Radio Astronomy Amplifiers, Receivers

Greg Taylor

University of New Mexico

Astronomy 423 at UNM

Radio Astronomy

Announcements

Identify 7 projects and the teams:

Projects	scheduler	member	member	member
Cas A	Brett	Christina	Raman	
Cyg A	Alexandra	Stephanie	Dylan	
M87	Isabela	Alexis	Aniketh	
Sun	Lily	Sharleen		
Starlink	Ella	Jacob	Sarah	
Sag A	Rachel	Annalisa	Madeline	Mark
Jupiter	Charlie	Sara P.	Joaquin	Yifu

Please get together as a team and plan your observations

Schedules should be submitted by Feb 17 and completed by March 15.

Each project can have up to 10 hours of LWA observing

Announcements

Contact info:

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Colloquium on Feb 7

"Opening a new window on the universe with the Hydrogen Epoch of Reionization Array"

Physics and Astronomy Colloquium

February 7, 2025 3:30 PM - February 7, 2025 4:30 PM
PAIS 1100

Host:
Greg Taylor
Presenter:
Dr. Daniel Jacobs (ASU)

Zoom link (Pass: PandA)

The redshifted 21 cm hydrogen line is a probe of large scale structure which could be used to answer questions about fundamental physics, cosmology, and astrophysics.

Upcoming Events

"Opening a new window on the universe with the Hydrogen Epoch of Reionization Array"
Dr. Daniel Jacobs (ASU)
Physics and Astronomy Colloquium
Feb. 7, 3:30 PM - Feb. 7, 4:30 PM
PAIS 1100

TBA
Evan Rule (LANL)
Nuclear, Particle, Astroparticle and Cosmology (NUPAC) Seminars
Feb. 11, 2:00 PM
PAIS 3205

More useful is the limiting flux density ΔS

$$S_\nu = \int_\Omega B_\nu \cos\theta \, d\Omega$$

$$S_\nu = \frac{2kT}{\lambda^2} \Omega_a \qquad \frac{\Omega_a}{\lambda^2} = \frac{1}{A_e}$$

$$S_\nu = \frac{2k}{A_e} T$$

$$\Delta S = \frac{2k}{A_e} \Delta T$$

radiometer equation

$$\Delta S = \frac{2k}{A_e} \frac{T_{sys}}{\sqrt{\Delta\nu\,\tau}}$$

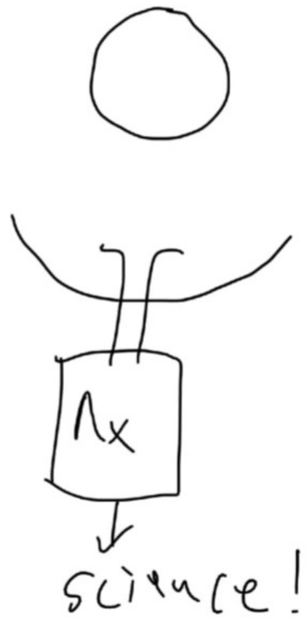
single polarization

Defining Gain $= \frac{A_e}{2k}$ in $\frac{K}{Jy}$

$SEFD = \frac{T_{sys}}{Gain}$ in Jy

$$\Delta S = \frac{SEFD}{\sqrt{\Delta\nu\,\tau}}$$

Radio Astronomy Notes 5-1



Lets look at the moon, as all telescopes should be able to do ...

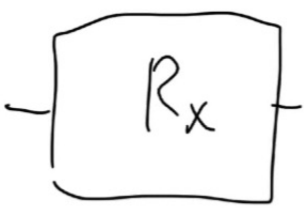
$$T_a \approx T_s \approx 225\ K$$

power received $W_\nu = kT_a = 4 \times 10^{-14}\ erg\ s^{-1} Hz^{-1}$

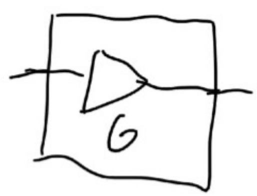
$$W_\nu = 4 \times 10^{-21}\ W\ Hz^{-1}$$

Electronic detectors are sensitive to signals as faint as 1 nanowatt $= 10^{-9}$ W so we need $G \gtrsim 10^{10}$ for detection

$G_{dB} = 10 \log(10^{10})$ dB, so over 100 dB of gain!



becomes



which will add noise (T_{sys})
Why?

