EPFL

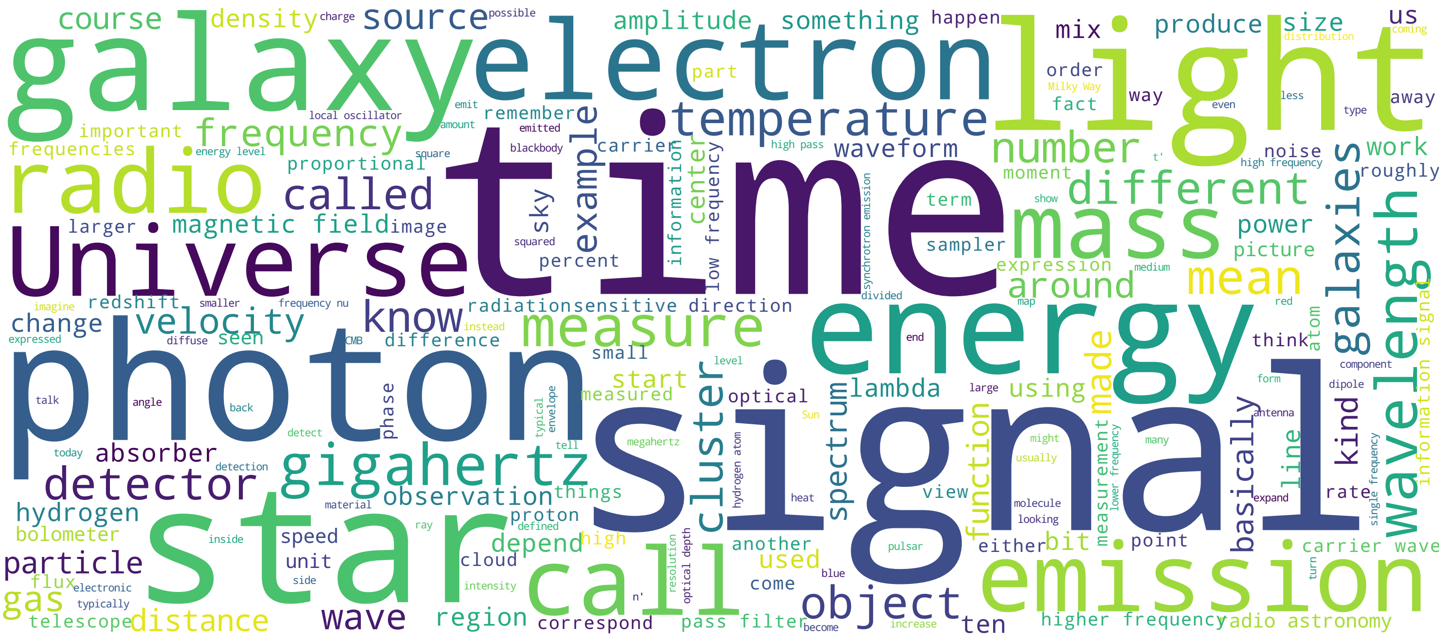
Radio Detectors

The Universe At Radio Wavelengths

Griffin Foster

One dish of the MeerKAT radio telescope

Image: SKA South Africa



Search MOOC

Video

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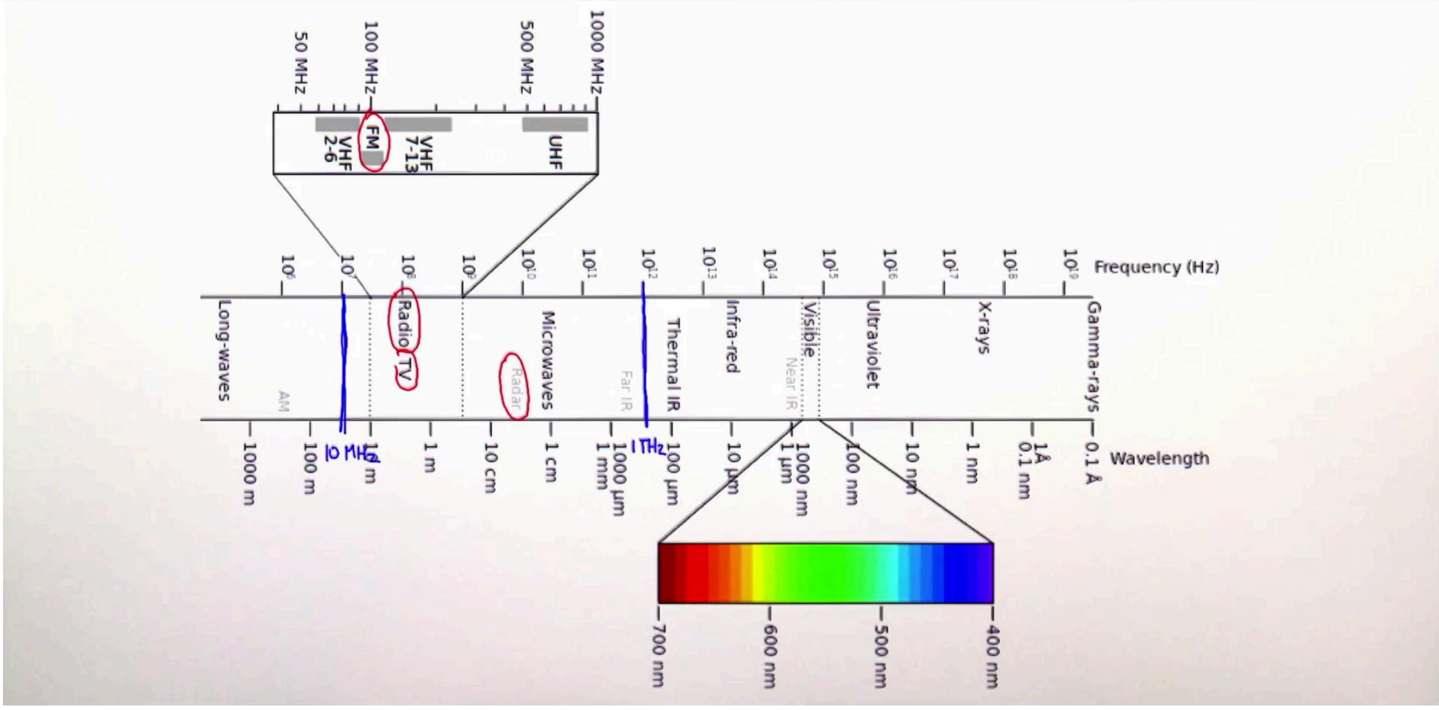
In radio astronomy our detectors are fairly different from optical, UV and infrared detectors. When we think about electromagnetic radiation we can think of it as either a stream of particles or a continuous wave. This is the classic duality of light. When we are working at radio wavelengths we tend to think of light as a wave. This is because we can actually sample the waveform to measure both the amplitude and phase of that light. At optical infrared and UV wavelengths we can only measure the power of the radiation. Think of CCD cameras, for instance. Or in the case of high energy X-ray and Gamma ray astronomy, we might only be able to count the number of photons at certain energy levels. By sampling the electromagnetic field and not just the power we have the ability to do some nice tricks when observing at radio frequencies.

