation law and the, this circuit law suggests that there must be something which is allowing the current to pass.

So maximum suggested an edit addition over this term, which was  $\nabla \times \mathbf{D} = \mathbf{J} + \nabla \times \mathbf{D}$ . And this was kind of groundbreaking because this took the entire electrostatics and magnetostatic regime to the electrodynamic means the, in between this, the Faraday's law came, which says that the circulatory electric field produces time-changing time variant magnetic field. Okay. And this negative sign is due to Lenz law that the, it will be opposite in the kind of direction will be opposite. So this was, this was already there that curling of electric field will generate a magnetic field, but the concept means like those, the both things are linked with each other was not yet present.

Okay. Without something called a source term. So there was always a source term there. Source term is like a charge of a converted electron is called a source, I mean source and a following current through a wire is also a source to generate magnetic field. So this, when the, this term is this term was introduced, this made the electromagnetic theory as a whole. Okay. This suggested that even if the field change is present means the curling of magnetic field generates means is generated can also be generated by time varying electric field as  $\mathbf{D}$  is nothing but displacement, which is also called displacement current.

And this is also called displacement current  $\nabla \times \mathbf{D} = \mathbf{J} + \nabla \times \mathbf{D}$ .  $\mathbf{D}$  is nothing but  $\epsilon_0 \mathbf{E}$ . So that is, is time varying electric field can generate curling of a magnetic field or curling of a magnetic field can generate it time varying electric field. So this equation, if there is no source term, so this term is essentially source term for electric, electric fields.

Okay. So it's, it suggests there is a source and ampere circuit law when it was not whole. So  $\mathbf{J}$  is here the source term. So this is, this was also not present. So earlier it was only the curling of magnetic field was due to a source term.

Now there is also time varying term. Now this two equation laid, means became the groundwork for the plane wave equation. So if there is no source term, the curling of magnetic field can be generated by time varying electric field and the curling of electric field is generated by time varying magnetic field. And this two became the entire means kind of base for the electromagnetics theory means whatever the electromagnetism is right now.

Okay. So this is how the story goes. Now this is something called mind map of the means electric field theory. So don't bother about the numbering over here. So we have we took this from a paper, which was, means, which was about some kind of neural algorithm for studying

electric field theory, but it's, it's something goes like this. Okay. So the first game charge, something called charges was identified.

Then came something called interaction between the charges and identification of charge led to definition of charge. What is charged? And with this interaction, a definition of charges and interaction between them generated Coulomb's experiment, which led to Coulomb's law. And this is how everything is inter linked.

You can go through this. You can go through this. I mean, we'll share this, these slides with you. And this kind of creates how the theory is linked with one and another. And this way means this is the kind of a trick you should learn how to relate one particular concept with another. Okay. So moving on, then we then in week three, we went to something called antennas.

So why antennas? Now antenna is as defined as a transducer, which can convert one form of energy to the other form. Okay. And this energy is electrical to radiation. So it can, it can produce radiation energy given the electrical energy and also do the vice versa, given the radiation energy, it will convert it to your electrical energy and which is also called sigma. Now, with the understanding of all the electromagnetism, we need to go for the practical field of this.

So how we will detect those things, because radiation, the visible light we can see, but the non-visible spectrum, we know from the theory, there is non-visible spectrum with, there's a huge, there's an infinite bandwidth, which we cannot see. So how we will detect those things. So there comes the concept of antennas and their relation. So the primary thing, if you revisit week two, you will learn about something called Hertz dipole or infinitesimal dipole, where the theory is elaborated that if we have a very infinitesimal wire, and if we provide a signal, I mean, kind of a signal to it, time varying signal to it, it will radiate isotropically.

So infinitesimal dipole can radiate isotropically. Whereas if you want to go for practical designs, we will go to the lambda comparable antennas. So typically for wire antenna, lambda by two dipole is there, lambda by four dipole, lambda by four monopole is there. Okay. Lambda by four, that is monopole and also lambda by four dipoles are also there.

