Engineering Aspects for Radio Astronomy

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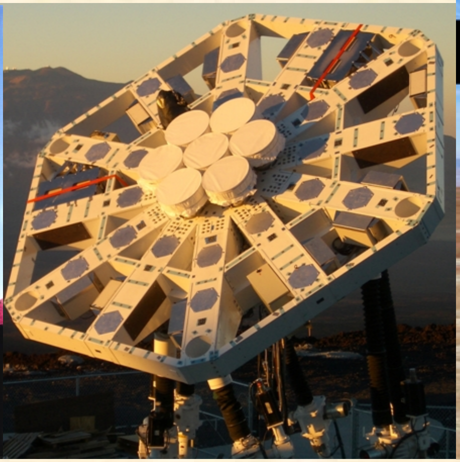
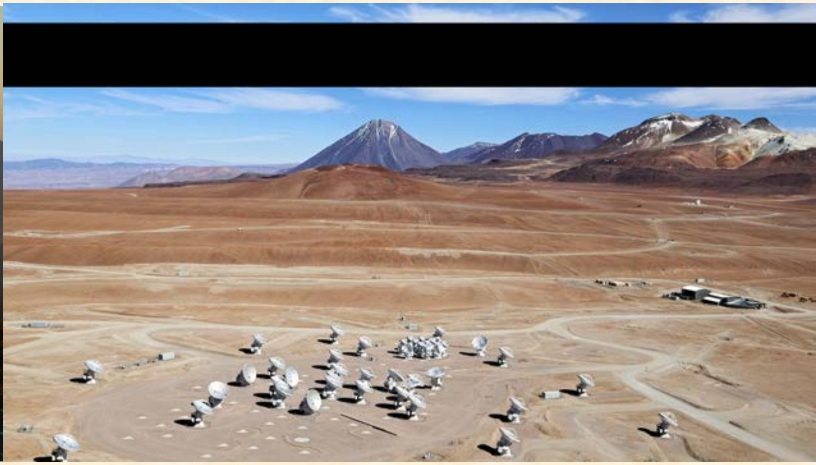




July 24, 2018

2018 ASIAA Summer Student Lecture Series

Introduction

- What we have learned:

(1) Radio Astronomy (Science) (July 10, 2018)

- Brief history
- Introductory to Radio Telescopes
- Science

(2) Interferometry and Synthesis of Radio Astronomy (July 13, 2018)

- Principle on how interferometric telescope array works

- What we will learned in **Radio Astronomy (Engineering)**
  - Technical Challenging
  - Concept of Signal and Noise
  - Antenna and Propagation
  - Receiver Front-End: Detectors, Mixers, Amplifiers
  - Signal Processing and Correlator

Technical Challenges

- Challenges on building instruments for radio astronomy:

(1) High spatial resolution with relatively long wavelength

(2) Detect extremely faint signal

(3) Overcome strong interferences

(4) High spectral resolution for accurate velocity and distance measurement, if necessary

- These challenges lead to the technical development for advanced radio telescopes

Technical Challenge (I)

- **high spatial resolution with quite long wavelength**
  - Optical / NIR wavelength = 0.400-1.300μm (take 0.6μm as average)
  - Radio wavelength = 21cm for HI line (wavelength ratio: 3.5 x 10^5 times)
  - Microwave ~ 10 cm to 1 cm (~ 10^5 times)
  - Millimeter wave ~ 8mm to 1mm (~ 10^4 times)
  - Submillimeter wave ~ 1mm to 0.3mm (~ 10^3 times)
  - Terahertz wave ~ 0.3 to 0.05mm (~ 10^3 times)

- Diffraction limit
  - Diffraction limit ~ 1.22 D/λ, larger this number, the spatial resolution is better, where D = the diameter of the collecting aperture (antenna, lens, or mirror), λ = wavelength

Technical Challenges (I)

- The advantage of the radio engineering (if compare to the optical engineering) in general

(1) artificial signal source with precise frequency and stable phase is available.

(2) signal detection and processing is not just **the amplitude** but also **the phase.**

(3) Frequency conversion is feasible because of the nonlinear device and filtering is available → **high spectral resolution** achieved

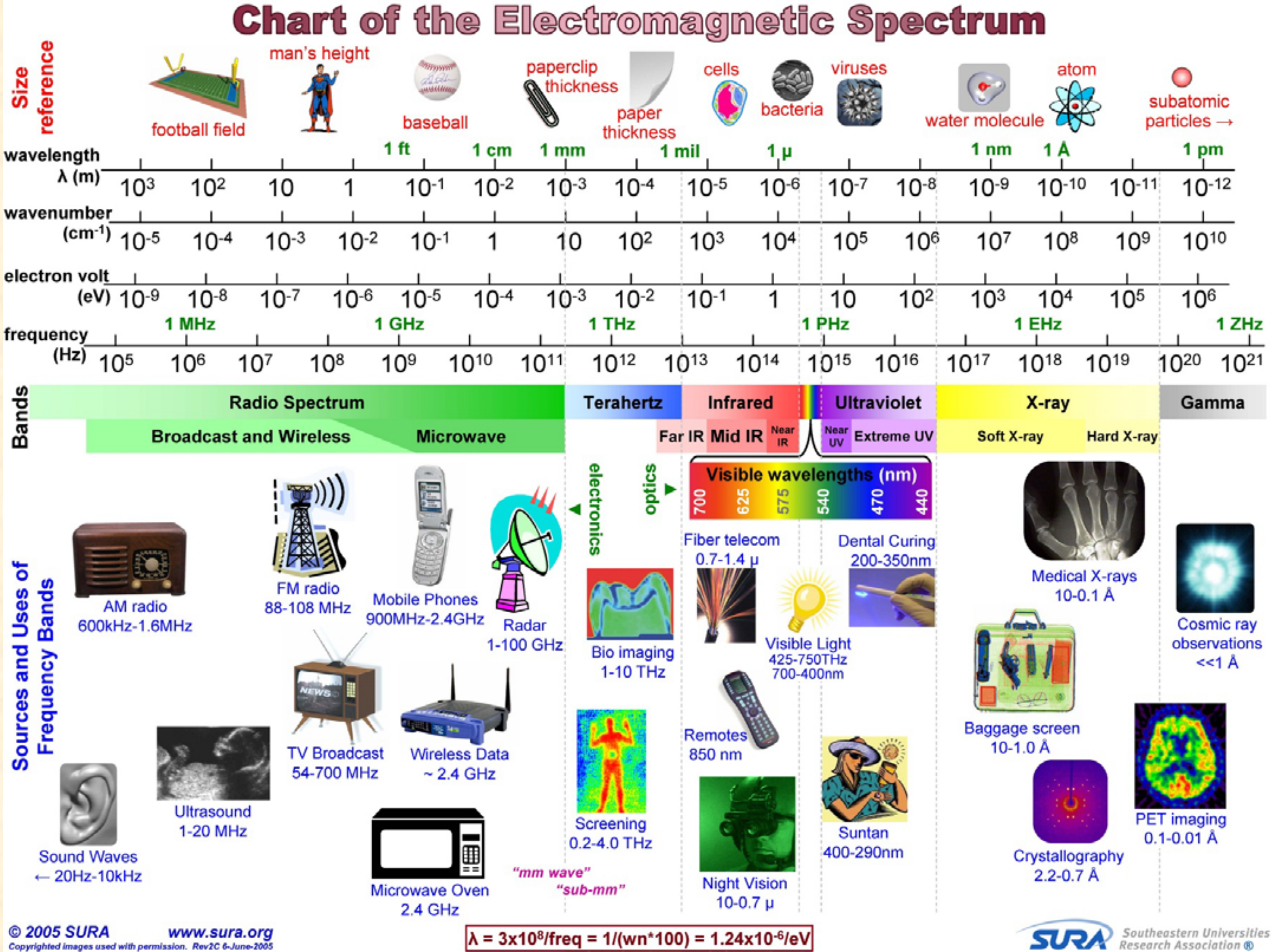
- The signal from various telescopes in spatial distance can be collected and process to synthesize the image → **interferometry and aperture synthesis** feasible (see Interferometry slides @ July 13, 20168) → **high spatial resolution achieved**

Technical Challenges (II)

- **Detecting extremely faint signal**
- If spectral information is not required: broadband detection of power only → **bolometric receiver**
- If spectral information is required: **heterodyne receivers**
- High sensitivity is required:
  - Noise in the instrument has to be minimized to approaching to **quantum limit**
- **Stability Requirement**
  - To detect faint signal, even quantum limit receiver is not enough, **long integration time** is required. With excellent **stability**, longer integration time is feasible

Technical Challenges (III)

- Overcome **strong interference**
  - For lower frequencies, strong interference comes from artificial EM activities, we call them electromagnetic interference (EMI)



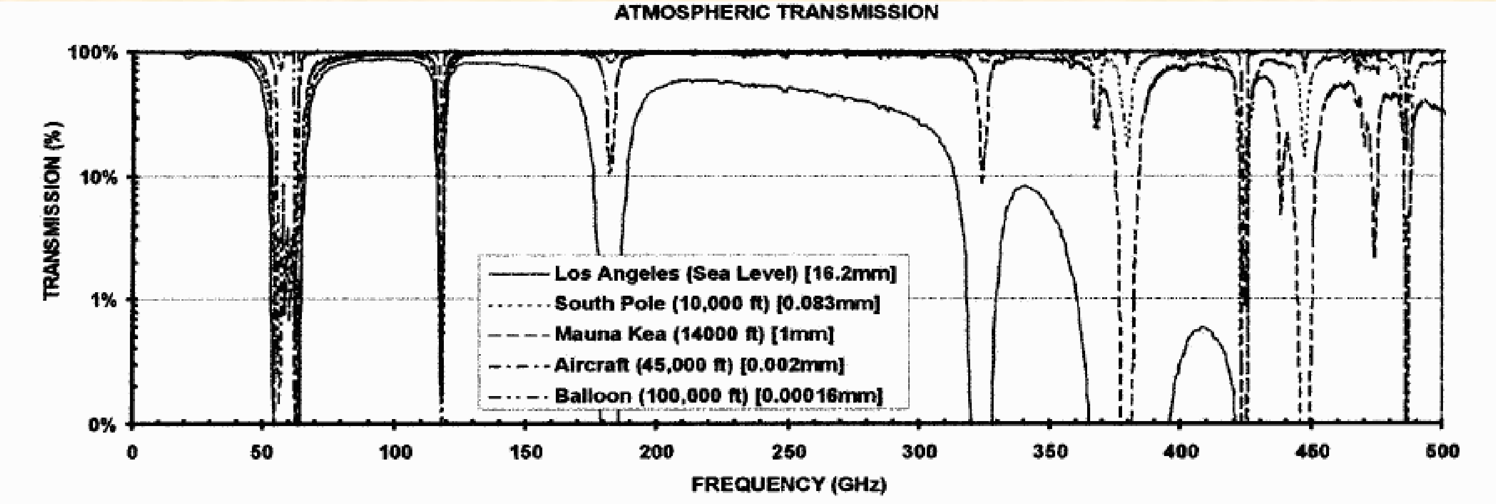
Technical Challenges

- For lower-frequency radio telescope: EMI from human activities like communication, radar, and even microwave ovens could lead to failure of the observation!
- Solution: set **Radio Quiet Zone**, or install high-Q bandpass filters in receiver front-end.
- Near to radio telescope, special diesel vehicles are used for transportation (to avoid EM pulse introduced by sparkplug).

Technical Challenges

for higher frequency, dry and cold location with high altitude is required.