Notes

Summary

0m 06s

The Radio Spectrum



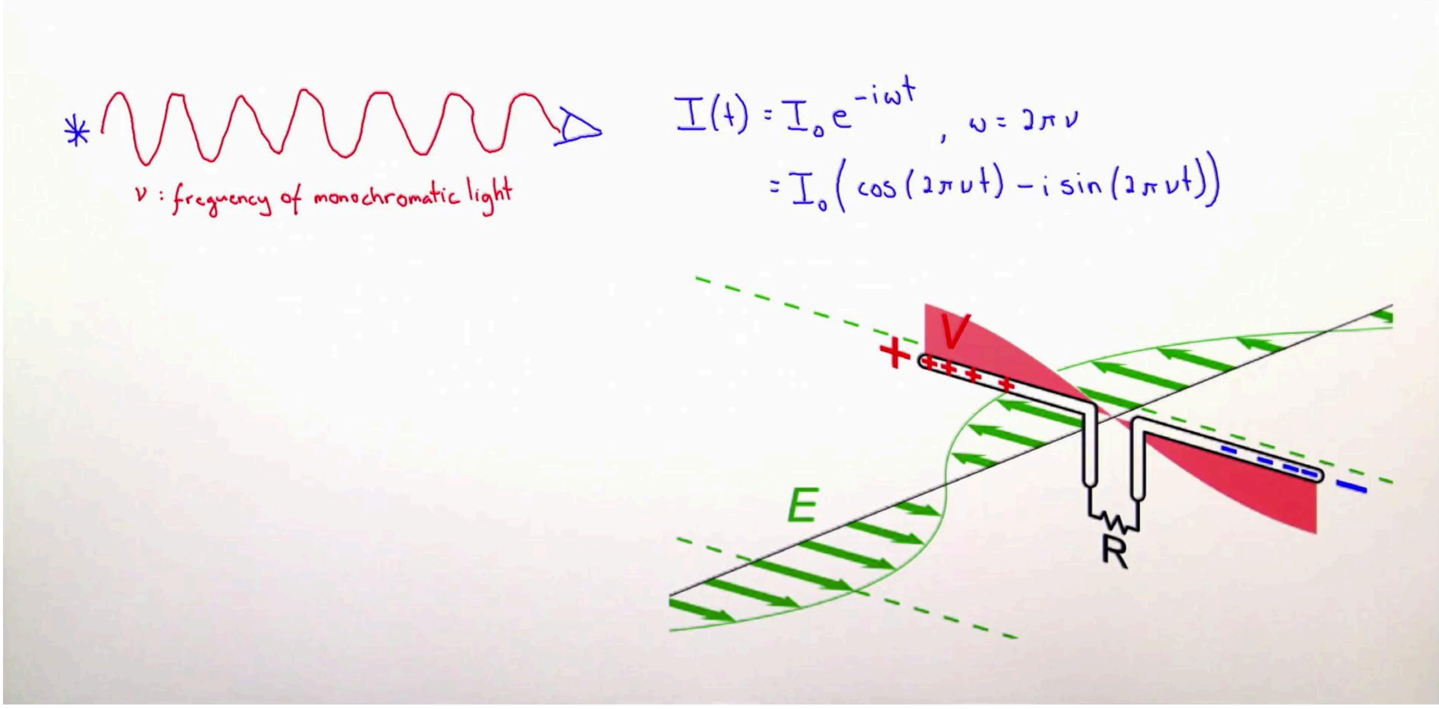
When we talk about radio astronomy, we're usually talking about frequencies between ten megahertz where the ionosphere blocks incoming radiation and up to one terahertz. This would be the upper end of the ALMA receivers, for instance. Beyond one terahertz, it’s difficult to build stable detectors that can measure the waveform so we use different detectors at these frequencies. As you can see things like TV and radio operate at these frequencies. There's also planetary radar systems that operate around five gigahertz. Most countries allocate the radio spectrum for commercial, military and scientific use. Things like FM radio operate around a 100 megahertz. So we obviously use the radio spectrum in modern life quite a bit and much of the same technology we use in radio astronomy.

Notes

Summary

0m 58s

A Simple Receiver



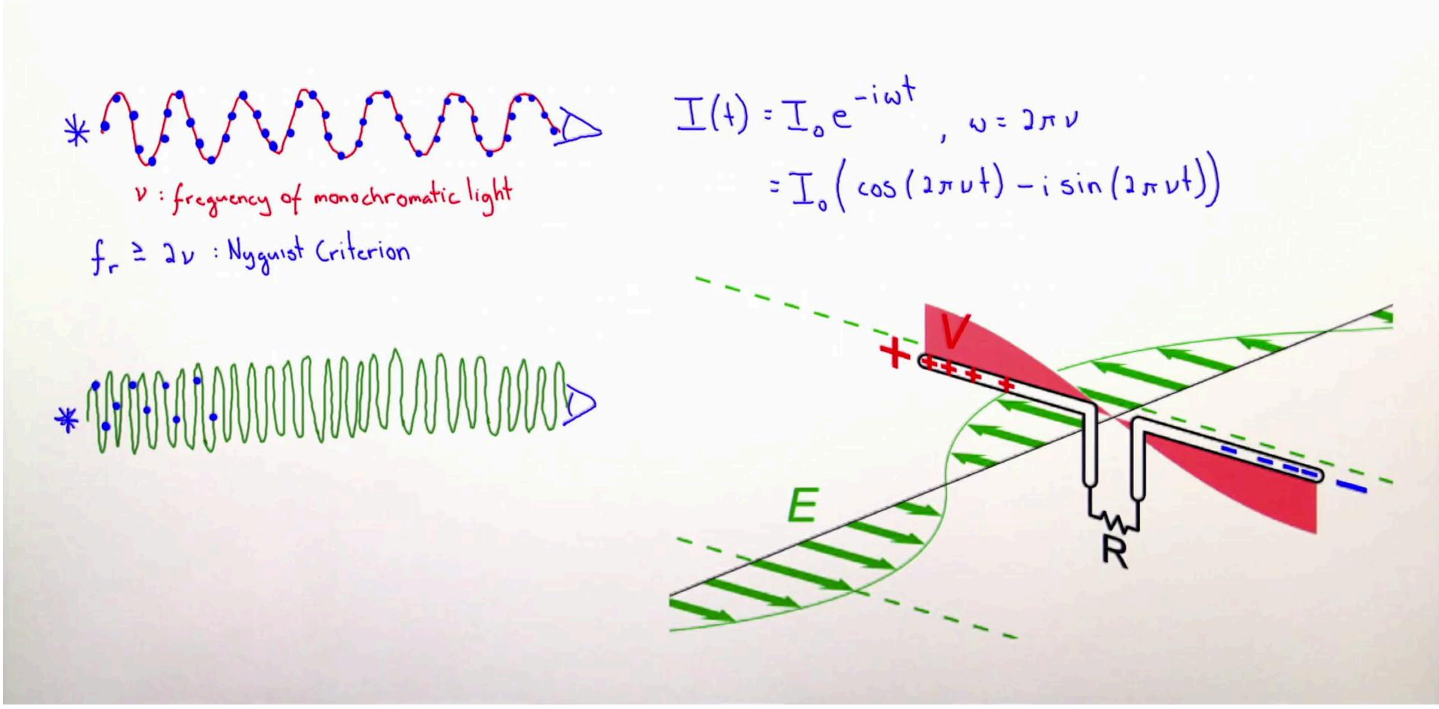
So let's imagine a simple situation. A monochromatic electromagnetic wave from some astronomical source arrives at our telescope our detector. By monochromatic, I mean a single frequency nu of light. Now this is, of course, an idealization. Astronomical sources emit over a broad range of frequencies. That's all right. This is an approximation that holds up pretty well. And we can write a wave equation as the intensity of the light as a function of time which is equal to some amplitude 'I not' times exponential minus 'i' omega 't' where omega is equal to two pi nu. By using Euler’s equation we can expand this equation out. So the light wave is made up of a real wave and an imaginary component. So the wave arrives at our detector. In the case of radio astronomy we start with an antenna which converts the electromagnetic signal to a voltage. The simplest form of an antenna is a dipole. A dipole has two arms. As a wave arrives, it creates a potential across the arms inducing a current. Connected to the arms is the electronics of our detector represented generically as a resistance here. We then measure our voltage with our detector. We can work back to determine the current and from that the flux of the electromagnetic radiation.