Okay. And these are all, these all depends upon few of the characteristics of the antenna as well as your system. So if you want to observe any electromagnetic spectra, let it be from the perspective of radio astronomy or communication. Okay. You have to design in antenna as well as the system, which will detect those signals. So for that, this there is something called max power transistors here that should be satisfied.

So, so before proceeding to that, there are a few things you should understand for the antenna that antenna has from the perspective of radio astronomer, you will always deal with something called full width half maxima, as we say it, and which is also the antenna called half power beam width. Okay. Full width half maxima and half power beam width is one and the same thing.

And there is also first null beam width. Okay. FNBW. Okay. Sorry. FNBW. So these two terms,

radio astronomers used very frequently. And also with this also comes something called efficiency of efficiency, aperture efficiency, which is  $\theta$  maximum time demoted as  $\theta_a$  or ECD, something like this. And also there is something called beam efficiency in means learn in few slight minutes a bit later.

Okay. Beam efficiency. Okay. So these, there are, these kind of terms are quite common. You will encounter in when you are doing any kind of data analysis and all in radio astronomy. Okay. So how this came into picture. So we have an antenna which will have its radiation pattern, radiation power pattern.

And with that, you can find out the something called normalized power pattern. And when you equate this normalized power pattern means this is normalized power pattern. When you equate this with 0.5 and zero, you get if you equate with 0.

5, you will get full full width half maxima. And if you equate with zero, you will get first null beam width. Okay. And also there's something called radiation resistance. This is very important if you're viewing in radio astronomy from instrumentation perspective, because you have to then design a system which will kind of log or record the data, electromagnetic data for the further processing. So you have to design systems such that, or you have to design antenna such that it will follow the max power transfer theorem.

Max power transfer theorem is a very simple theorem. Say if you have any voltage source, which is connected, uh, means any source have its own internal resistance  $R_S$ . So any practical source will have its internal resistance. And if it is connected to a load, okay.  $R_L$ . So maximum power can only be transferred if this  $R_L$  matches  $R_S$  and you can, uh, you can very well, uh, see, uh, you can very well, uh, do the math by yourself.

If, if that the power will be maximum, but  $R_L$  equal to  $R_S$ . Yes. Okay. So, uh, for the simplest, uh, so the power is covered for electrical, uh, circuit power is calculated by  $V^2$  by  $R_S$  plus  $R_L$ . So, so this term will be maximum only when  $R_L$  equal to  $R_S$ .

Okay. Now, now, and this is also can be written as  $I^2 R_S$  plus  $R_L$ . Okay. So, and sorry, this is here. You will multiply, uh, voltage across this. We have to calculate voltage across this.

Okay. So voltage across this will be  $R_L$  multiplied by this  $R_S$  plus  $R_L$ . So this is the, this is, uh, what the power equations looks like. Okay. Now, uh, this is only possible if, uh, these, this situation is matched now coming to, the formula, which is very important, which is this effective area, which is equal to  $\lambda^2$  by four by  $D$  you can find, uh, the derivation and of detailed derivation of this in, uh, several references, which we reference books, which we have, uh, means shared in week two also the names of the book we have shared in week two. So the directivity is nothing but the area of maximal, uh, where the maximum radiation is occurring. Say if we have an antenna, like everybody knows how the parabolic antenna radiates, it radiates in a single direction like this.

So it radiates in a single direction. So area, uh, the way, if this area is minimal, the area of, the area where it radiates is minimal. The directivity is maximum, but it is directed towards a single point that that was directivity means if directivity is very high, that means antenna is pointing towards a very small point. Okay. And this term is linked with the gain of the antenna, which is equal to efficiency of the antenna multiplied by the directivity.

This is how the gain is linked with the directivity. So you will have gain is equals to efficiency multiplied by your four by area over Lambda square. So this is your gain equation. And if you remove the efficiency, this will become your directivity equation. Okay. So moving forward in week, uh, so we learned about in week two, we learned about the, means kind of a base for the entire radio astronomy, which is electromagnetism.