Fundamental noise limit, start with Heisenberg uncertainty principle

$$\Delta E \, \Delta t \geq \frac{\hbar}{2} \qquad \hbar = h/2\pi$$

$$\Delta E \, \Delta t \geq \frac{h}{4\pi}$$ and recall $E = h\nu$ so lets switch to ν

$$\Delta E = E_{photon} \cdot \Delta n$$ Δn = uncertainty in number of photons

$$\Delta E = h\nu \, \Delta n$$

Change in phase, ϕ, is freq times change in time

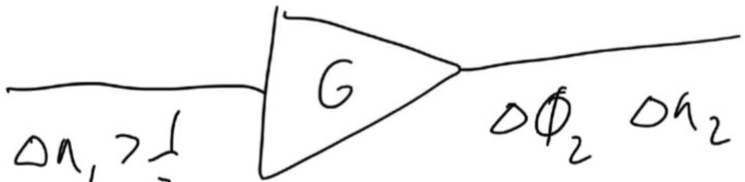
$$\Delta \phi = 2\pi\nu \cdot \Delta t$$

$$h\nu \Delta n \cdot \frac{\Delta \phi}{2\pi\nu} \geq \frac{h}{4\pi}$$

$$\Delta n \, \Delta \phi \geq \frac{1}{2}$$ and in radio astronomy Δn can be large

Radio Astronomy Notes 5-2

Lets apply the fundamental limit to an amplifier



$\Delta\phi_1 \Delta n_1 > \frac{1}{2}$ $\qquad$ $\Delta\phi_2 \Delta n_2 > \frac{1}{2}$

and $\quad n_2 = n_1 G$

$\Delta n_2 = \Delta n_1 G \qquad \Delta n_1 = \Delta n_2 / G$

output phase $\quad \phi_2 = \phi_1 + C \quad$ shifted

$$\Delta\phi_2 = \Delta\phi_1$$

$\therefore \quad \Delta\phi_2 \Delta n_2 = \Delta\phi_1 \Delta n_1 G \quad$ and $\quad \Delta\phi_2 \Delta n_2 > \frac{1}{2}$

$\Delta\phi_1 \Delta n_1 \geq \frac{1}{2G}$ but this can't be true for any real gain $G >> 1$

In reality $\quad \Delta\phi_2 \Delta n_2 = \Delta\phi_1 \Delta n_1 (G + \Delta G)$ $\quad$ amplifier must add noise amplifier noise limits