Notes

Summary

1m 57s

A Simple Receiver

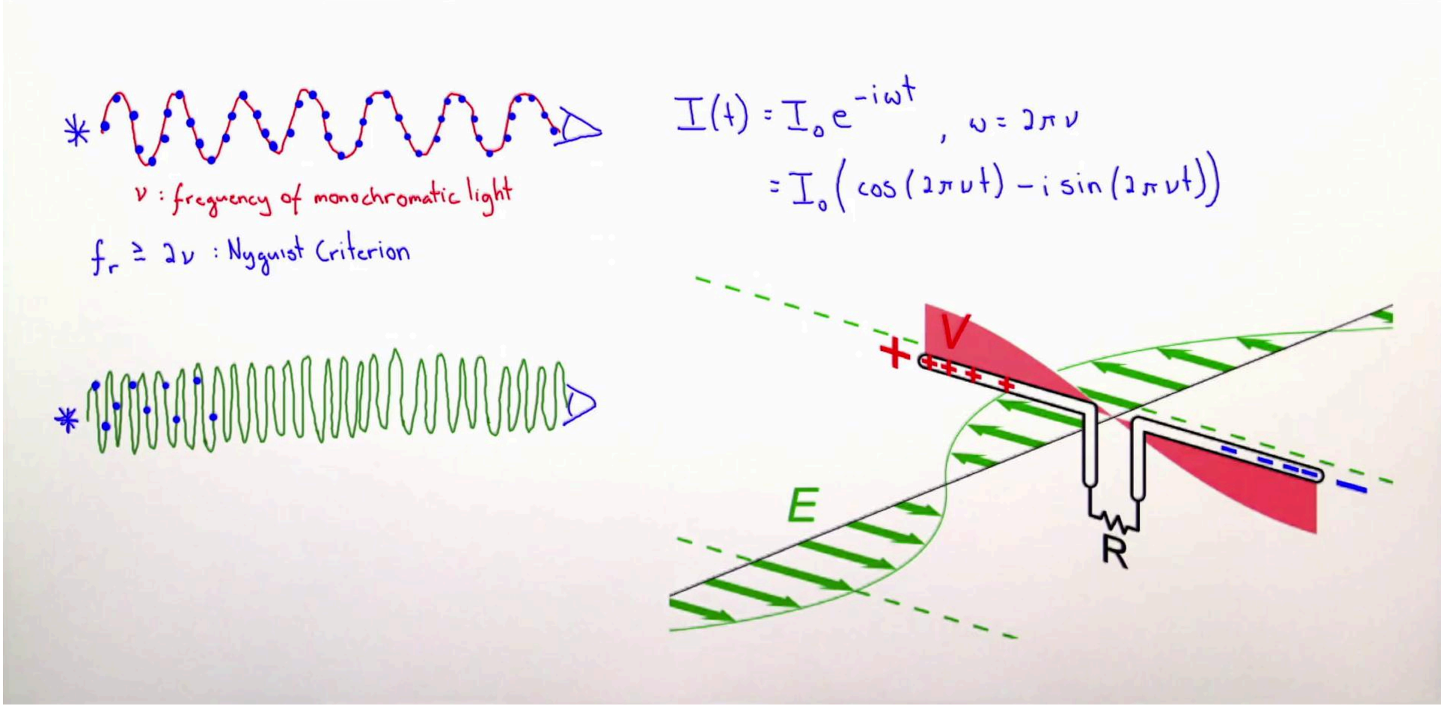


Now we make a detection. We measure the waveform. This requires at least Nyquist sampling the wave, that is, as long as we sample a cycle of the waveform at least twice, we can find the amplitude and phase the waveform. We do this by using an analog to digital converter to digitize the voltages. So what that means here is we have a sampler that regularly samples the waveform at some rate. Now this rate, let's call it ‘fr’. That's the frequency of our rate. In order for us to fully sample this monochromatic signal, ‘f’ of ‘r’ must be at least equal if not greater than two times the observing frequency or the frequency of the monochromatic light. This is the Nyquist criterion. Now the sampling rate is fine for the low frequency case where it is easy to sample a waveform with modern electronics but what happens when we go to higher frequencies, you know, say a 100 gigahertz or even a terahertz. In that case we have some waveform that's much higher frequency and looks like this. Now in the case of our sampler, our sampler is not Nyquist sampling this higher frequency signal et cetera. And so since we're not fully sampling the signal, we need to do something to this high frequency signal.

Notes

Summary

3m 44s



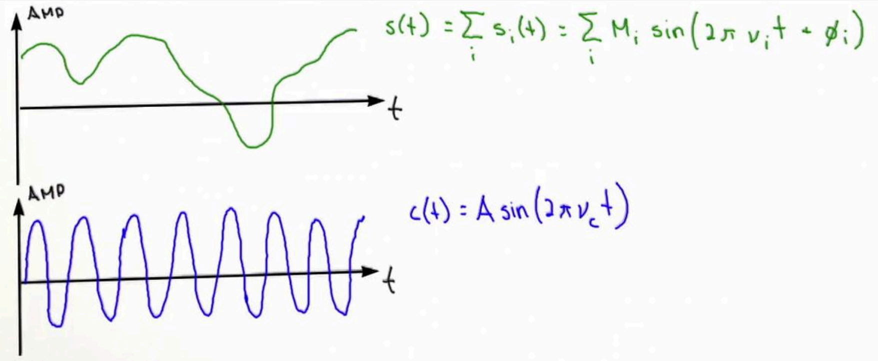
Well, we have a few choices. We can build a new faster sampler but this is difficult, expensive and actually turns out to be unnecessary. We can use what's called the heterodyne receiver system instead.