Then in week three, we learned about how to detect those electromagnetic waves. We need some kind of a sensor or a transducer. Okay. And we learned about something called antenna. As we move forward in the week four, we, we saw something called system.

We introduced something called signals and systems. So, so whenever you receive something or some electrical wave or whatever data you are getting, we term it as signal, anything which will contain which contains information is signal, whether it is processed on, uh, unprocessed that doesn't matter, but it is termed as signal. So in this, what we learned, there is different types of signal. We can classify signals of different types. Also we, uh, we can classify systems also into different types.

It's means there are, uh, we will come to this later. What actually system means. So, so, and something we learned also like LTI linear time invariant system. Okay. Now, and in week four, we also learned something called Fourier series and Fourier transform from the formulas for which are written over here and, uh, with Fourier transform, there also came discrete Fourier transform and, and DTFT also DTFT and then discrete Fourier transform, discrete time Fourier transform and discrete Fourier transform. And also we learned something called FFT also.

FFT is nothing but an algorithm to implement discrete Fourier transform. Now, now coming back to the point, what is system system? We can consider it as a black box. We considered that as a black box in the week four, which has its own response or the, uh, own characteristics, which adds onto the signal and we get some output signal. Okay. Say, uh, for example, uh, for example, if you have, uh, kind of an amplifier, if you're putting, uh, if you're giving a sound, a sound signal to it, it will amplify it and you will see the loudness of the voice increased. So there is a system, uh, amplifier system, which did something to the signal and the output changed a bit.

So the loudness changed a bit. So that is also, uh, something called proportional system, which it nothing, it did nothing, but added again to the signal. I didn't mean it's multiplied a factor to it and we get, get the output signal. So those that constant signal. So we, then we introduced something called LTI linear time invariant system, which means a system which follows linearity and also invariant with time.

It doesn't change with time. And this is very important to us because if, if the system is time variant, we won't be able to figure out what the signal was, was what is, what is the signal at a particular amount of, at a particular time. Say if we have a time variant signal, a time variant system, and if we give at  $T$  a signal and  $T$  at  $T$  one has a signal. And if you don't know the, uh, how the variation is happening in the system, um, so how we will figure out at  $T$  a signal,  $T$  one, how we will back calculate the  $X$  of  $T$ , what, what we, uh, what has been input. Okay. So this is very important because we are receiving signal from, uh, celestial sources and, and using a system, we, do some processing over it and save the data, but we need the information of the system to back calculate what  $X$  of  $T$  actually we are getting from the source.

So the system is, should be very well defined here. Okay. So there are, uh, uh, different, uh, means concept discussed in week four. If you, uh, are, uh, if you have any doubt, please revisit week four lecture and, uh, means, uh, get back to us in discussion forum. Now in this only we learned something about, uh, super heterodyne receivers. Okay. So super heterodyne receiver is, is something heterodyne, uh, is a word for something called mixing, mixing two things up.

So here super heterodyne receiver is a receiver, which can down convert or up convert a frequency. Now this is a very, uh, interesting concept to down convert or up convert a frequency. We know that from, uh, if you, from class 11, 12, there are something called transformers was down convert and up convert AC voltages. Okay. But we can do similar thing with frequency. So this requires something called local oscillator, which is, uh, means, which is providing a stable, a stable frequency or the control frequency.

We can say, say, okay, so we have a local oscillator  $f_L$  and we get some signal from the antenna and which is amplified, right? Such that the, uh, signal doesn't go, uh, doesn't attenuate to a level where we can't, we won't be able to detect it. Okay. Now this is coming at something called, uh, some, some bandwidth  $\Delta f$  okay. Now what will happen if you multiply this two, if you, uh, remember correctly, the trigonometric functions as the Fourier series suggested that every, any signal can be represented in the form of a sign and co-sign moves.