Atmospheric Limitation of Radio frequency



For >100GHz, the absorption of the water vapor and oxygen (at certain frequency range) turn to limit the observation

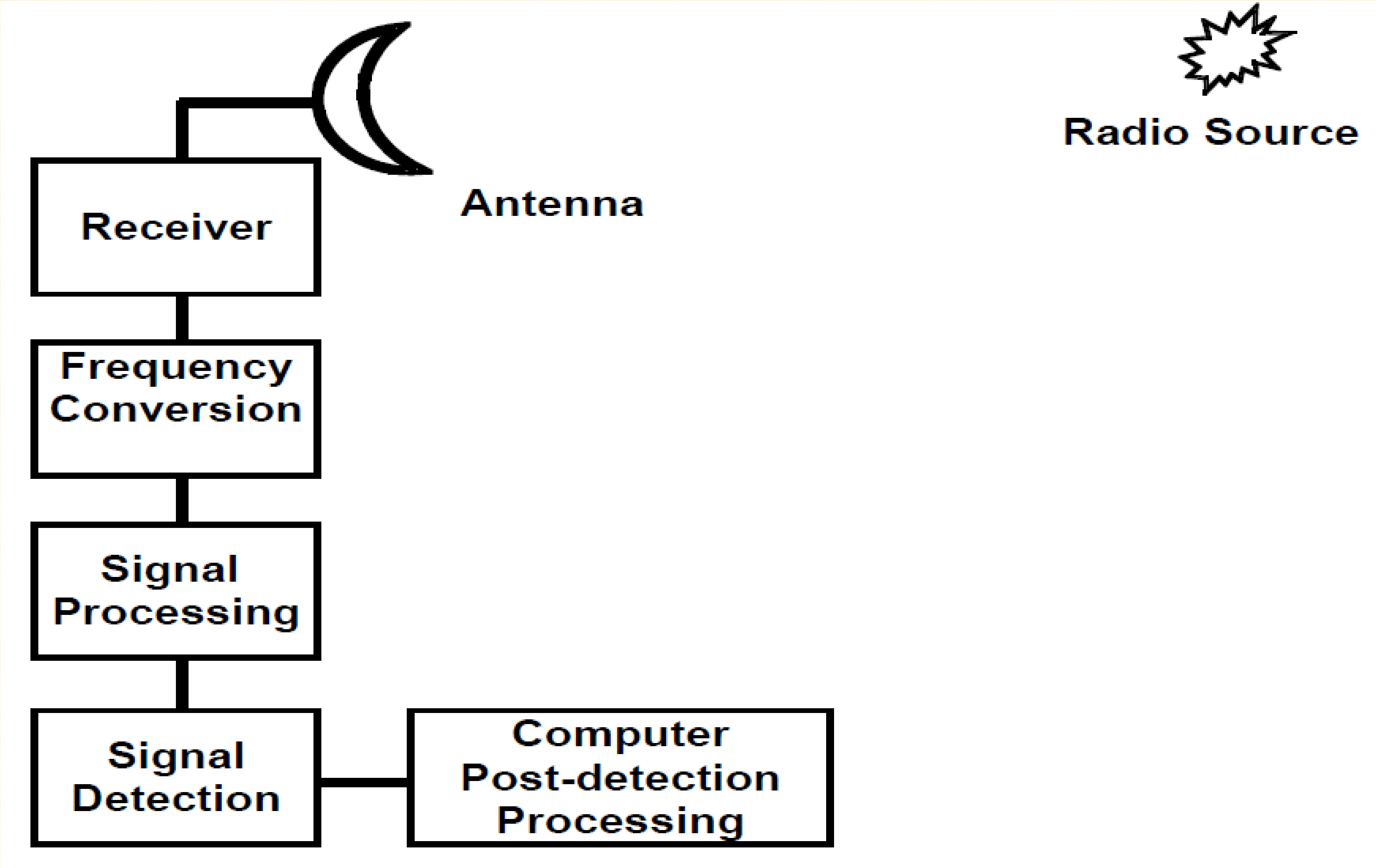
The turbulence and cloud of the atmospheric above the telescope also introduce the accuracy of the interferometry → various **calibration techniques** are required

Signal and Noise

- Basic Block diagram of a radio telescope
- Signal
- Thermal noise
- Quantum Limit
- Measuring Microwave noise
- Low-frequency noise and Stability

Radio Telescope: Individual Key Blocks

- Radio Telescope System Block Diagram



Electromagnetic Signal for Radio Astronomy

- **Continuum signal**: thermal radiation, synchrotron radiation, cosmic back ground radiation, etc.
  - For very fain signal without spectral resolution, or lower spectral resolution is required, **bolometric receiver** is preferred.
- **Spectral signal**: quantum transition due to atoms, molecules and ions. For microwave and millimeter-wave, it is typical spin transition, or vibration/ rotational quantum state transition.
  - Typical high resolution is achieved by **heterodyne receiver**, the receiver with frequency conversion to preserve the spectral information

Microwave Noise (Thermal noise)

- Microwave noise power is basically originated from thermal fluctuation, and it can be expressed as equivalent noise temperature – consider a resistor at a temperature of T degree Kelvin, the nonzero rms voltage due to Plank's blackbody radiation is

$$v_n = \sqrt{\frac{4hfBR}{e^{hf/kT} - 1}}$$

- h = 6.546 × 10^{-34} J-sec (Plank's constant)
- k = 1.380 × 10^{-23} J/K (Boltzmann's constant)
- T : operating temperature in kelvin
- B : Bandwidth of the system in Hertz
- f: center frequency of the bandwidth in Hertz
- R: resistance in Ohm.
- In microwave frequency Rayleigh-Jeans approximation applied,

$$v_n = \sqrt{4kTBR}$$

Quantum Limit of Thermal Noise

- Quantum limit: under Rayleigh-Jeans approximation, when intrinsic thermal energy of the receiver is equivalent to single photon count, then

$$kT \sim \hbar\omega$$

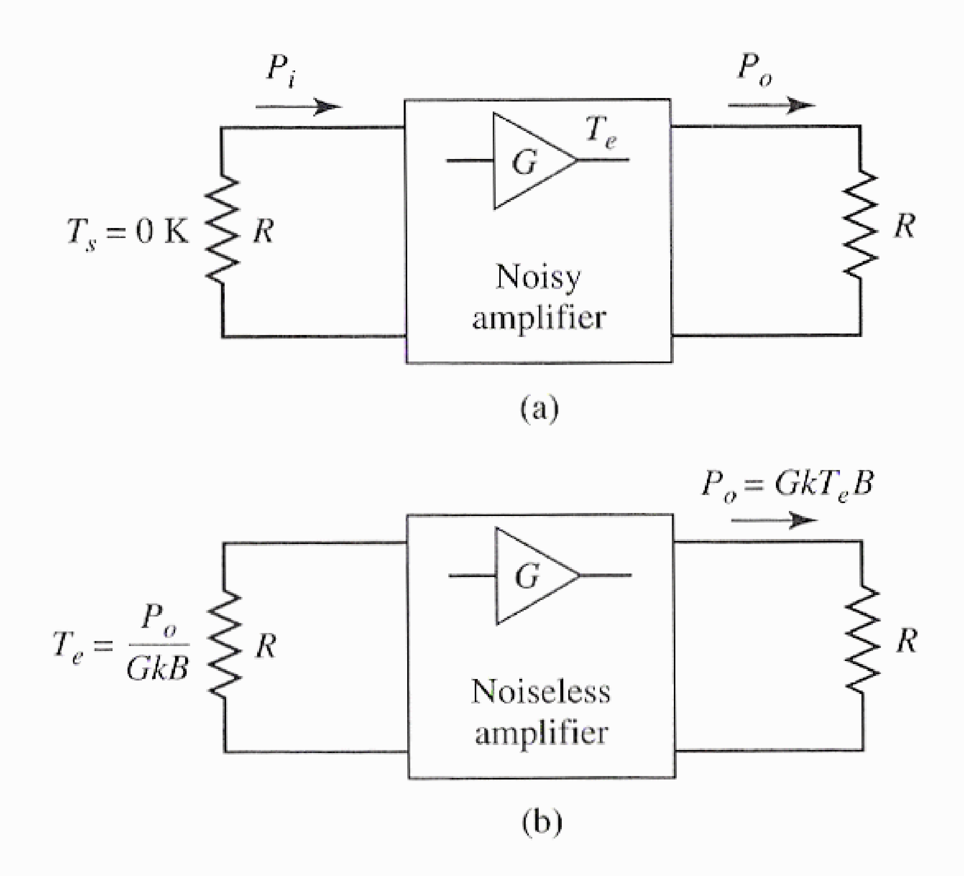
$$T \equiv T_{QL} \sim (\hbar / k)\omega$$

- T_{QL} is define as the quantum-limit noise temperature
- T_{QL} = 4.80 x 10 $^{-2}$ f (GHz), ~ 2.4K at 50GHz.
- In good cryogenic LNA or superconductive mixer, noise temperature can reach this limit.
- Receiver noise temperature specification usually counts as several times of the quantum limit.

Measuring Microwave Noise

- Concept of equivalent noise temperature –
- If an arbitrary source of noise is **white** (noise power is not a strong function of frequency) and it delivers a noise power P_s to a load resistor R, then the equivalent noise temperature of the resistor

$$T_e = \frac{P_s}{kB}$$



- If this white noise is amplified by a noiseless amplifier with gain G, then the output power $P_o = P_sG = GkT_eB$
- For a noisy amplifier with a bandwidth B and gain G, the equivalent temperature T_e is defined as

$$T_e = \frac{P_o}{GkB}$$

Measurement of Noise Temperature

- Y-Factor Method (Hot-cold Load Method)