Notes

Summary

5m 23s

A Short Digression: AM Radio



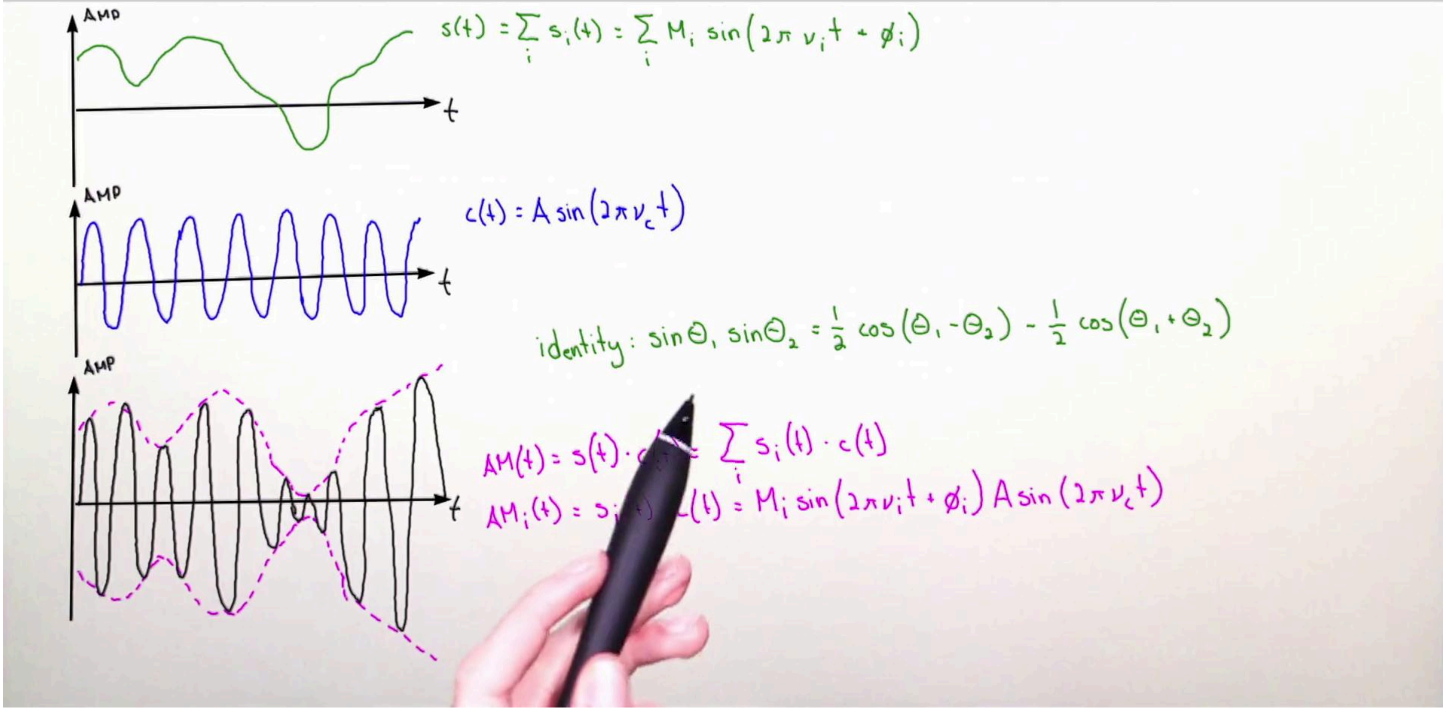
Let's talk about AM radio signal for a moment. Say we have a signal with information a human voice or music which ranges from anywhere from zero to 20 kilohertz. Let's call this ‘s’ of ‘t’ for signal and it's made up of many frequency components and so it's hard to say exactly what the frequency is but there's information there and that's what we're interested in transporting. And so ‘s’ of ‘t’ is made up of many frequencies. Let's make the approximation that's made up of a series of monochromatic frequencies. So that's the sum over these individual frequencies. Each frequency has some amplitude which is a function of time plus there's some offset phase and that's just there for completeness but it doesn't actually play a significant part in this discussion. Now in order to transport that signal long distances we need to mix that up to a higher frequency. That's what we do in the case of AM radio where we use a carrier wave at about one megahertz to amplitude and modulate the information signal. We'll call this ‘cft’ for carrier. A carrier is a single frequency has some amplitude. I'll call it the frequency nu sub ‘c’ and it doesn't have a phase offset.

Notes

Summary

5m 37s

A Short Digression: AM Radio



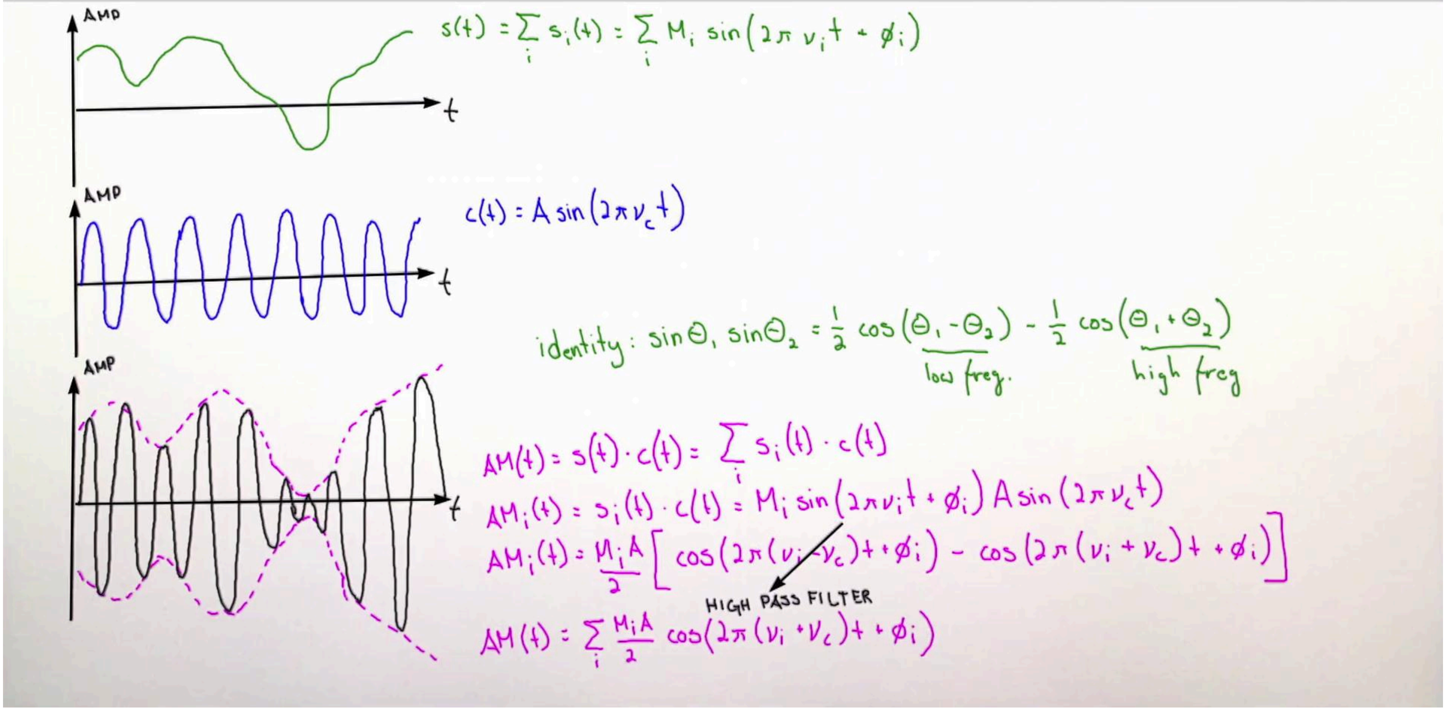
We're defining phase zero to be the beginning of this carrier wave. Now in order to modulate our signal with the carrier we simply multiply them together. So I'm going to draw this dashed line here as an envelope. I'll explain that in a moment. Between this envelope which is basically a copy of the signal we have a higher frequency signal which is actually what's being generated which is at the same frequency as the carrier. So the carrier wave has been modulated with the signal. So the black here's the actual signal and this envelope is just to indicate that it's being modulated by this signal. So the AM signal is equal to the signal with information times the carrier wave. We can expand this out a bit. For a moment let's only consider a single frequency of the information signal. Because it's a summation, we can easily add that summation in later. So we have a multiplication of two sine functions. We can use a trigonometric identity here. So we can take the multiplication of two sines and turn it into a difference of two cosines and notice we have for this we have two different frequencies.