Okay. Now, if you, uh, remember the, elementary, elementary trigonometry. So what will happen if you multiply two cosine terms or two sign terms, what will happen? You will get  $f_L$  plus  $\Delta f$  and  $f_L$  minus  $\Delta f$  or, or this or  $\Delta f$ , you can write this like this also minus sorry, plus  $f_L$ . Okay. Now, uh, why I wrote like this and this. So this is, this expressions are used when your received signal is at higher frequency than the local oscillator.

Okay. Okay. And this is used when you are kind of up converting your, um, signal. Okay. So down conversion. So essentially it doesn't matter because a negative of any angle is reflected in that particular, uh, term and it does nothing, but just the, just shift the phase a bit. Okay. So you can use any of this term terminology.

Okay. Now, after that, after this, we have a filter and this decides what we are doing. We are up converting or down converting. Okay. We, we will be up converting if, if we are using a high pass filter and neglecting the low, lower frequency part, this is the lower frequency part here.

Here. This is the lower frequency. If you are neglecting this, we are stopping it to propagate further into the system. So we are up converting. And if we use a low pass filter and we remove the higher frequency to, uh, to propagate in further in the system, we are down converting. So these are the concepts, but, uh, what we use in radio astronomy is mostly a down converter or, or we use two stage heterodyne receiver, where we first up convert, then filter, then down convert. And this two stage is because us, because in higher frequency filter designing is easier and filter, filter, I mean, and the frequency selection is easier.

Okay. So this was a bit, uh, kind of a extra tidbit for you. Now, now we also saw that how the entire chain will look like, uh, means like a generic, uh, chain for the, um, our radio observatory observatory will look like we will have an antenna and there will be something called RF front end, which will consist of two LNA, low noise amplifiers, and with combination two or one based on the, uh, uh, signal strength and, uh, pre-filtering. Okay. Pre-filtering, which can be high, uh, low pass, high pass band pass based on the, uh, band you're observing.

Okay. Now, now then it will come to the backend using RF cables, RF cables, or nowadays it's something RF or optics. There is something you can read, read about it. So RF backend and RF backend generally will, will consist of heterodyne receiver. If you're observing at a high frequencies, if you are observing within hundreds of megahertz, hurts, you can, there are systems which can directly, uh, uh, convert those into, uh, digital data points.

So, uh, there is no heterodyne receiver for that, uh, heterodyne receiver used. Okay. Now this will be consist of, uh, means LNA combinations of filters. Then again, high gain for high gain RF amplifier and heterodyne, uh, whatever the heterodyne principle suggests LPF, then again, amplification if needed, and there will be a digital backend also. So the backend consists of RF and digital. So what it does, it will have ADC in it, which will convert analog, means the continuous signal into discrete form and store it, uh, into some memory. And also you can, that can be processed for a, for further with Fourier transforms and all different, uh, uh, things you can do with the saved data.

Now, now why, what is LNA? And from this, we came to something called noise, noise, figure, noise, temperature. So we studied, uh, something called noise power. Noise power is something  $kTB$  where  $k$  is Boltzmann constant and, uh, uh, temperature and bandwidth. So for, for a resistor to be at a temperature  $T$  it will generate  $P$  amount of noise power. So this noise power concept is very important to us, whatever, as, because whatever we are watching is due to what some kind of radiation mechanism.

Okay. So, so in week, uh, week five, I believe, uh, week four or week five, uh, Okay. So in the, uh, first, the first two weeks, we also studied about something called radiation mechanism. So they are popular radiation, uh, uh, radiation mechanism. One, uh, uh, one of them is black body radiation where the planks law and religions law, Stefan Boltzmann law, all these things comes and there is something called non thermal radiation, which you studied in, I think week, uh, eight or nine, which consists of synchrotron radiation or cyclotron radiation.

Okay. Where a charge and brimstone long radiation, where a charge, uh, charge interacts with the fields. Okay. Or the, uh, media, uh, media because of, uh, which big radiation is generated. Okay. Now coming back to the topic. So this is very important because what we are observing is, is the sky, whatever noise coming from the sky. And from that, we can, we will see further how we can relate it with the R we can relate it with our source stress temperature and all.