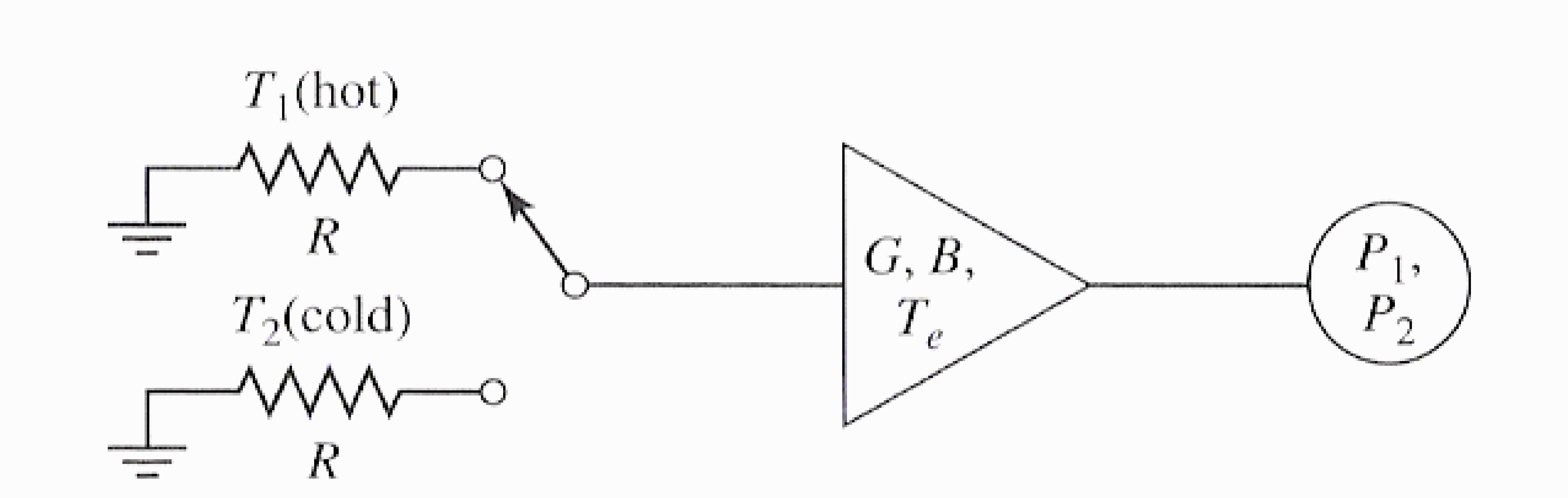
$$P_1 = GkT_1B + GkT_eB$$

$$P_2 = GkT_2B + GkT_eB$$

$$Y = \frac{P_1}{P_2} = \frac{T_1 + T_e}{T_2 + T_e}$$

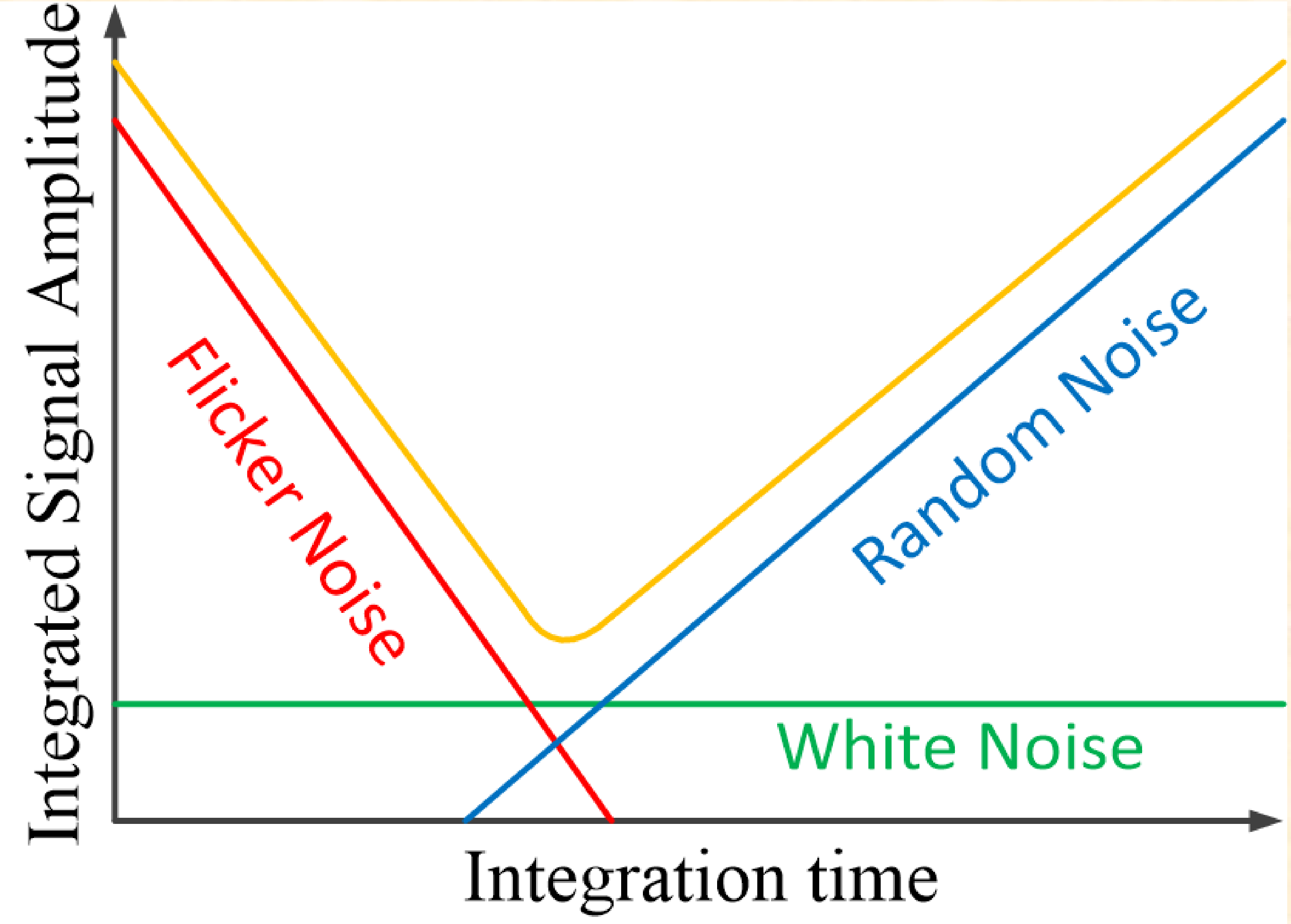
$$T_e = \frac{T_1 - YT_2}{Y - 1}$$

Valid for both amplifiers and mixers



Lower Frequency Noise

- For amplitude and phase stability, three major components: (i) white noise, (ii) flicker noise, and (iii) random noise.
- Integration time is mainly limited by the noise of the instruments



Antenna and Propagation

- Reflector antenna
- Feed antenna
- Gaussian Beam

Antenna and Propagation

- Parabolic Antennas: Symmetric v.s. Offset
- ALMA 12 meter GBT 100 meter

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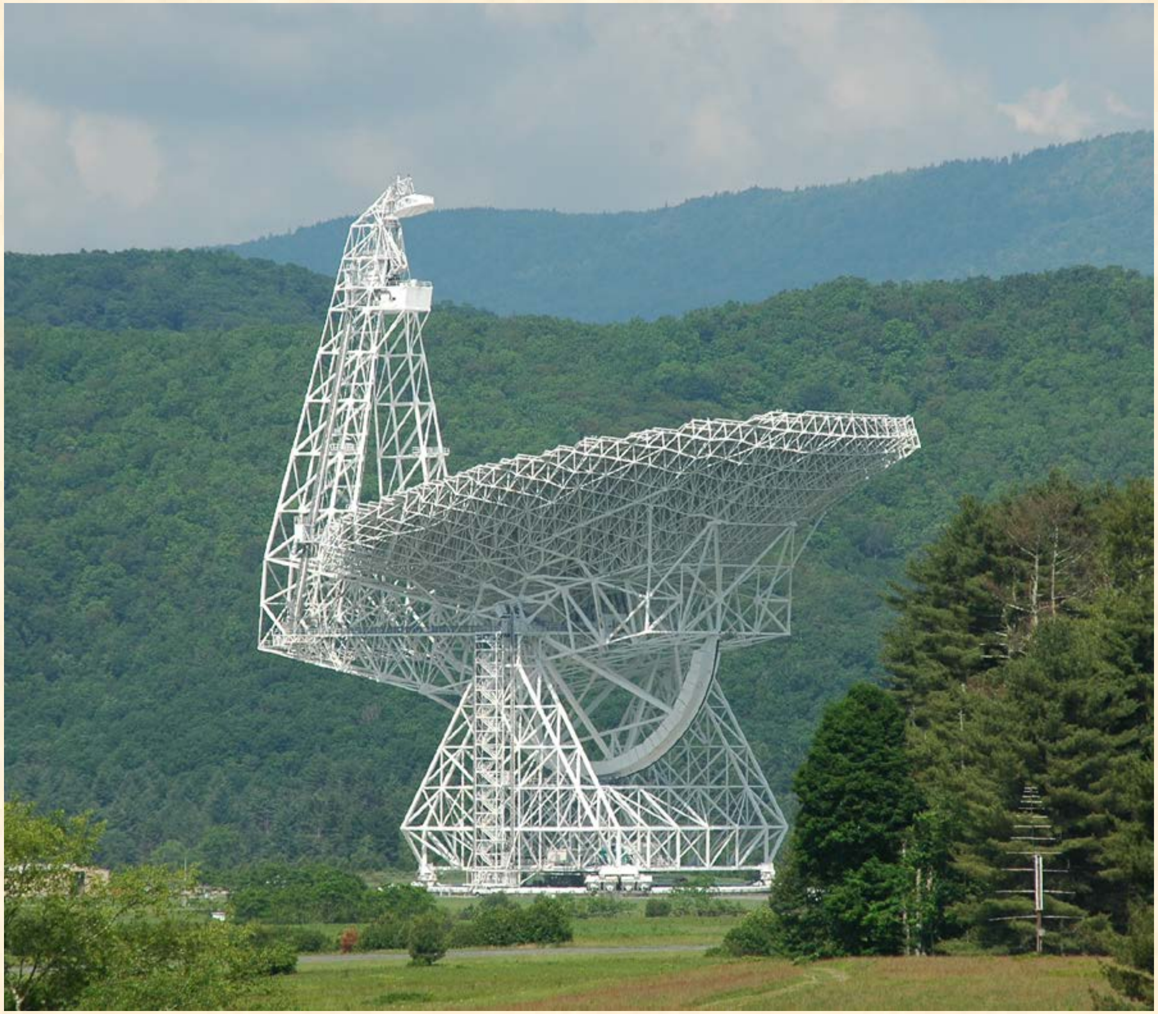


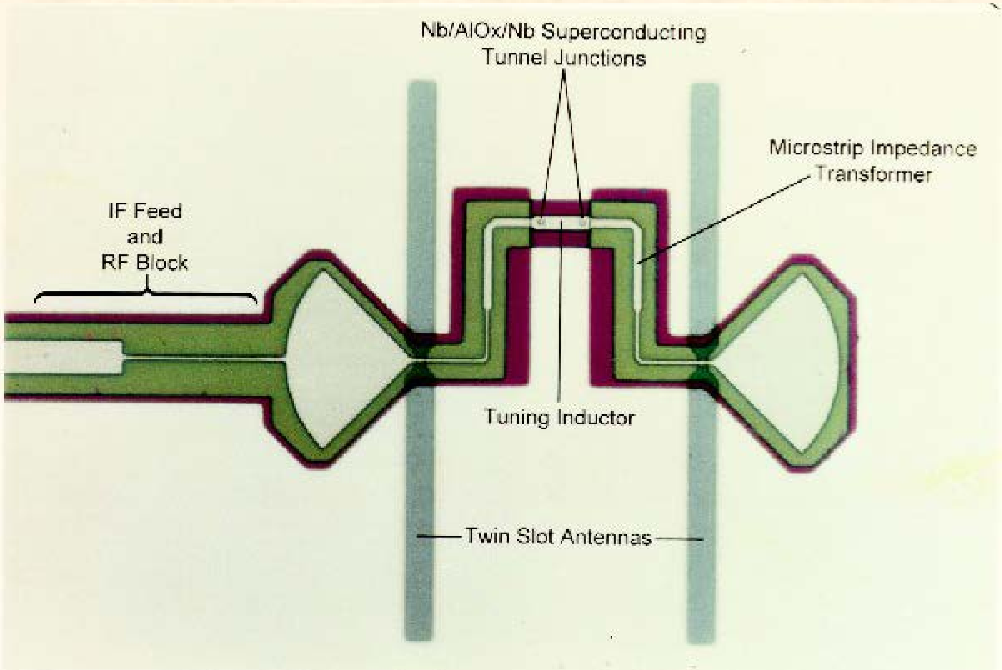
Antenna and Propagation

- The structures to collect or transmit electromagnetic wave propagated in the open space.
- For radio telescopes, highly efficient coupling from large reflector to the feed antenna in front of the receiver is required.

SMA-7, 5.17.2001, MTC

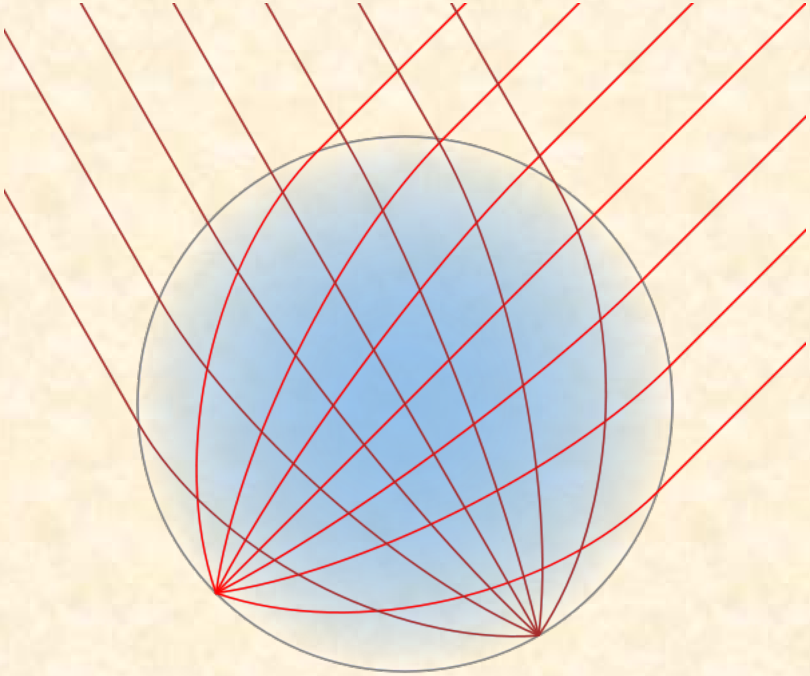
Antenna and Propagation

- Example of the feed antennas: (left) Corrugated feed horn antenna, a variation from circular cross section waveguides. (right) slot antenna, a variation from planar microstrip antenna



Antenna and Propagation

- Metallic antenna v.s. dielectric antenna -- reflective v.s. refractive
- Examples of the dielectric antennas: (left) Lundberg antenna with gradual refractive index, (right) traditional dielectric lens antenna.