Notes

Summary

7m 14s

A Short Digression: AM Radio

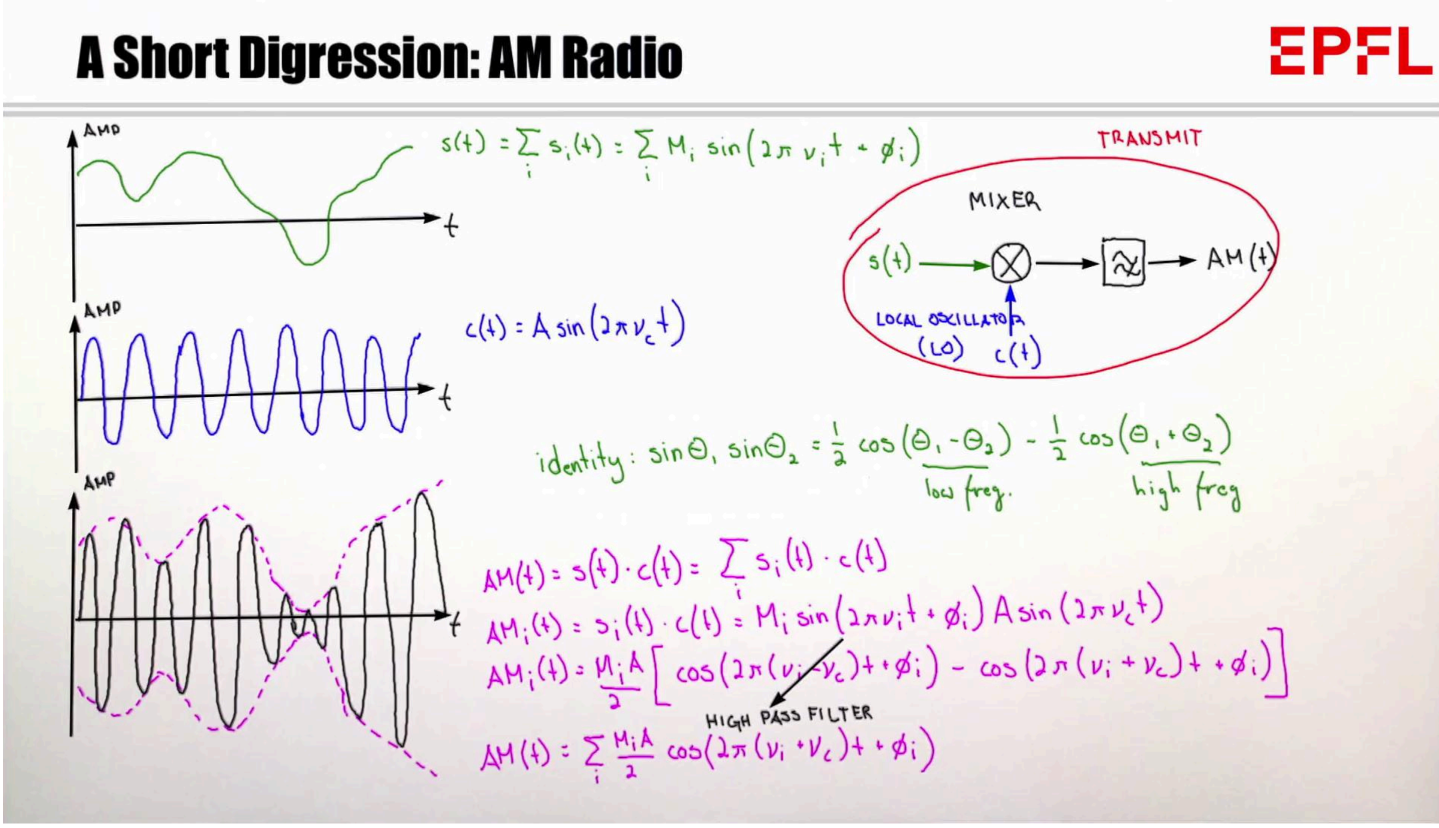


In our case we have a single frequency of the information signal times the carrier wave signal and if you look because we know the carrier wave is much higher frequency than the information signal, these differences and additions will be a little different. So this will be lower frequency. This will be a high frequency. We'll use this in a moment. So getting back to our AM signal using this identity. Now here's a bit of a trick is that we then we have a high frequency component and a low frequency component. We can use what's called a high pass filter which cuts out lower frequencies and keeps higher frequencies to remove this signal. This is just a bit of electronics we use. So then our final AM signal becomes so you see we've up mixed the signal. We've taken this low frequency, you know, kilohertz range signal and mixed it with a one megahertz signal to mix it up to a higher frequency. Now on the receiving side, you know, in the radio which we use the opposite operation is performed. We down mix the signal and shift the information signal back to baseband. Instead of using a high pass filter we instead use a low-pass filter when we mix. So the mixing surprisingly uses a bit of electronics which is called the mixer.