$$kT_{out} = G(kT_a + kT_{rx})$$

$$kT_{rx} = h\nu$$

$$T_{rx} = \frac{h\nu}{k} \quad \text{Quantum limit}$$

Freq	λ	T_{min}
5 GHz	6 cm	0.2 K
300 GHz	1 mm	14 K
IR	10^{-6} m	14,000 K

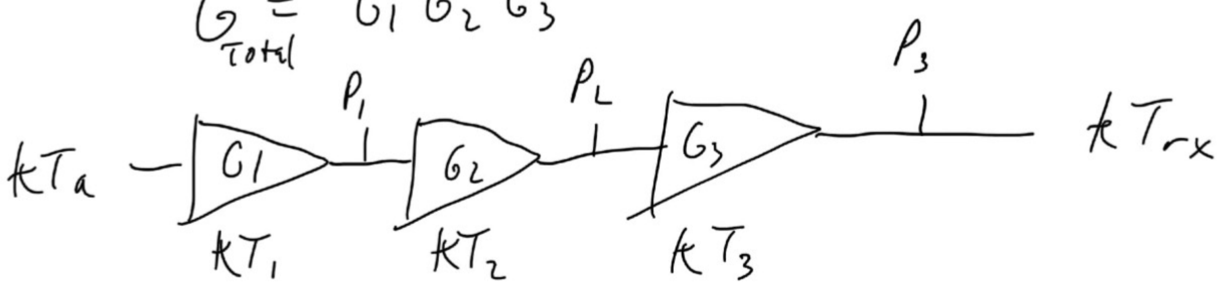
amplifier noise goes up with frequency

$$T_{rx} = T_{min} + T_{ambient}$$

Make $T_{ambient}$ small by cooling amplifier

Receivers

$$G_{Total} = G_1 G_2 G_3$$



$$P_1 = (kT_a + kT_1)G_1 \quad \text{and} \quad P_3 = k(T_a + T_{rx})G_1 G_2 G_3$$

$$P_2 = (P_1 + kT_2)G_2 = (kT_a + kT_1)G_1 G_2 + kT_2 G_2$$

$$P_3 = (P_2 + kT_3)G_3 = (kT_a + kT_1)G_1 G_2 G_3 + kT_2 G_2 G_3 + kT_3 G_3$$

$$(\cancel{k}T_a + \cancel{k}T_{rx})G_1G_2G_3 = (\cancel{k}T_a + \cancel{k}T_1)G_1G_2G_3 + \cancel{k}T_2G_2G_3 + \cancel{k}T_3G_3$$

$$T_{rx}G_1G_2G_3 = T_1G_1G_2G_3 + T_2G_2G_3 + T_3G_3$$

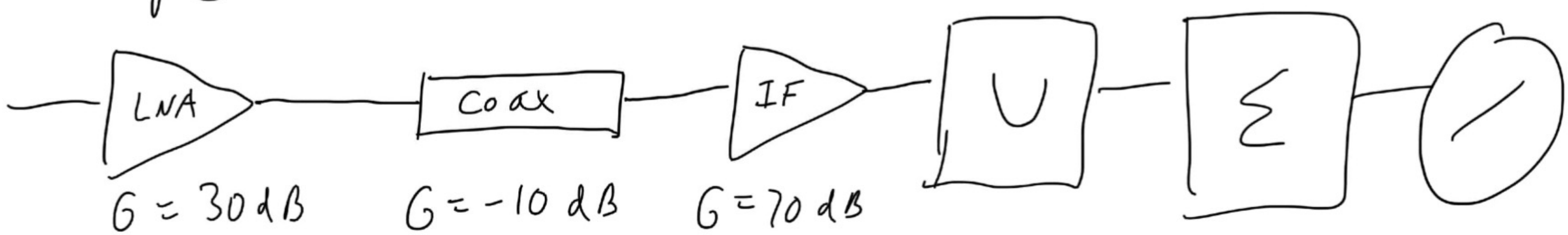
$$T_{rx} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1G_2}$$

which amplifier noise is most important?

why do we care?