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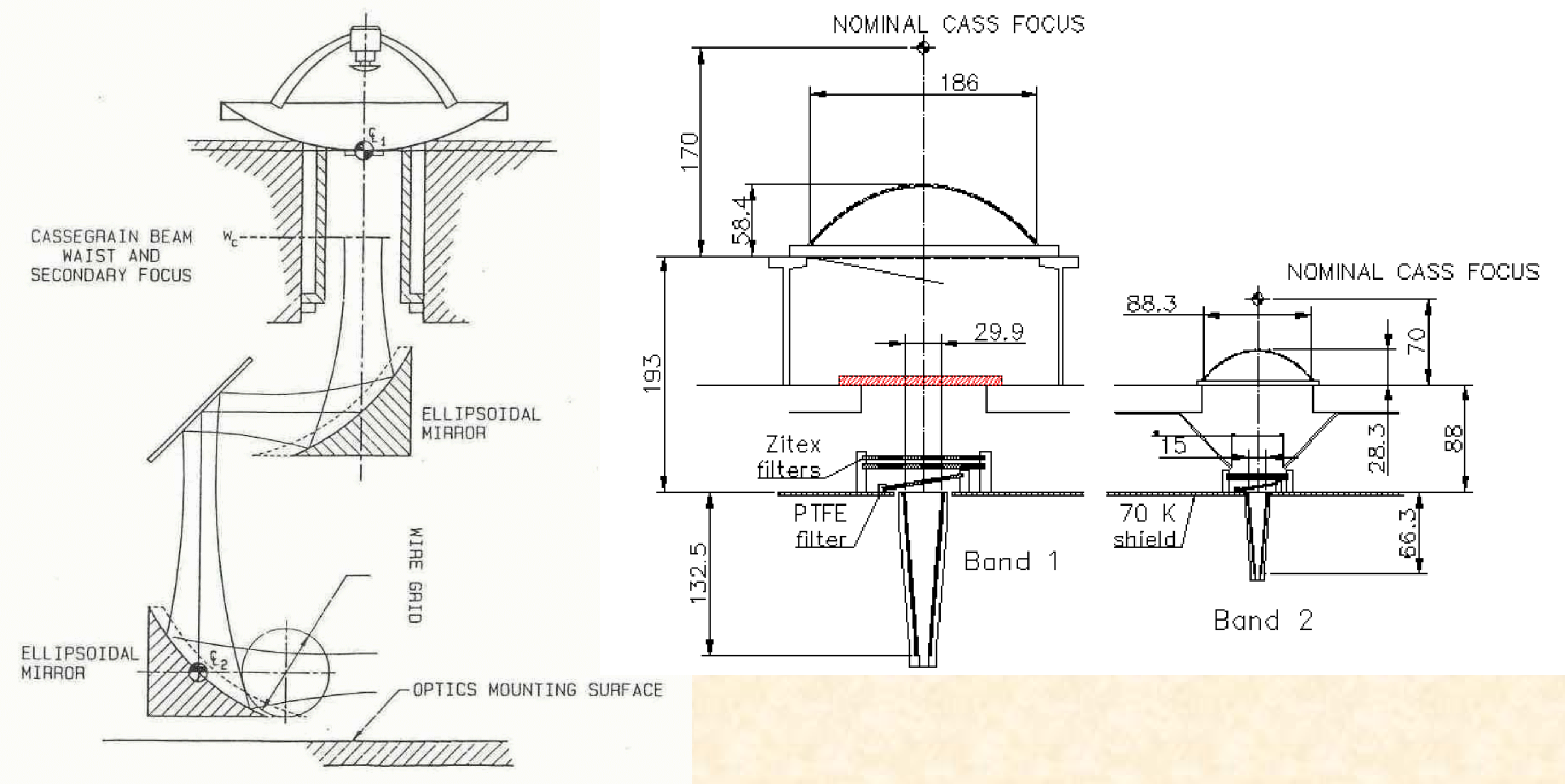
https://commons.wikimedia.org/w/index.php?curid=7968871

https://www.micro-radar.de/en/technology/lens-antenna.html

Antenna and Propagation

- Gaussian Optics (Long-wave Optics): For antenna / wave propagation sub-system design



Antenna Propagation - Gaussian Optics

- **Hemite-Gaussian Optical Beam Formulation**
- Consider a electromagnetic radiation travel along z-direction, with amplitude profile finitely extended along X-Y plan expressed as

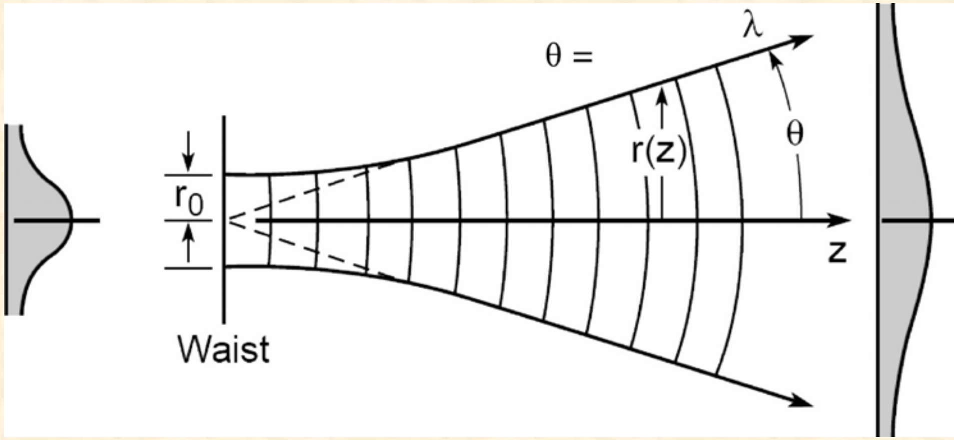
$$(\nabla^2 + k^2)\psi = 0, \qquad \psi(x,y,z) = u(x,y,z)\exp(-ikz)$$

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} - 2ik\frac{\partial u}{\partial z} = 0$$

- Under paraxial approximation, variation of u along the z-direction is small, then

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} - 2ik\frac{\partial u}{\partial z} = 0$$

$$\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} + \frac{1}{r}\frac{\partial^2 u}{\partial \varphi^2} - 2ik\frac{\partial u}{\partial z} = 0$$



Antenna Propagation - Gaussian Optics

- **Hemite-Gaussian Optical Beam Formulation (cont.)**
- For lowest order mode, the wave amplitude profile is axially symmetric, then

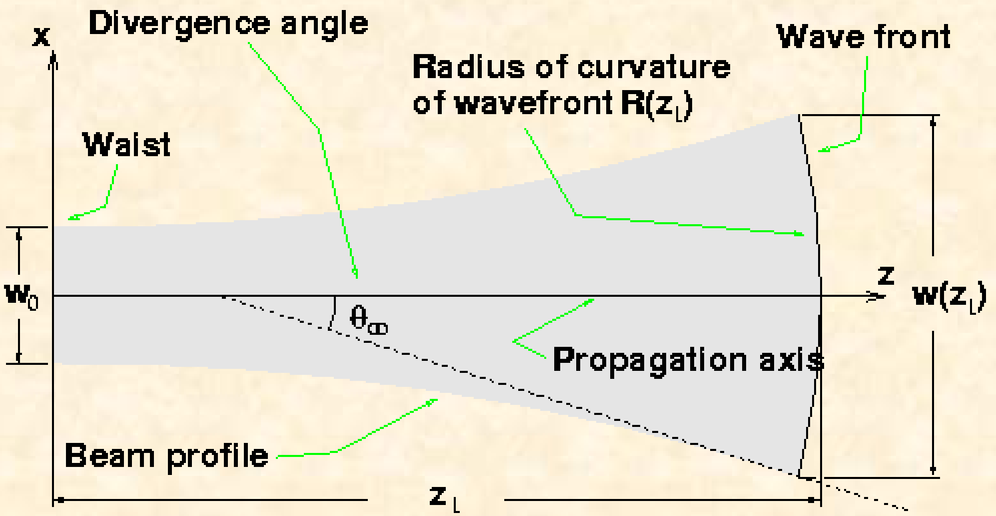
$$\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} - 2ik\frac{\partial u}{\partial z} = 0$$

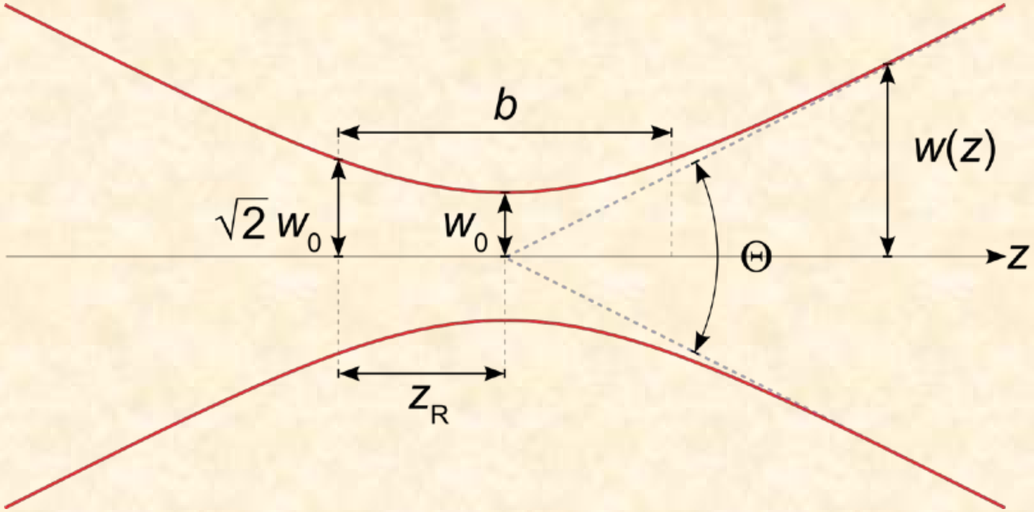
- The solution of the equation is

$$u(r,z) = \frac{w_o}{w}\exp\left[\frac{-r^2}{w^2} - \frac{i\pi r^2}{\lambda R} + i\phi_o\right]$$

$$w = w_o\sqrt{1+\left(\frac{\lambda z}{\pi w_o^2}\right)^2} \qquad R = z + \frac{1}{z}\left(\frac{\pi w_o^2}{\lambda}\right)^2$$

$$\phi_o = \tan^{-1}\left(\frac{\lambda z}{\pi w_o^2}\right)$$

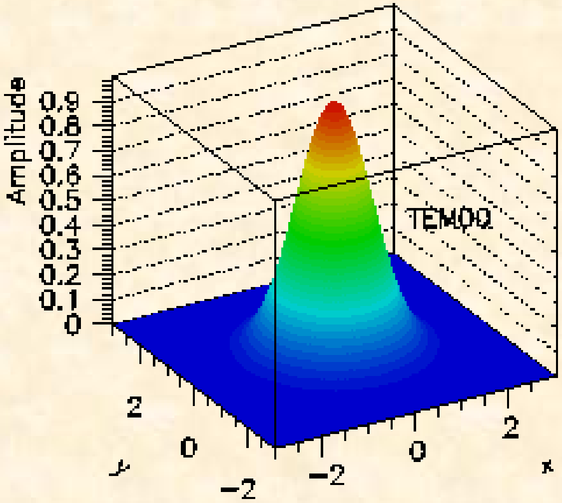


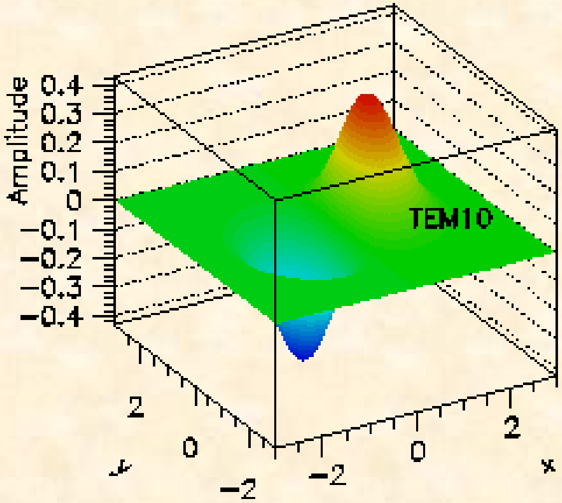


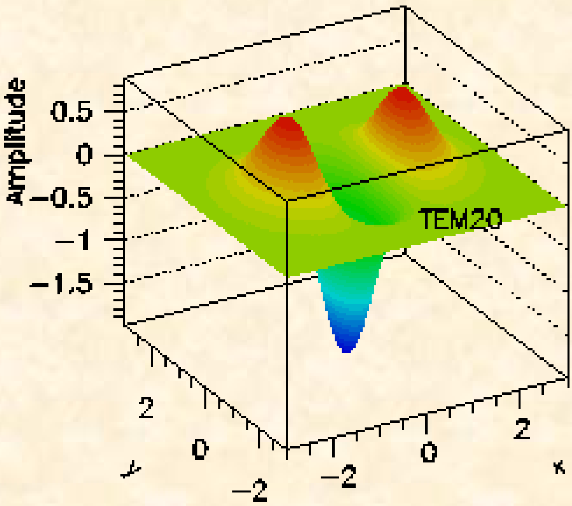
Antenna and Propagation

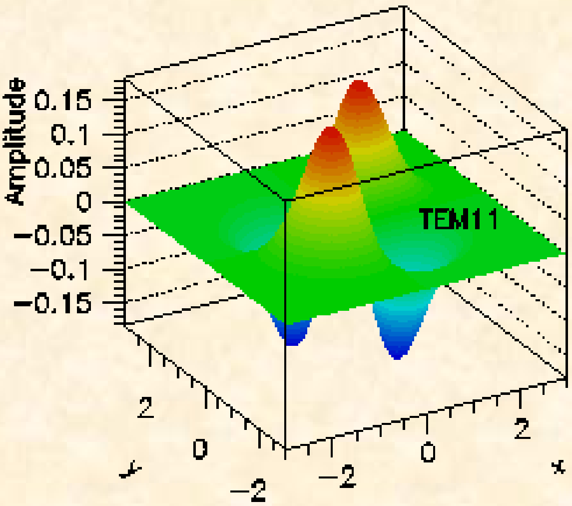
- Gaussian Optics for antenna/ wave propagation in astronomical instrumentation emphasize the efficiency.