Now nice temperature is given by  $T_{ref}$  noise figure in DB and minus one. So nice figure, noise figure is a kind of a, uh, figure of merit for, uh, uh, RF system. And noise figure is defined by SNR at, uh, input to the SNR, uh, output. Okay. Signal to noise ratio at the input to a signal to noise ratio at the output. So, so, so the maximum value of a noise figure can be one, because if system, whatever the system you have contributed nothing to the noise, uh, contributes, it doesn't contribute anything, any noise to the system.

So you will get what, whatever the SNR at the input was signal to noise ratio at the input was.

Okay. So the maximum you can attain is one and in DB, if you say it will be zero DB. Okay. In DB score. Okay. It will be zero. Okay. Now, if you see here, everything we are connecting to each other, each another, one, one to another, one to another. So for this kind of connected systems, how deep noise figure is calculated, noise figure that is also called cascaded noise figure. Now the cascaded noise figure is given by this equation, which is also called Ferris equation. Now this suggests that F I mean, this came from something called control system where you look from this side, how the noise figure will be.

So the, so from this equation, you can see that the first amplifier in the system sets the noise figure for the entire system. If it has a very high gain, if it has a very high gain, then this term will be almost negligible. This will be also almost negligible. And so now here, if you see the first, we will put LNA to set the noise figure. And again, after a long wire, we put a LNA such that we doesn't we don't contribute much to the noise.

Means we don't contribute noise to the signal. Okay. Now with this, all the concept of noise figure and all, and also the radiation mechanism and everything, we went to single-dash radio telescope observations. So wherein we studied how a single dish can be used for observing any celestial objects. So with the general formula of the power at the, whatever you have collected in this recorded, we said that the flux from the source multiplied with the collecting area into the bandwidth is whatever the power we will receive from the telescope.

Means flux you can consider as a kind of a flow of water or something. And you are collecting it in a big dish, which is telescope. And for a particular amount of bandwidth. So that much amount of power you will receive. And from this concept, we went to elaborate several features of the single dish telescope. Now, revising, revisiting something called, what are the basic measurements, which is done using single-dish telescope.

So in a electrical system of a single-dish telescope, we will have, we will get something called

voltages. So any little signal you will get as an voltage. Now, using those voltages, how we will say that what is, what we are observing. If say we have a system of single-dish telescope, where we will have a telescope, and with which we have some system attached and it is recording something. It is recording something. Now, if we switch off, switch on the antenna, what we will get, we will get antenna temperature plus system temperature, whatever the noise temperature contributed by the system is.

And if we cut off the antenna, whatever we are getting, what we will get will be due to the system temperature. So in general, what we will have, if we subtract these two, we will get something proportional to the antenna temperature. Means we can figure out what the antenna temperature is, is provided that we know the gain of the receiver and Boltzmann's constant with your voltage and alpha is a proportionality factor, which is also known as responsivity of detector, which is in volts per watt. Okay. Now, with this knowledge, what we can do, we can determine the system temperature, or we can point to something called calibrated temperature.

Means we have a fixed temperature source or something radiating at a particular noise temperature. And from that, what we can calculate, we can calculate back, calculate the system temperature. So if you point our antenna towards the calibrated source, okay. So we know the temperature of the calibrated source. So, uh, so the  $V_{cal}$  will be looking at the previous equation. It will be some  $\alpha G$  Boltzmann's constant  $\Delta$  new into  $T$  and plus  $T_{cis}$  and this  $T$  and is nothing but  $T_{cal}$  because we know the, uh, uh, source, what we are watching and what its temperature is.

Okay. So if we, if we divide it by of  $V$  of means, if we switch off the antenna, which then the, uh, then we will have this term, correct? We will have this term. And if we do that, we will get, get the ratios of the temperature. And if you do the mathematics, uh, math, math, some mathematics, we can find out what is the system temperature here.