Sensitivity $\quad \Delta T = \frac{T_{sys}}{\sqrt{\Delta\nu\,\tau}}$

LWA example



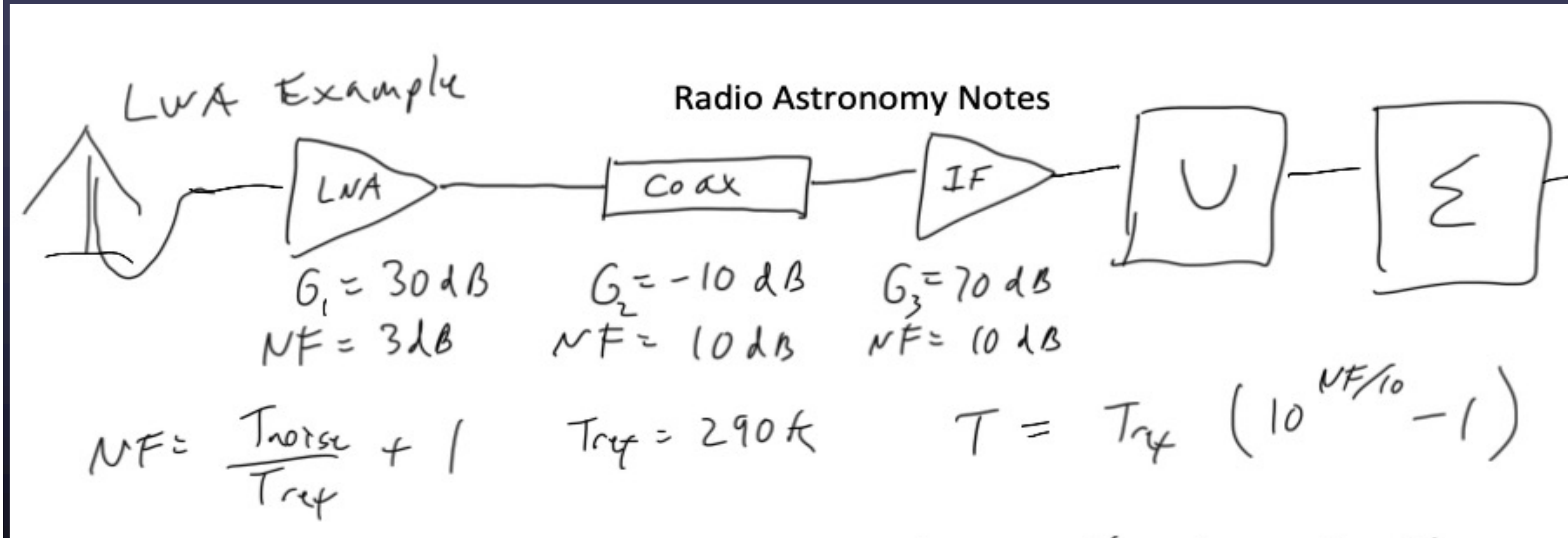
$G = 30\,dB$ $\quad$ $G = -10\,dB$ $\quad$ $G = 70\,dB$

$NF = 3\,dB$ $\quad$ $NF = 10\,dB$ $\quad$ $NF = 10\,dB$

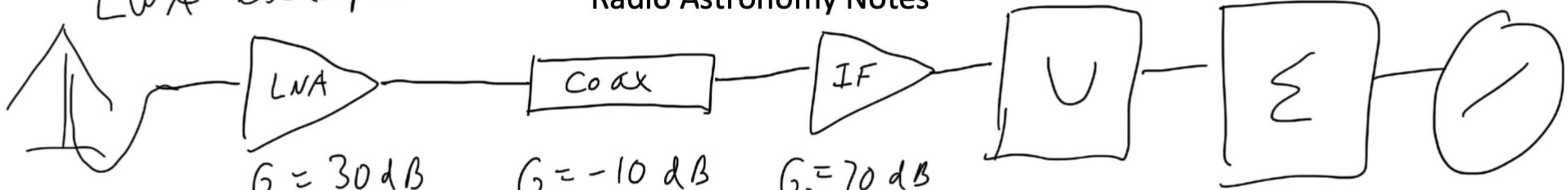
$$NF = \frac{T_{noise}}{T_{ref}} + 1 \qquad T_{ref} = 290\,K$$

Worksheet #3

Consider the receiver chain for the LWA. Given the diagram below, calculate the total gain and the noise temperature of the receiver.