- High efficiency --- low loss
- Higher order modes have to be minimized and suppressed.





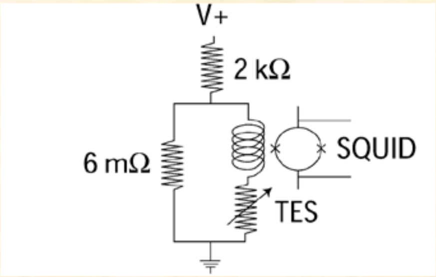




Receiver Front-end: Detectors, Mixers, Amplifiers

Bolometric receiver

- Receiver based on the detector very sensitive to the incident power, typically detect power by physical property change of the material under incoming power, not capable to detect or preserve phase information during power detection.
- Popular bolometric detectors: TES (Transition-edge sensor), MKID (Microwave kinetic inductive detector), <350 milli-Kelvin operating temperature is typically required.
  - TES: radiation absorbing element + superconducting thin film with Tc (with constant ext. bias voltage) + weakly coupled heat sink at To~ Tc/2
  - MKID: make use the complex AC surface impedance (inductor) changed by the generation of the quasi-particle electrons induced by the incident power. This kind of power dependent inductor with transmission line to form resonator, the resonating frequency changed at microwave frequency

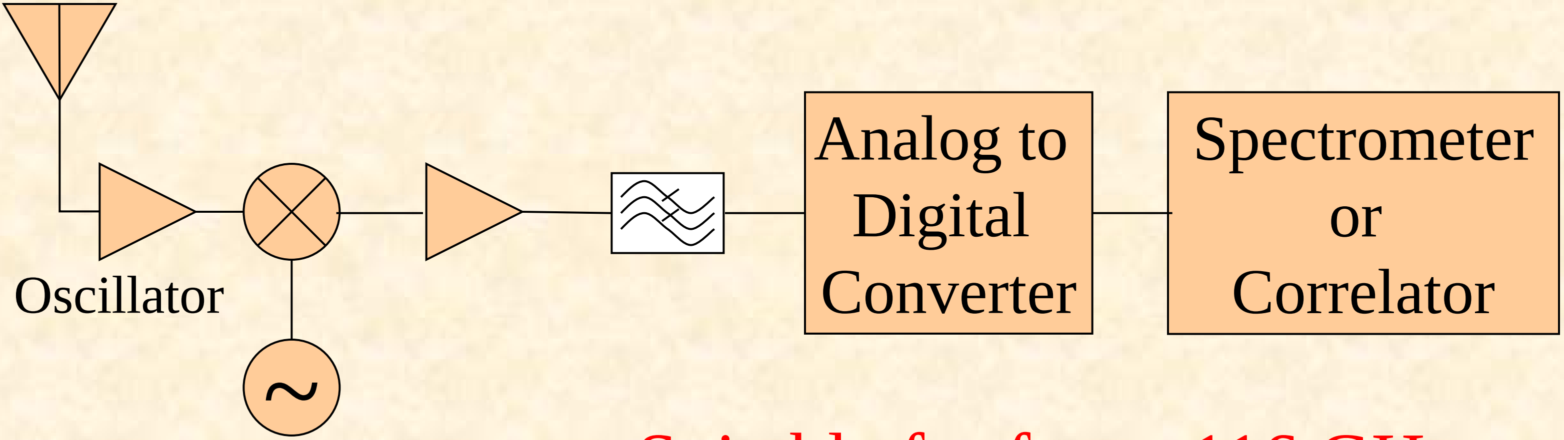


Heterodyne Receiver

- **For resolving technical challenge (IV)**
- **high spectral resolution** for accurate velocity measurement (via Doppler Effect) and distance measurement (via Hubble's Law): by heterodyne receivers.
- **heterodyne receiver**:
  - for low frequency, the signal is amplified and then divided into different frequency bands and then digitized, correlated and generated the digital spectral information.
  - For millimeter-wave frequency, the signal is amplified and then down-convert the frequency (by **mixer**) into intermediate frequency (IF), amplified and then divided into different frequency bands and then digitized, correlated and generated the digital spectral information.
  - For submillimeter-wave frequency, no low-noise amplifier with quantum-limited performance available, signal is down-convert the frequency (by **mixer**) into intermediate frequency (IF), amplified and then divided into different frequency bands and then digitized, correlated and generated the digital spectral information.
  -

Typical Heterodyne Receiver Configurations

- Receiver Feed
- RF Amplifier
- Mixer and Local Oscillator
- IF Amplifier
- IF Low-pass filter
- Spectrometer or Correlator

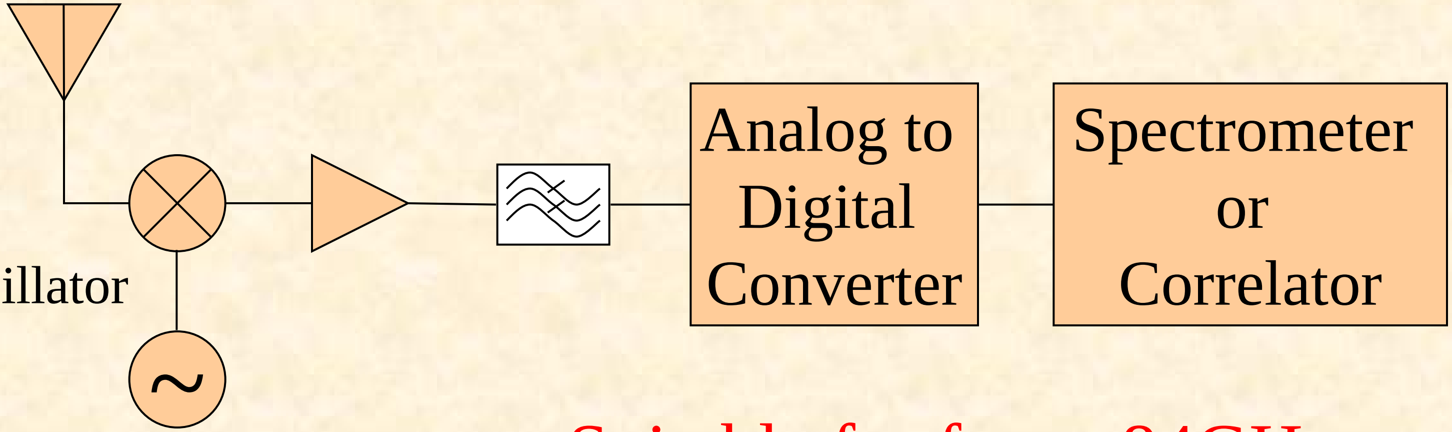


Analog to Digital Converter

Spectrometer or Correlator

- Suitable for $f_{RF} < 116$ GHz

- Receiver Feed
- RF Amplifier
- Mixer and Local Oscillator
- IF Amplifier
- IF Low-pass filter
- Spectrometer or Correlator

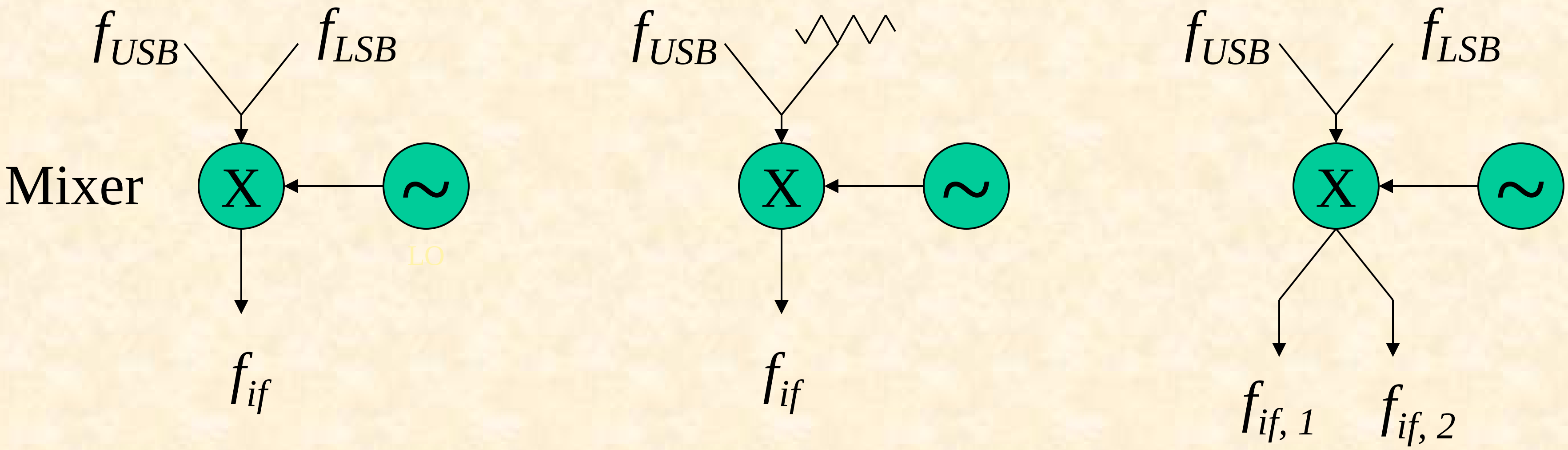


Analog to Digital Converter

Spectrometer or Correlator

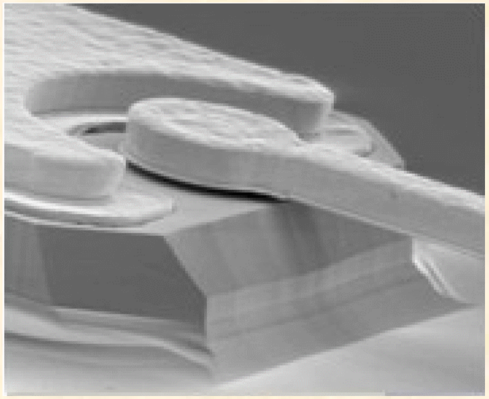
- Suitable for $f_{RF} > 84$GHz

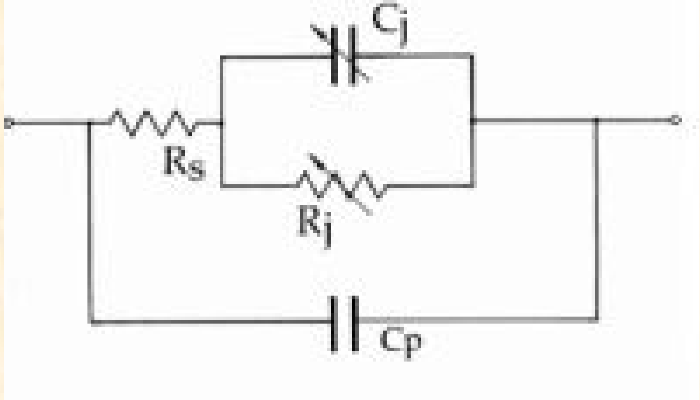
Mixer Varieties: Frequency Conversion

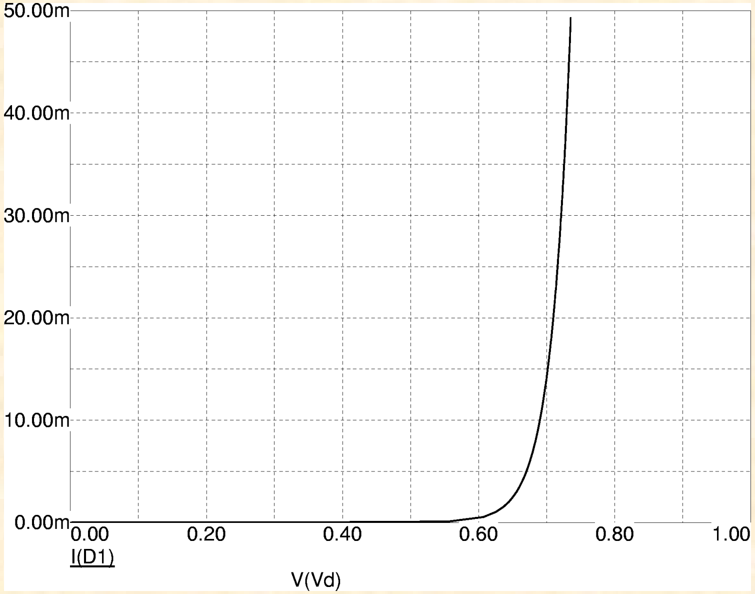


- Double side-band receiver (DSB) : f_{if} is a mixture of both f_{USB} and f_{LSB} . Side band separation can be done in the later stage of signal processing.
- Single side-band receiver (SSB) : f_{if} is either f_{USB} and f_{LSB} . Either side-band can be suppressed, or terminated, before output of the mixer.
- Two side-bands receiver (2SB): Complication in design.