Notes

Summary

9m 02s



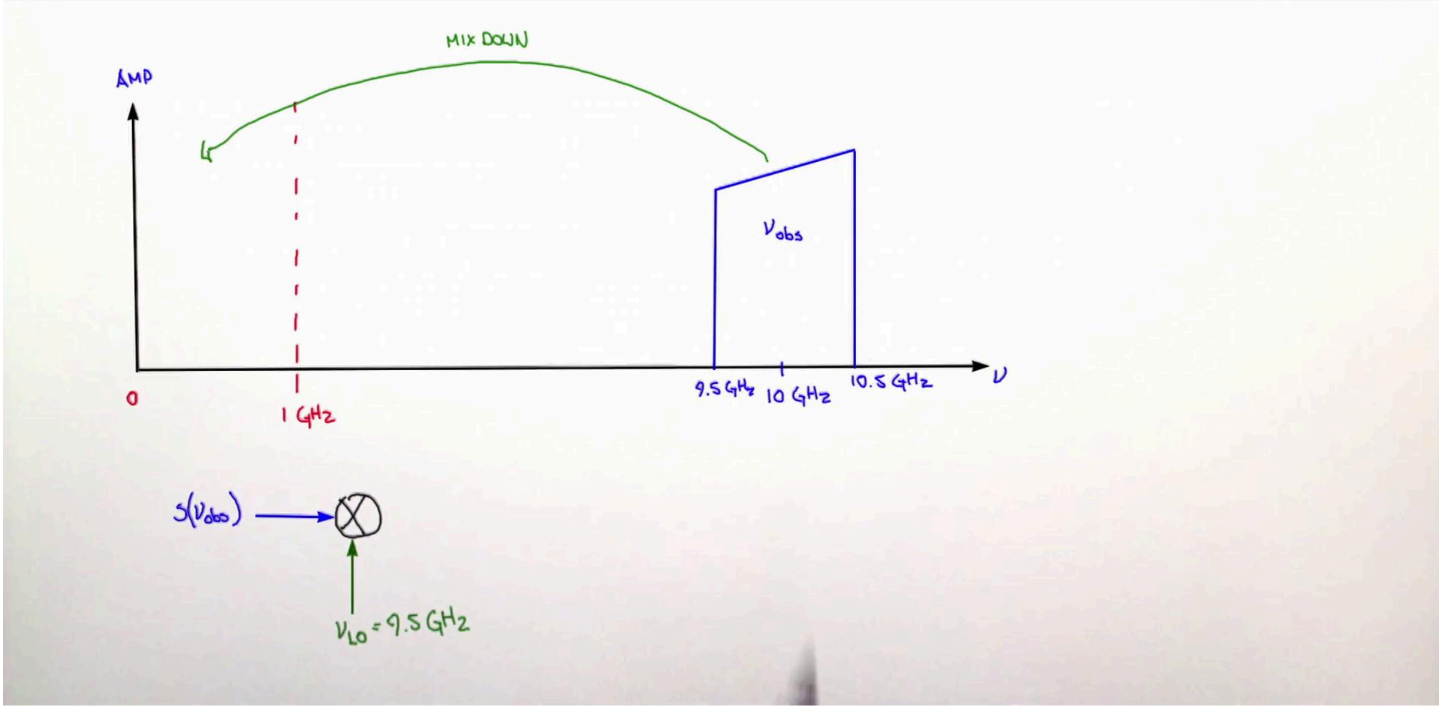
It's made up of what's called the multiplying circuit and a local oscillator. This is a notation for multiplication when we talk about signal processing. So we have a mixer. So we have take 's' of 't'. We mix it with a carrier. Now comes a signal which we then need to low-pass filter or need to high-pass filter. This is the notation for high-pass filter. It's kind of you have a I guess to understand this you have a high frequency side and a low frequency side and the dash means we've cut out the low frequency. Then from there we produce our AM signal. This is to transmit. Call the carrier signal the local oscillator or LO.

Notes

Summary

10m 43s

Side-band Mixing

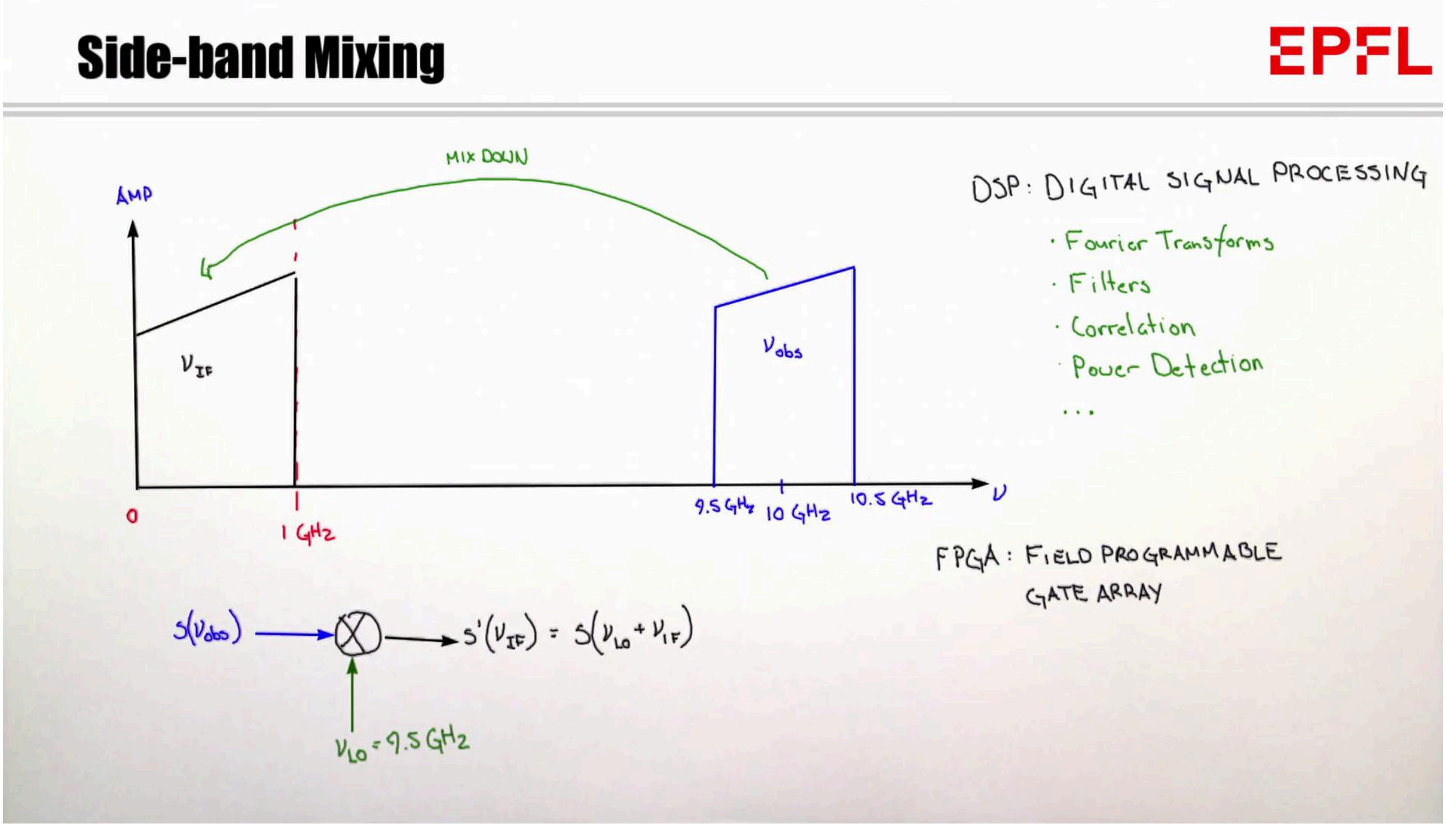


Now back to radio astronomy. We do the same thing as the AM modulation but in reverse. Say we want to measure a gigahertz of bandwidth centered at ten gigahertz but we only have a sampler that works from zero to one gigahertz. We use this style to represent a band limited signal that is, for in our case it's a gigahertz band that starts at 9.5 gigahertz and goes to 10.5 gigahertz. We use the slope here to indicate the direction of the band. Sometimes we have these aliasing effects where we just flip back and forth. We'll set this one gigahertz range to be where our sampler actually operates at so it's zero to one gigahertz. So our signal of interest is up here and we want to mix it down to here. We want to, we can think of it as kind of we've amplitude modulated the signal so we want to demodulate it. Even though in reality the signal is not really modulated. It's just kind of a reverse operation of amplitude modulation. Say there's some frequency in this band 'nu obs' that we want to mix down. So our mixer is a signal ‘nu obs’. We need to put in a local oscillator and we'll call this 'nu LO'. Now in our case we want an LO equal to 9.5 gigahertz or the low end of the observing band.