LWA Example



$G_1 = 30\,dB$, $NF = 3\,dB$

$G_2 = -10\,dB$, $NF = 10\,dB$

$G_3 = 70\,dB$, $NF = 10\,dB$

$$NF = \frac{T_{noise}}{T_{ref}} + 1 \qquad T_{ref} = 290\,K \qquad T = T_{ref}\left(10^{NF/10} - 1\right)$$

$$G_{Total} = 30 - 10 + 70 = 90\,dB \qquad NF_{total} = 23\,dB$$

$$T_{rx} = T_{LNA} + \frac{T_{coax}}{G_1} + \frac{T_{IF}}{G_1 G_2}$$

$T_{LNA} = 290\,K$

$T_{coax} = 2610\,K$

$T_{IF} = 2610\,K$

$$T_{rx} = 290 + \frac{2610}{1000} + \frac{2610}{1000 \cdot 0.1}$$

$$= 290 + 2.6 + 26$$

$$= 319\,K$$

What if T_{LNA} doubled? $T_{rx} = 609\,K$ (ouch)

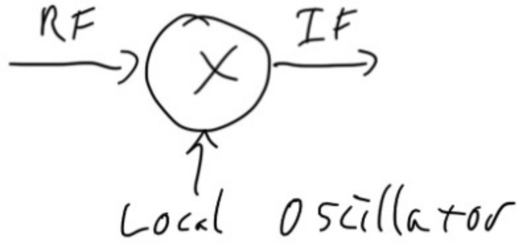
What if T_{IF} doubled? $T_{rx} = 345\,K$ (not so bad)

Radio Astronomy Notes 5-4

Heterodyne receiver

What if we want to transmit signals at a fixed frequency?