Schottky Diode Mixers







- Use the nonlinear IV curve formulation with large-signal sinusoidal voltage signal applied

$$C_j = C_{jo}(1-\frac{V_j}{\phi})^{-\gamma} \qquad R_j = \frac{1}{\alpha\cdot i_o} e^{-\alpha\cdot V_j} \qquad \alpha = \frac{e}{\eta\cdot k\cdot T}$$

$$g_j = R_j^{-1} = \alpha\cdot i_o\cdot e^{\alpha\cdot V_{j,LO}\cdot\cos(\omega_{LO}t)} = \alpha\cdot i_o \sum_{n=-\infty}^{n=\infty} I_n(\alpha V_{j,LO})\cdot e^{jn\cdot\omega_{LO}t}$$

- Where I_n *(x)* = Modified Bessel Function of the First Kind

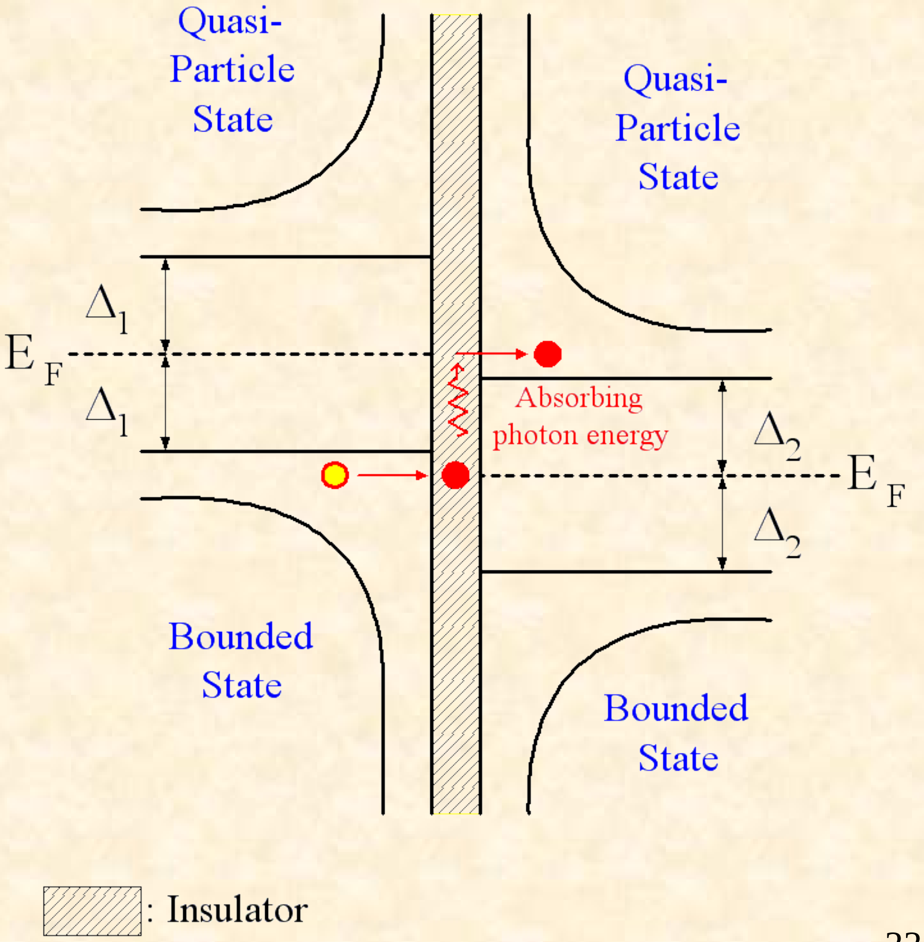
SIS Mixers - Basic Operation Principle

- Quantum tunneling of the quasi-particle electron in superconductor. When the SIS junction is biased at Vo, the incident photon with frequency f, then the condition of tunneling

$$eVo > D_1 + D_2 - nhf$$

- n is arbitrary integer.
- Copper pair electron (component of super-current) can also tunneling through junction, however, due to its boson behavior, the tunneling super-current usually induced noisy oscillation which is not suitable for low-noise mixing.

Energy Diagram of a Biased Superconductor-Insulator-Superconductor (SIS) Barrier

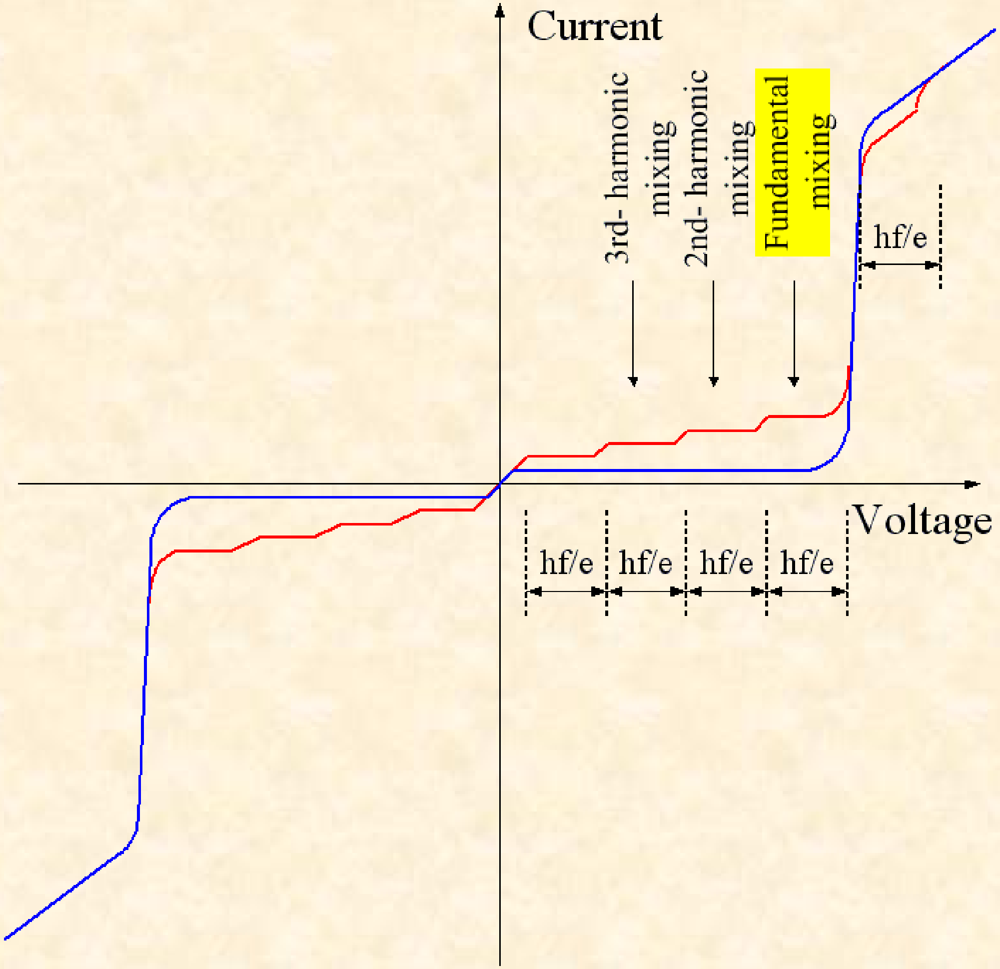


SIS Mixers - Basic Operation Principle

- The pumped SIS IV curve is quantized as shown in right figure, when the signal photon with frequency f_s is incident with pumped photon f_p, the wave function of these two photon interact with the barrier potential function to form a quantum mixing.
- Detail description see:

  Tucker et. Al, Review of Modern Physics, vol. 57, no. 4, Oct 1985.

DC IV Curve of a SIS Junction under Pumped Signal Injection



Hot-Electron Bolometer (HEB)

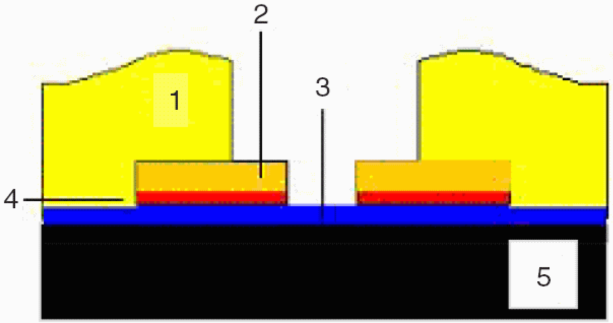
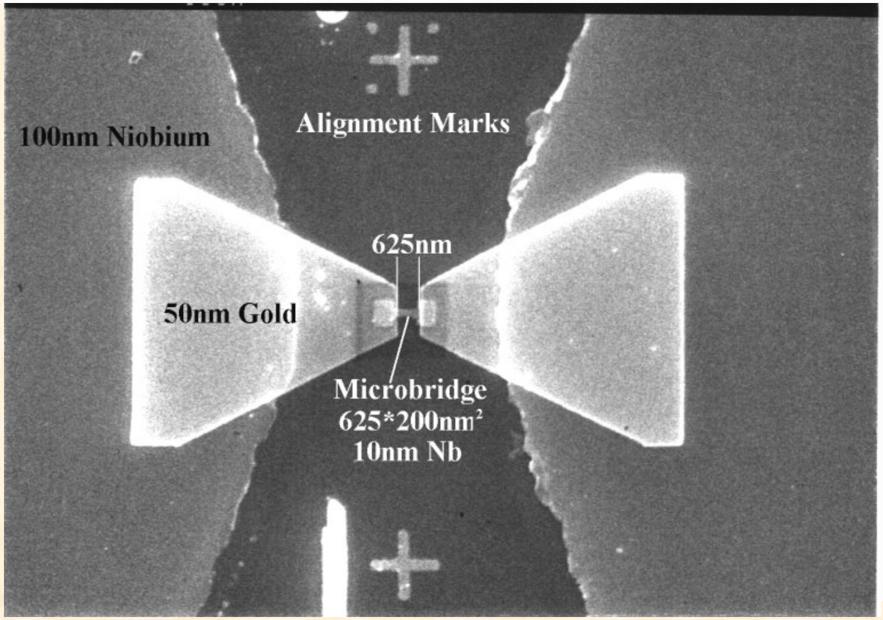
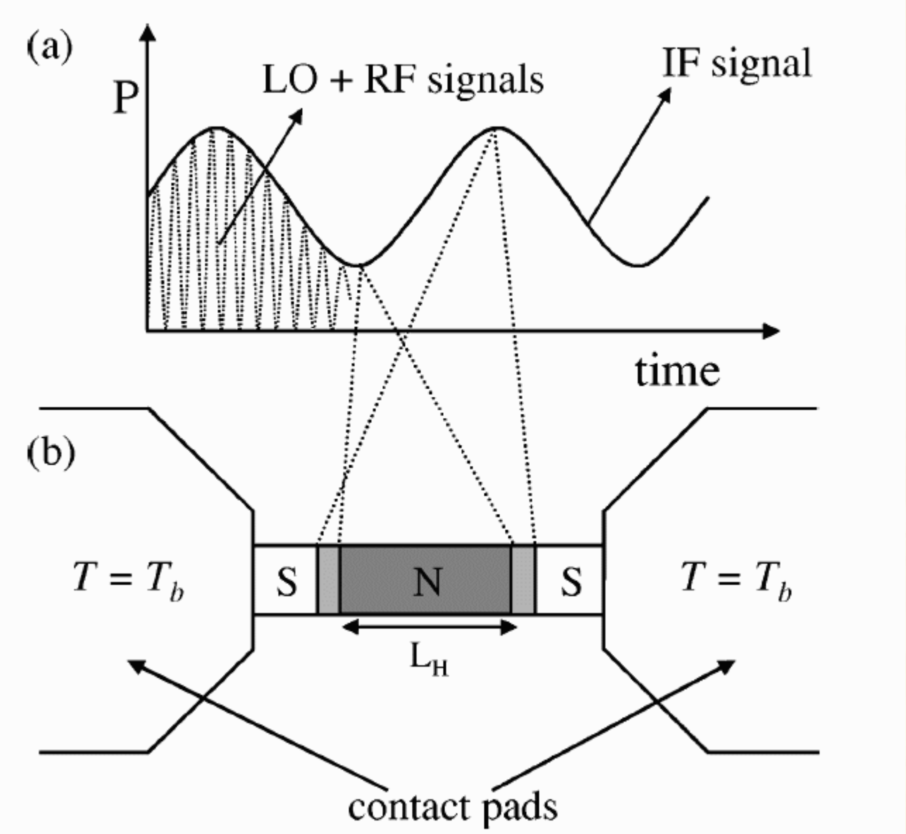