Notes

Summary

11m 37s



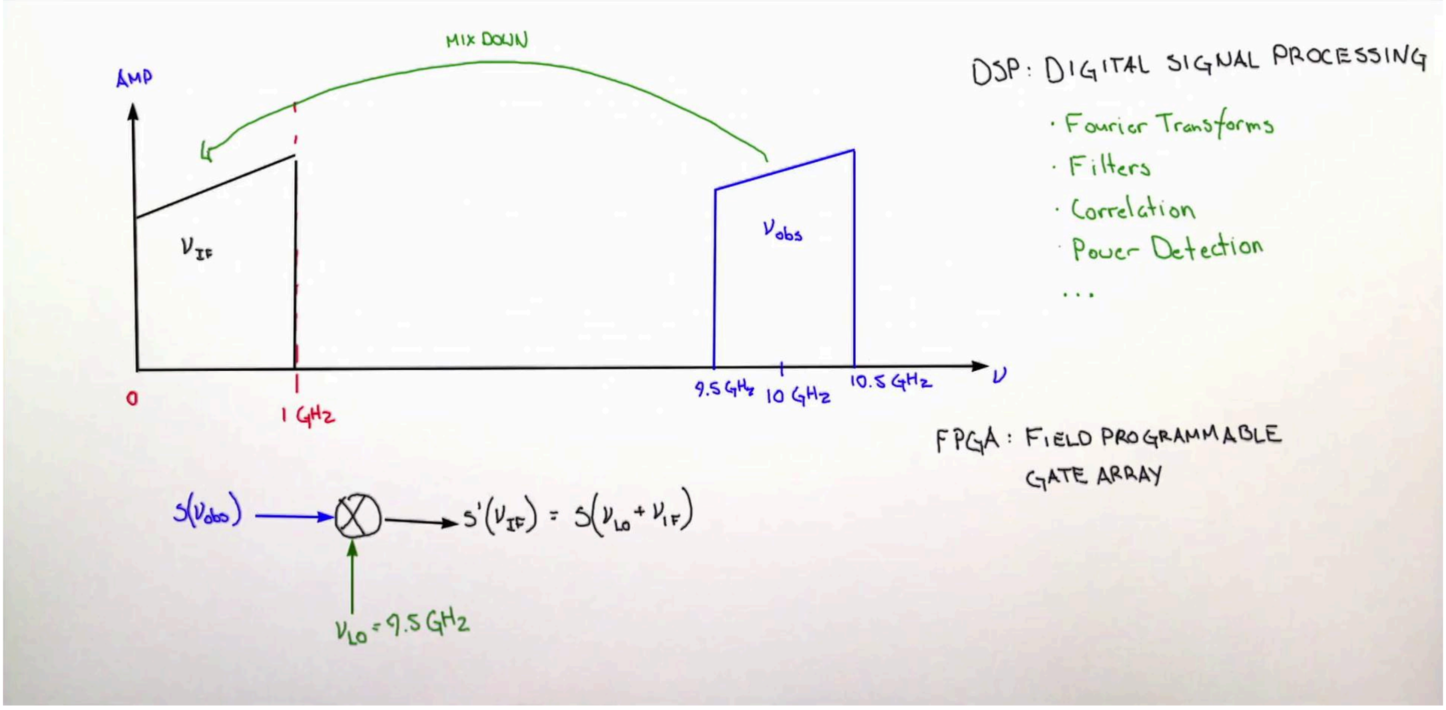
So remember once we do that we shift this whole 9.5 to 10.5 to zero to one. Out of that we get a new signal called 's' prime and we'll call it output frequency 'nu IF'. We use the LO to mix down the 10 gigahertz signal to a lower frequency. We call this lower frequency the Intermediate Frequency or the IF. Then we can use our samplers to digitize the one gigahertz of bandwidth. So ‘s’ prime is simply equal to 's v' to 'LO' there 'nu IF' but we've mixed it down. Once we've digitized the wavefront, we can then do a number of things. We can channelize the time series into narrower frequency bands using a Fourier transform. We can correlate the signal with another detector to build an interferometric array or we can simply power detect the signal. This is all done using Digital Signal Processing methods or DSP for short. DSP is usually done on low power efficient chips called Field Programmable Gate Arrays or FPGAs. Once we've done some sort of DSP operation to the data usually to reduce the amount, we can then transfer it to a typical computer and do further processing. This is where kind of the instrument ends and the science begins.

Notes

Summary

13m 37s

Side-band Mixing



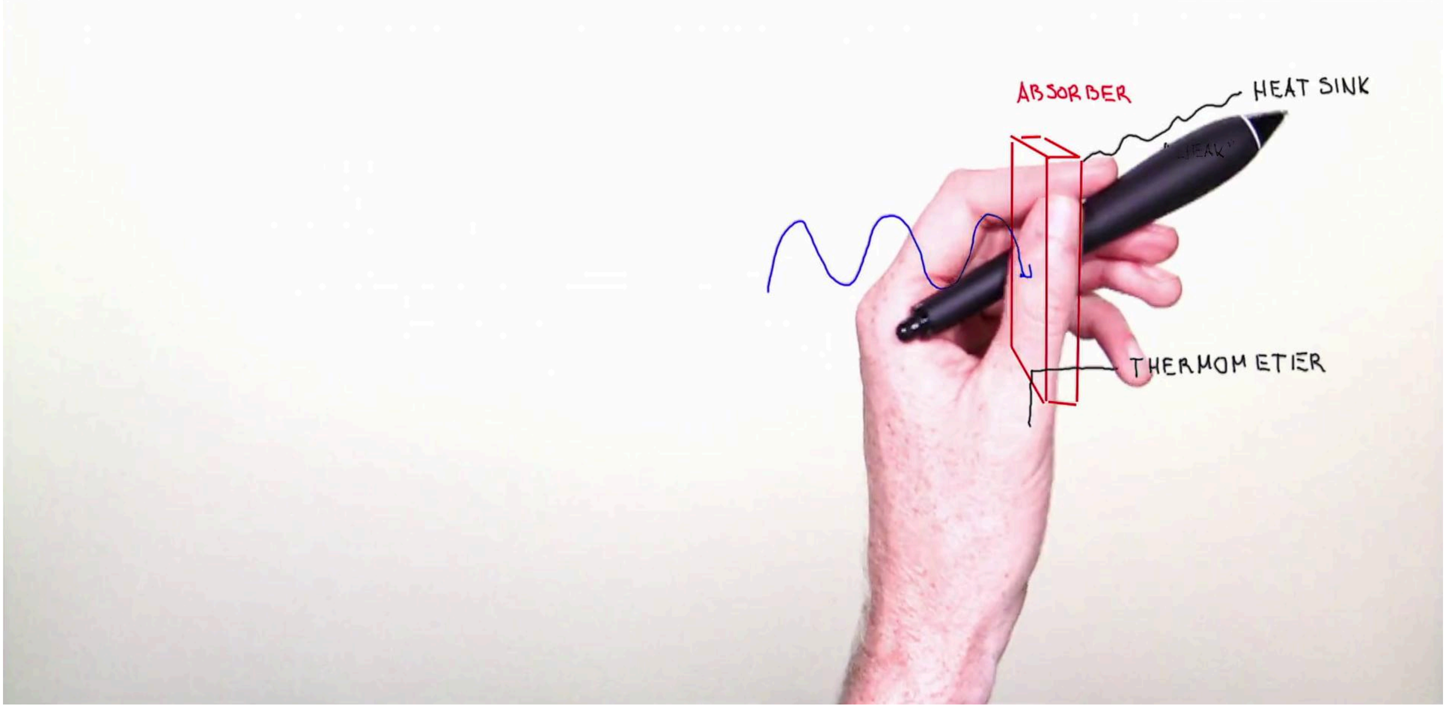
This is a really unique advantage of working at radio frequencies because we sample the electromagnetic wave. We have complete information about that wave which allows us to coherently combine signals from multiple individual detectors. This allows us to increase sensitivity or resolution when we make an observation.