Okay. This is generally how, uh, uh, radio, radio, uh, radio, radio, radio, radio, astronomy facility calculates the system temperature. Okay. Now, now also, if you take it to a step further, then we can calculate antenna temperature. If you know the system temperature from the calibration, we can calculate the antenna temperature by the same mathematical calculations. And, and with that, we can move to something called what are the uncertainty we will get in the antenna measurements.

So, so those amount of uncertainty means what, what do you expect and what you got, which is also represented in RMS root mean square error. Okay. What mean to it? So if you see this, there is, uh, if there is a lot of points which are not on the line, so mean is going somewhere from here.

Okay. This is the mean line. Okay. But you have the outliers. Now this is what error is. So with that we can you calculate RMS and also we will, uh, we can see that the standard deviation or the mean fluctuation, whatever the, oh, sorry, this is capital RMS. So mean, uh, the fluctuation can be determined as the  $T-SIS$  over the  $\Delta T$  and  $\Delta \nu$  where  $\Delta T$  is the integration time and  $\Delta \nu$  is the bandwidth.

Okay. And this is the integration time. It's the time for which we observe the source. Okay. Okay. So if you see that, if we observe a source for a longer duration, for a longer and longer duration or over the, over a large bandwidth, the fluctuation will diminish. Okay. Okay. So, uh, so, and as I said earlier, earlier, we also have few concepts like aperture and beam efficiency encounter. So with this, uh, here, uh, here all the measurements, uh, for a single dish, means there means with our elementary knowledge, what we can solve are, uh, till here.

And then comes something called aperture and main beam efficiency. So aperture efficiency is nothing, but say anything you design, there will be some kind of, uh, faults in it, or you, it won't, uh, perform as I ideally should. So you will have something called geometric area, which will be the view through area. And also you will have something called effective area, which, which is, which is less, less than or equal to the geometric area. So with this efficiency comes into picture, comes into picture and efficiency of an, uh, uh, area of a telescope is defined as and effective over the geometric.

Okay. Or the original area. So this is always less than one, less than equal to one. Now, now, as we know that the dimension of the antenna governs the, uh, whatever the, your full width, full width, half maximize or the half power. And you can calculate the solid beam angle using that. Now, now, you know that the, uh, theta is equals to your  $\lambda/D$  and some proportionality factor here,  $K \lambda/D$ . Now, now using this and the approximation of our solid beam, what we can calculate, we can calculate the main, main or the, uh, solid beam effective solid beam.

Okay. Effective solid being considering the effective area. And we can also calculate the gain, uh, gain kind of a hundred percent efficiency solid beam, and we can calculate beam efficiency,  $\eta_{beam}$  as effective over a hundred percent efficiency. So, so, and this, you will get always greater than equal to one. Why? Because if, if area is maximum, the diameter is more and the, whatever the theta value or the resolution you will get is smaller.

So, so the degradation in your collecting area will result into broader beam size. Okay. And that what the beam efficiency means here. Okay. So, so with this, we extended our, uh, knowledge to the, uh, something called beam, beam dilution, or whatever the temperature we are observing from source to calculate the brightness temperature of the source. So we have, we have the salt. We know these, what is the solid beam of the antenna. And if we provided the solid beam of the source, we can calculate how much, how much of what, what will be the brightness temperature of the, of the source.

If we also have the antenna temperature. Now this equation is valid to calculate the source temperature. If, and only if this, these are provided and one of the term is provided. Now considering the setup, what we will have, we have a clear sky and we have a source here. Okay. Now, if we have an antenna, which is observing like this, so it will cover some part of sky or say this, this is at a temperature  $T_1$ , and this sky will also have its temperature  $T_2$ .

Now this, the antenna temperature  $T_A$  will, will be  $T_1 + T_2$ . Now, how much portion of it will be  $T_1$  and how much it will be  $T_2$ , how much the contribution of  $T_1$  is can be calculated using this equation with a slightly modified slight modification, where this will become  $\Delta T_A \omega_{source}$  by  $\omega_{antenna}$  into brightness temperature. So, so if the source size is smaller than your antenna size, then the, your, your incremental antenna temperature due to the source can be related by this. Okay. And this, this term is also called beam filling factor.