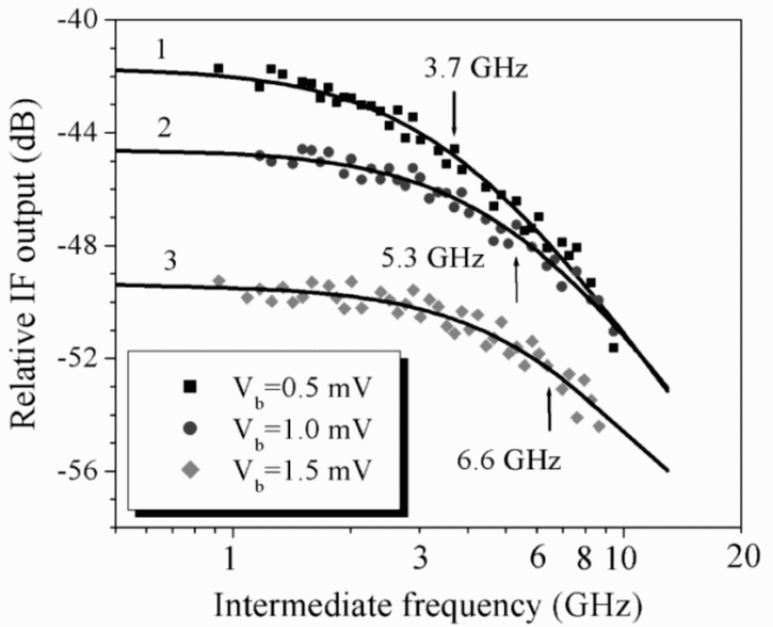
Figure 1. Spiral antenna coupled NbN HEB devices. A SEM picture of the top view of a device and a cross-sectional view of the device. ‘1’ indicates the Au spiral antenna structure which is ∼150 nm thick; ‘2’ the Au layer on the contact pads; ‘3’ the superconducting NbN film, which extends underneath the contact layer/antenna; ‘4’ the intermediate layer between the Au and the NbN film; and ‘5’ the Si substrate.

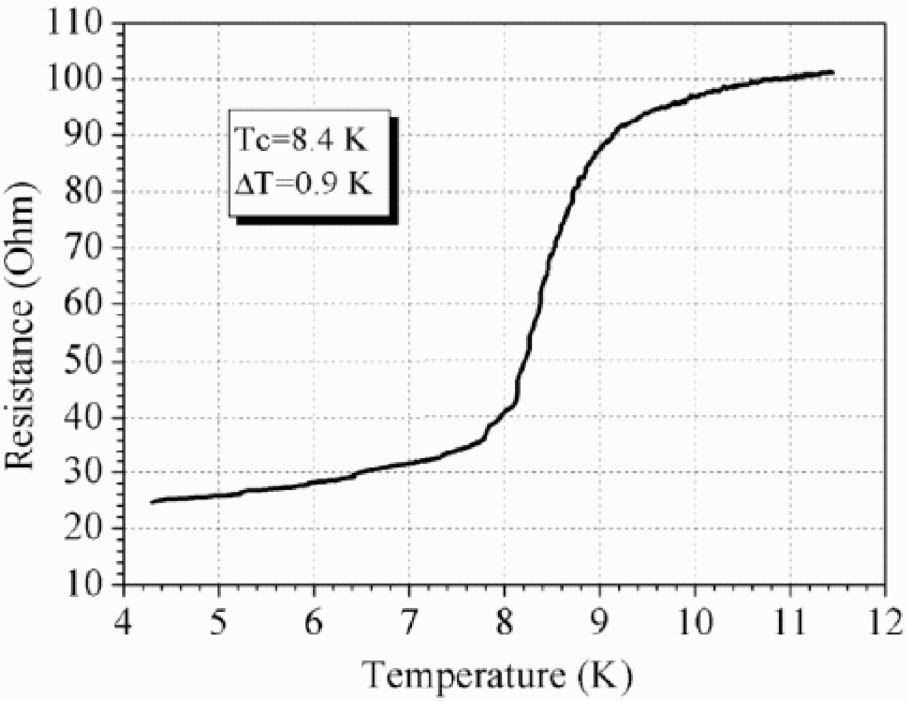


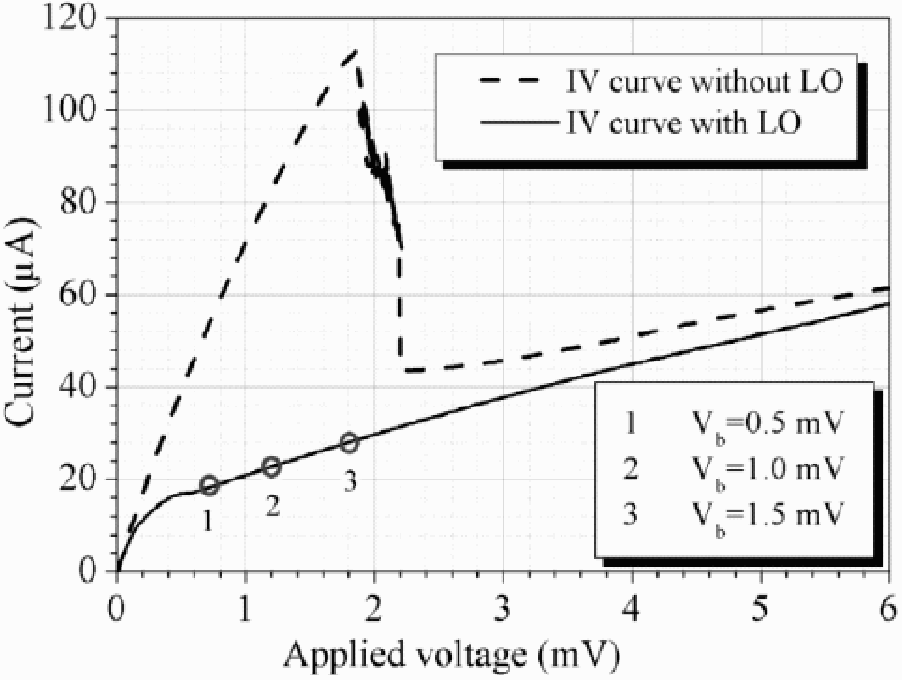


HEB Mixer

- The mixing is based on the physical property change (superconductor – normal metal) due to thermal flow, thus the device is intrinsically bolometric detector → thermal flow is with slow speed, so the IF bandwidth is narrow.





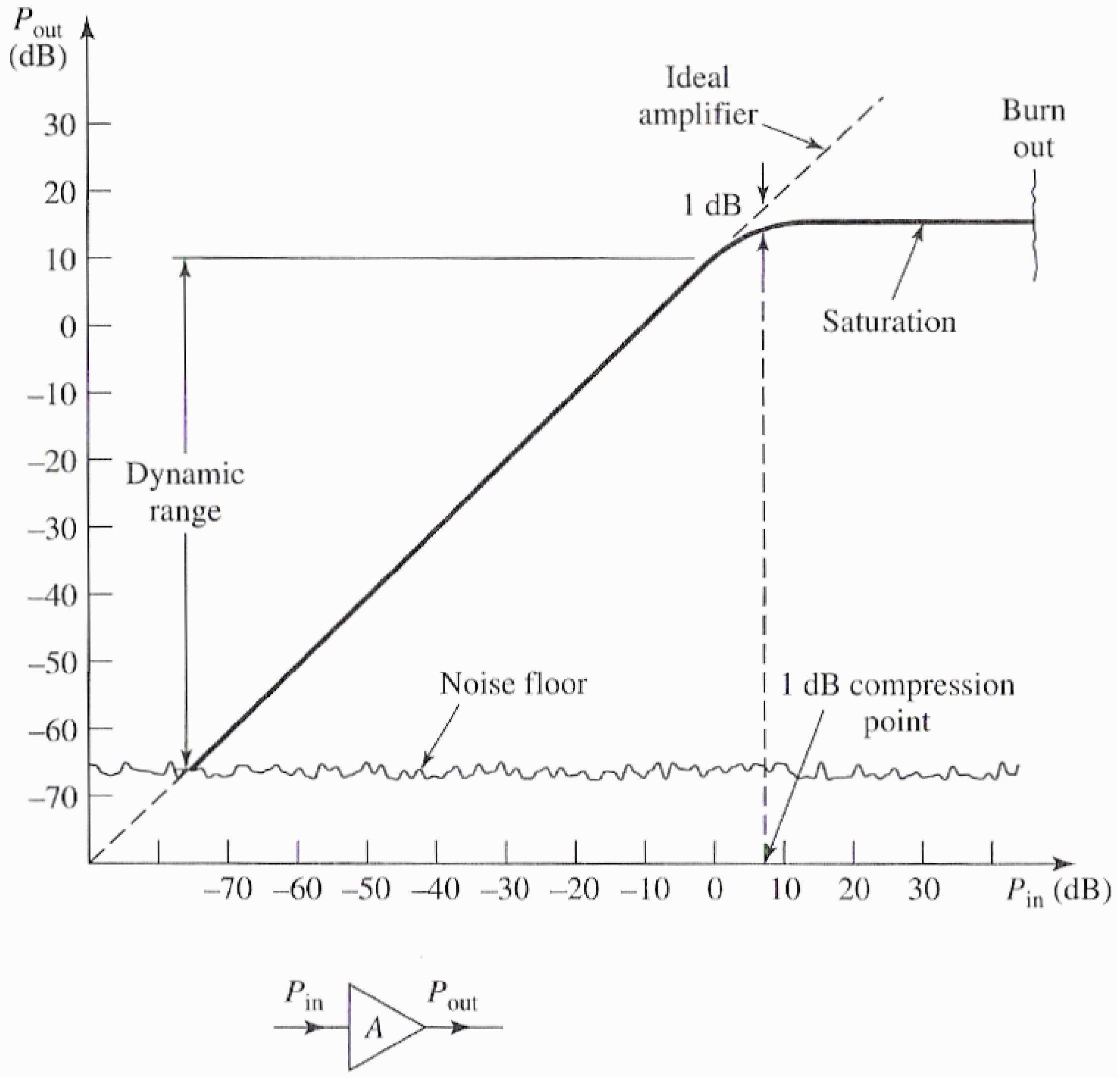


Basic Concept of Amplifier

- The active device made by transistor to provided larger output signal linearly proportional to the input signal power level. The ratio between the output signal and the input signal is defined as gain.