Notes

Summary

15m 17s

Bolometers



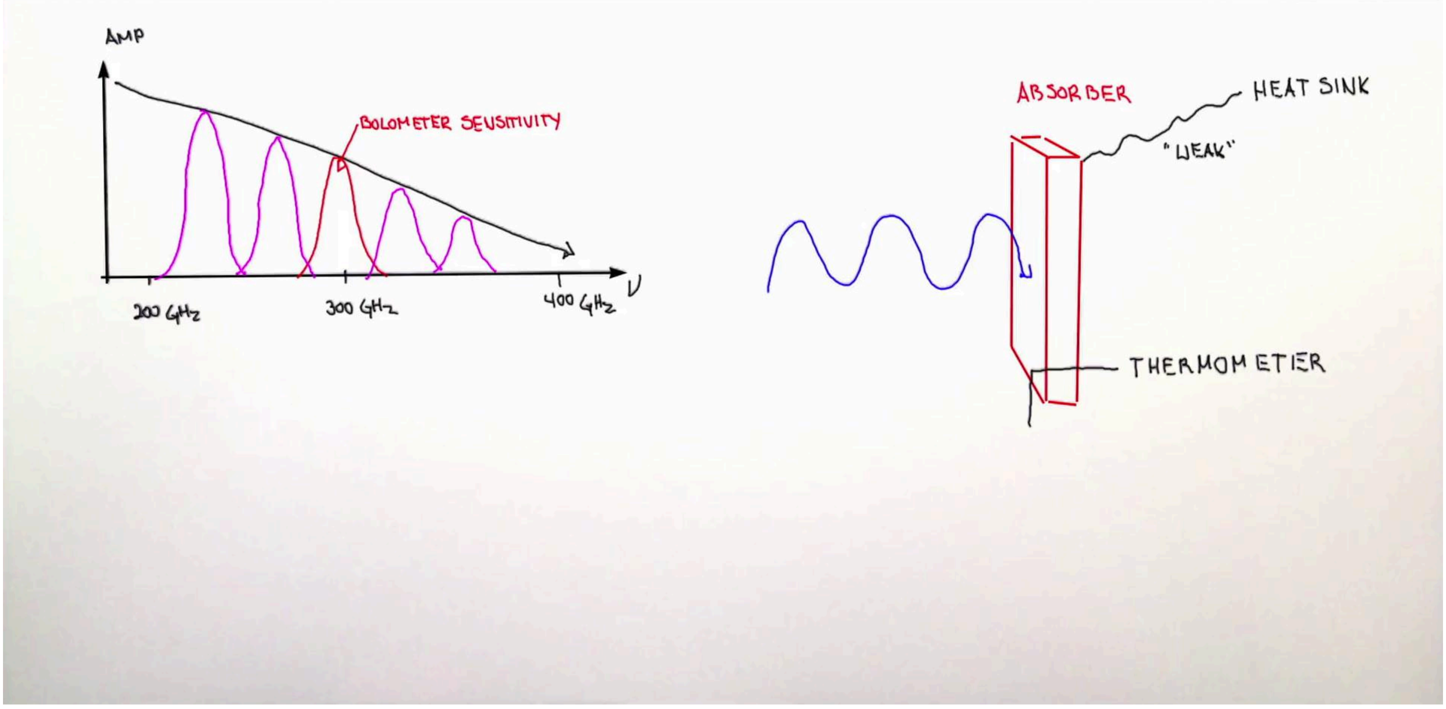
Now there's an upper limit to this. Though technological developments are pushing this limit, it's difficult to build stable local oscillators at high frequencies and the efficiencies of electronic components also decrease. Instead a different detector called the bolometer is used. A bolometer measures the temperature or power of a signal. We can no longer measure the phase information. We can think of a bolometer as a single pixel camera and an array of bolometers might be used to use similarly to an optical CCD. Bolometers are used at the highest radio frequencies hundreds of gigahertz from sub-millimeter wavelengths out to the far infrared. So how this works is we have some absorber. We have our incoming light. When this incoming light hits the absorber, the absorber absorbs that energy and it heats up slightly. Then we need some sort of way to measure this. So we have a little circuit. A little thermometer. The absorber is usually cooled down to very low temperature and so can be very sensitive to single photons. We also have is we need to connect the absorber to a heat sink. This connection to the heat sink is what you call weak. That means it takes a while for the heat to be transferred to this heat sink.

Notes

Summary

15m 36s

Bolometers



So there's some time constant related to this absorber and that acts as basically some an integrator so we take some average measurement of the energy of the photons coming in and then the average is measured by the thermometer. If this is too fast, the individual photons are too weak to be measured and so a thermometer won't register. If it's too long then our measurement will be filled with error and noise. So let's say we have some some source some radio source with some spectrum across the frequency band and let's say we're talking about something like 300 gigahertz right in the middle. Now let's maybe this is 200. This is 400. Now we want to measure the individual components of the spectrum so when we build our bolometer, we're only sensitive to a special region a certain band limited region. So our bolometer might only be sensitive to 300 gigahertz plus or minus 20 gigahertz. And then the bolometer has some sensitivity region and beyond that it's not sensitive. And so we can imagine we could have other bolometers. That kind of overlap if we wanted to measure more of this in this spectrum. So there's an effective channel maximum bandwidth to the bolometer which is limited basically by how the absorber is designed.

Notes

Summary

17m 22s

For this course we will mainly be talking about heterodyne systems where we can measure the amplitude and phase the wavefront. This allows us to observe the radio sky in unique ways. Most importantly by doing aperture synthesis with interferometric arrays but we will get there later in the course. Thank you.

Notes

Summary

19m 08s