So called intermediate frequency IF

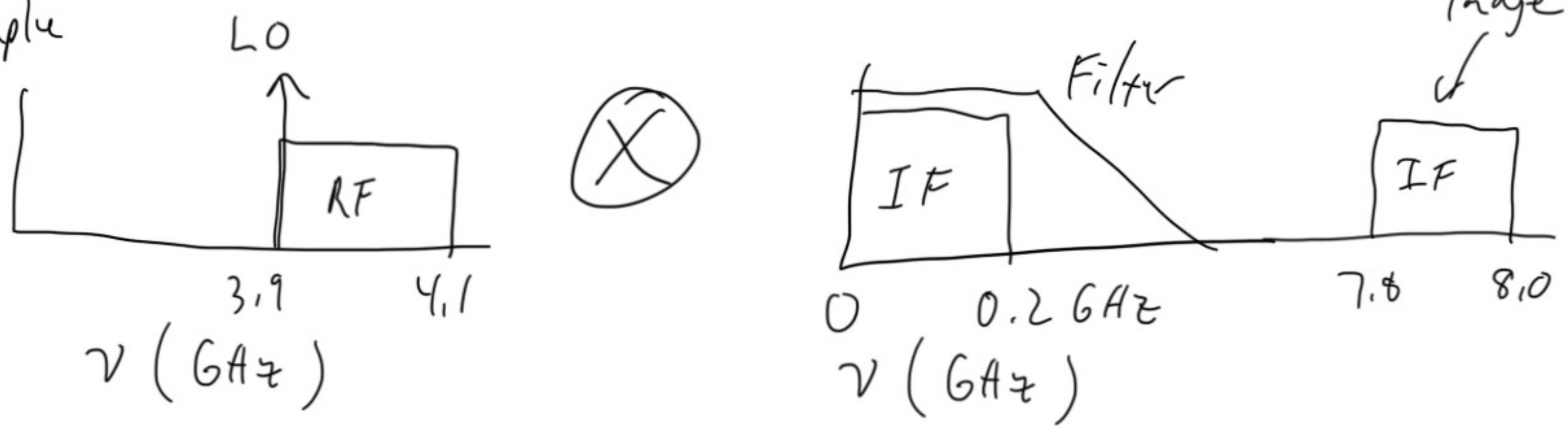


Mixers: multiply two signals in time domain

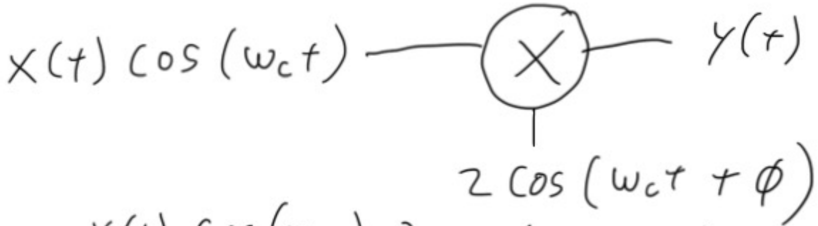
$$\text{IF: } \sin(\omega_{RF} t)\cos(\omega_{LO} t)$$

$$= \frac{1}{2}\left[\sin((\omega_{RF}-\omega_{LO})t) + \sin((\omega_{RF}+\omega_{LO})t)\right]$$

Baseband Transmission Example



What happens to phase of the RF signal?



$$y(t) = x(t)\cos(\omega_c t)\cdot 2\cos(\omega_c t + \phi)$$

$$= 2x(t)\cdot\frac{1}{2}\left[\cos(\omega_c t + \omega_c t + \phi) + \cos(\omega_c t + \phi - \omega_c t)\right]$$

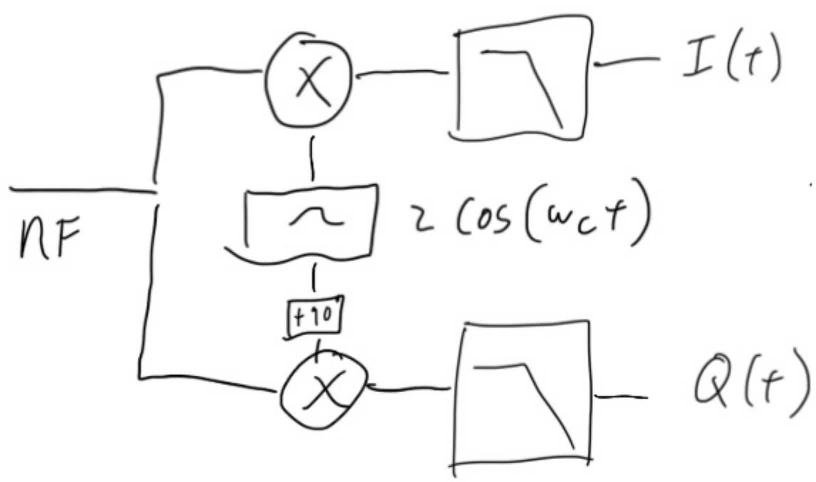
filter this high frequency term OUT

$$= x(t)\left[\cos(2\omega_c t + \phi) + \cos(\phi)\right]$$

$$= x(t)\cos(\phi)$$

downconverted signal depends on LO phase. what happens when $\phi = \frac{\pi}{2}$? $y(t) = 0$???