So, uh, this is, uh, what I explained earlier that what is, uh, aperture efficiency and what is beam efficiency? Okay. Now, now let's skip this. Yeah. So here, so with any telescope facility, there's, there's a term we call that sensitivity means how sensitive, how sensitive is the, your, uh, observational facility. Okay. Now that if you remember clearly, we said there is a fluctuation term, okay.

Fluctuation and a temperature fluctuation term, which is proportional to system temperature over the observational time and the bandwidth new. Okay. So this is how, uh, we said this, it was related. Now, now if you're talking about uncertainty or the sensitivity of the telescope, that means this will play a role that means fluctuation of the antenna temperature will play a role in this. So, which can be represented by this equation.

Why this equation? Because we know that the power received by a telescope is nothing but  $F_{new}$  into Boltzmann's constant  $\Delta_{new}$  and temperature. Okay. Uh, I, uh, it is no, no, no, sorry. Effective area, not temperature effective area. Okay. So, so it is, we knew that this is related like this.

Now, uh, from our general knowledge, we can say that  $F_{new}$  will be related to, uh, the power received by just by crossing over all the terms, a effective  $\Delta_{new}$ . So, and with all this manipulation, we arrive at this term where the sensitivity of any observational, I mean single dissipation facility is inversely proportional to the effective area and the integration time and bandwidth. Now, this makes sense. How, if you have a very large collecting area, definitely you should say that, yeah, we have a very large bucket, uh, to fill the radiation with.

So we should, we should have more sensitive observations. Okay. So this is inversely proportional, which suggests that, and if you observe a thing for a large amount of time, so that, that, uh, we will add means kind of add one, one reading to another, another, and that will become kind of redundant reading. So if you have large amount of observational time, that will also increase our sensitivity. So this thing holds logically also. So if you want to view derivation, which, uh, means, uh, there is something called blue book, uh, which is, uh, you can find on GMRT where a detailed derivation of this is given.

Okay. You can refer to that. And if you don't, uh, if you are having trouble in understanding, please get in touch with us. Okay. So, so, and similarly with that, we can relate the, whatever the minimum sensitivity with the SNR also signal to noise ratio. Now, how is that? So the signal to noise ratio is inherent in a system. Now, whatever the SNR we, um, we were getting, okay.

From the sky will be multiplied with the, whatever the fluctuations, the minimum sensitivity, minimum sensitivity term. So this is nothing but like this. So minimum detectable signal or the flux density, you can, uh, based on SNR. So your SNR is nothing but whatever the minimum flux you can detect minimum flux, this minimum flux, what you can detect, detect governed by SNR. So minimum flux over your sensitivity, your this, okay. Sensitivity of your system. Now, how this is, this is always done kind of practically you point, uh, means what we do here, we try to find out some instructable, um, backyard, uh, backyard interferometers, as well as a single, uh, dish observe observation, uh, we do.

So we have horn antennas and, uh, first, uh, horn antennas, which we, uh, we point towards the center of the galaxy and take a reading, you know, uh, means periodically. So what we do, we point towards the fender and fender sources, and we see when we are not able to detect anything. So this is a kind of practical thing or a makeshift way to see what are the minimum flux you can detect. And we know already the system temperature and time, okay.

The integration time and this, all this stuff. And we can relate it to, with this, we can relate it to what is the minimum, uh, uh, what is the SNR of the, uh, entire system. Okay. So, but suppose we have a telescope with gain  $G$  and this is all talking in practical sense. If we have a telescope with gain  $G$  okay. Then we can approximately relate it with the flux density, which we are observing it multiplied by the gain and the transfer and the time of observation multiplied by the bandwidth over the system temperature.

Now this will give you the rough estimate of the SNR what you will require from your system. Okay. It means a rough estimate of the SNR signal to noise ratio and provided whatever the noise figure of your system is, you can, uh, you can quote whether you will be able to detect or not. Okay. So, so with this, I will stop here.