Solution: use LO and 90° shifted LO to recover complete signal

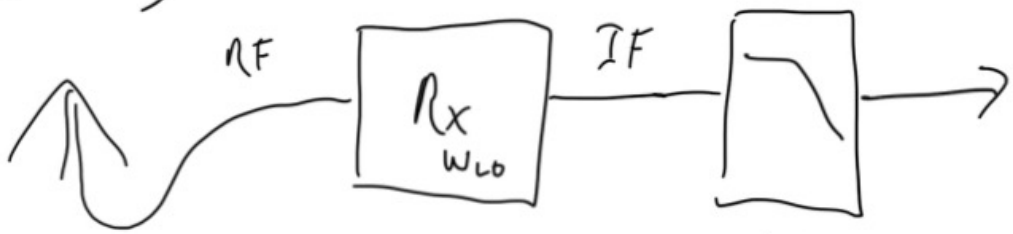


$$|RF| = \sqrt{I^2 + Q^2}$$

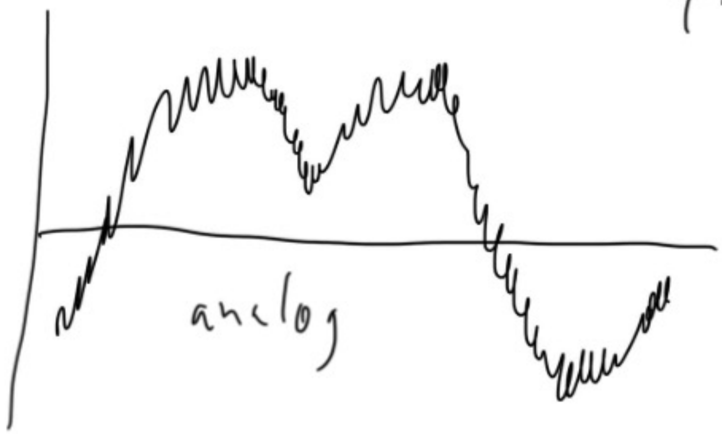
$$\phi_{RF} = \tan^{-1}\left(\frac{Q(t)}{I(t)}\right)$$

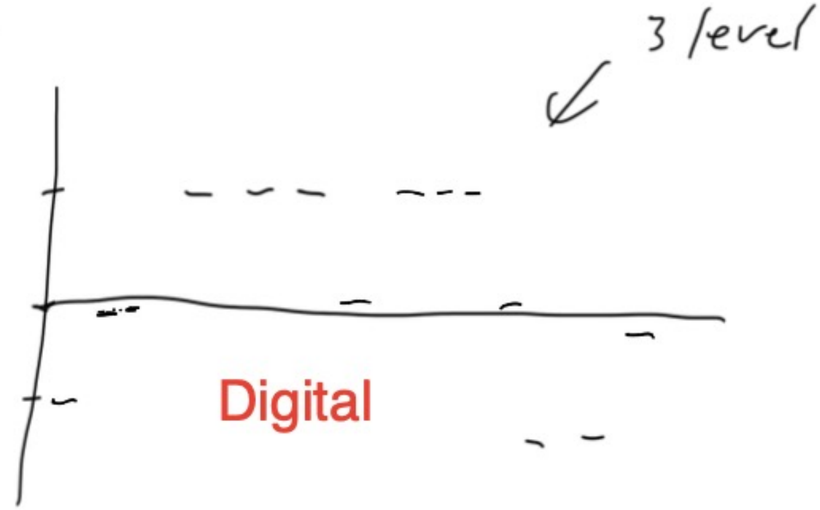
recovers amplitude & phase at baseband

Sampling



voltage time series





Some loss of information (η_s)

sample interval Δt

$\Delta t = \frac{1}{\Delta \nu}$

Nyquist sampling is $\Delta t = \frac{1}{2\Delta \nu}$

Efficiency η_s

# bits	$1/(2\Delta\nu)$	$1/(4\Delta\nu)$
1	0.64	0.74
2	0.81	0.89
3	0.88	0.94
∞	1.00	1.00

Problems: RFI

: weak signals

Data rates

Suppose you want to record 64 MHz × 8 tunings (512 MHz) in two polarizations (RCP, LCP) from a VLBA antenna and store it for 4 hours. How much storage do you need?

$$\text{Data rate} = \underset{\text{Nyquist}}{2\Delta\nu}\ \underset{\text{bits}}{N}\ \underset{\text{pol}}{2}\ \underset{\text{tunings}}{8}\ \text{Samples/sec}$$

$$= 2 \cdot 64\times10^6 \cdot 2 \cdot 2 \cdot 8$$

$$= 4096 \times 10^6 \text{ samples/sec}$$

$$= 4096 \text{ Mbps} \simeq 4 \text{ Gbps}$$

In 4 hours: 4096 Mbps · 3600 sec · 4 ~~hr~~ = 74 TB fill up 7× 12 TB drives

$2800