  $G = P_{out}/P_{in}$

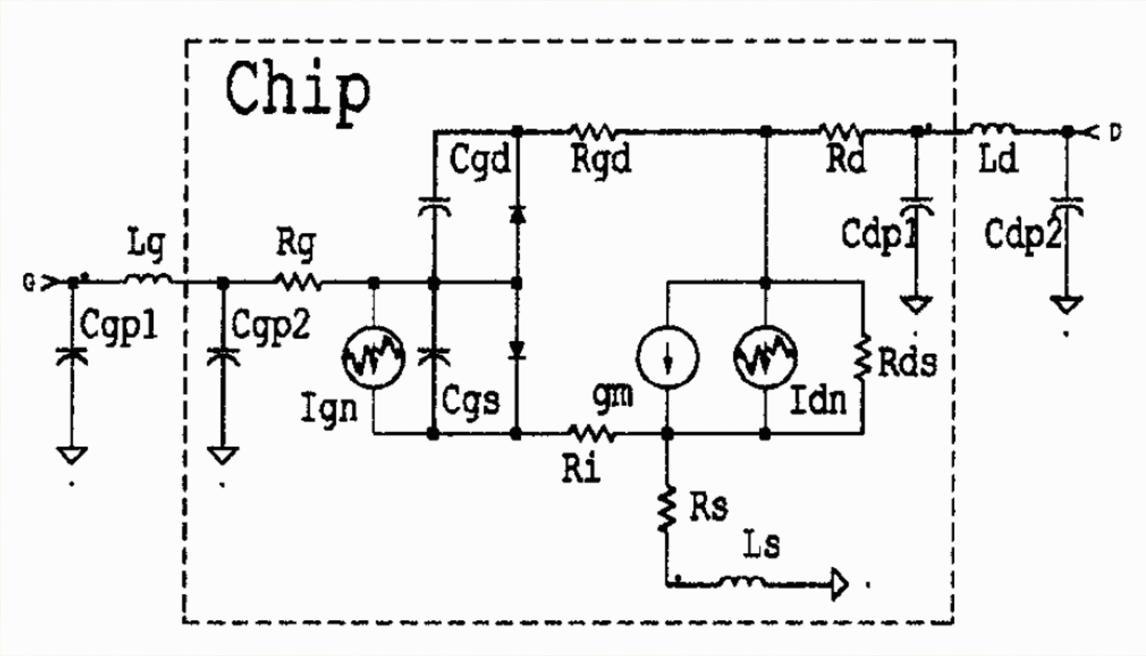
- For realistic amplifier, the range where it provide linear gain is limited by the **noise floor** and the **saturation point**.

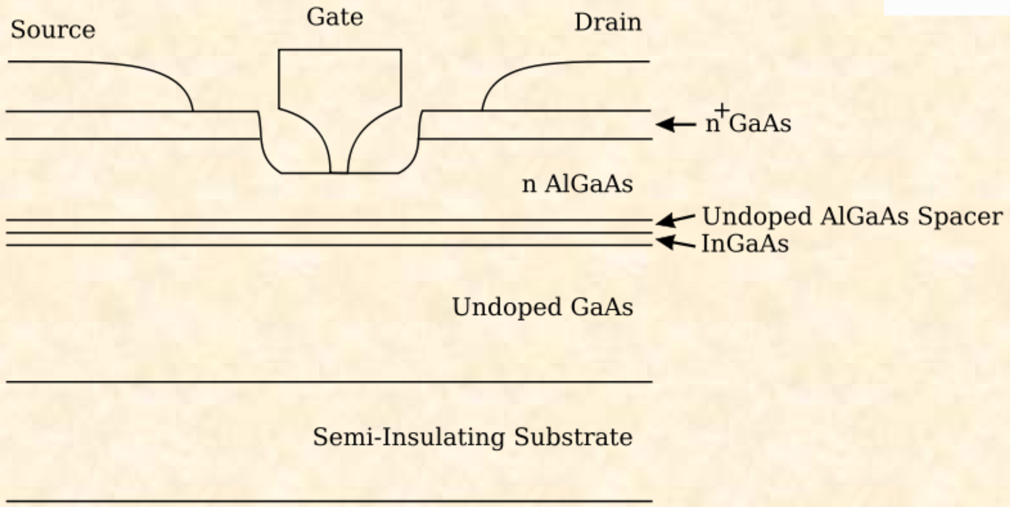


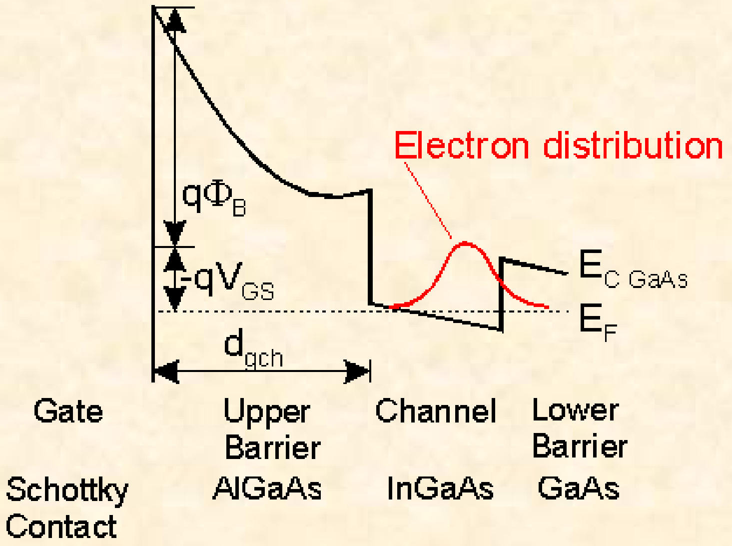
Illustrating the dynamic range of a realistic amplifier.

Cryogenic Low-noise Amplifiers

- The ultra-low-noise signal amplification – use the quantum mechanical electron devices: make use the compound semiconductor to generate 2D electron gas (quantum well), amplified the electronic signal in quantum well







Cascade Microwave Heterodyne Receiver Chains

- Cascade of microwave devices to form a basic receiver system to detect the spectrum of the celestial signal from outer space.
- Typical goal of the instruments for radio astronomy --- to get receiver noise temperature as low as possible!
- For cascade microwave chain system, the noise temperature

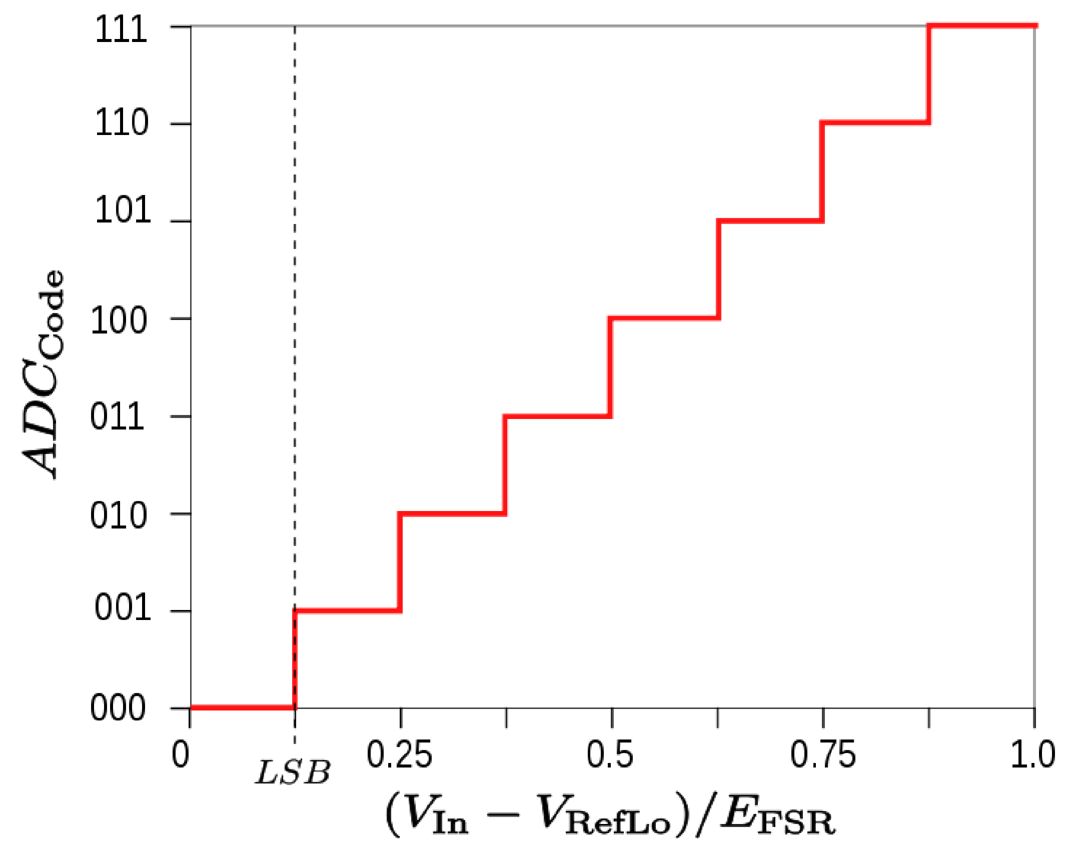
$$T_{\mathrm{rx}} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \cdots + \frac{T_n}{G_1 G_2 \cdots G_{n-1}}$$

Receiver Backend: Signal Processing and Correlator

Backend: Correlator / Signal Processing

- Receiving signal flow after antenna, mixer and amplifiers down-converting to low enough frequency, then the signal is digitized, analog-to-digital converters (ADCs) are required.
- Digitized signal can be directly recorded, and then processing afterword; or the digitized signal can be analyzed by the spectrometers, correlators, or power meters.

Example of 3-bit digitization



Backend: Correlator / Signal Processing

- For interferometer, digitized signals from different telescopes are cross-correlated. For two continuous signal f(t) and g(t), the cross correlation is

$$f(t)\otimes g(t)=\int_{-\infty}^{\infty} f^*(\tau)g(t+\tau)d\tau$$

- For single-dish telescope, the digitized signal pass auto-correlation process to make Fourier transform, then transfer to spectrum by spectrometers.
- Wiener–Khinchin theorem: power spectral density of f(t) (≡ *S(f)*) is Fourier transform of the auto-correlation of f(t) (≡ $R_{ff}(t)$)

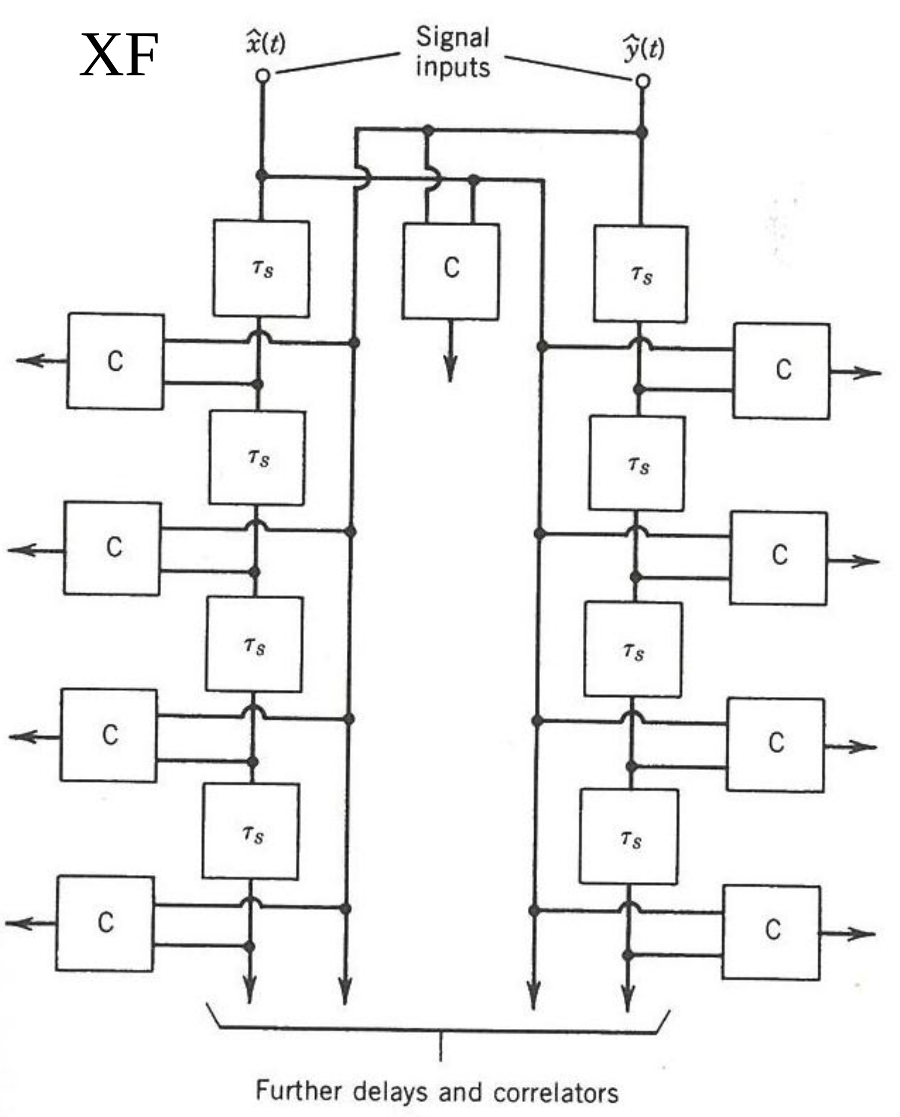
$$S(f)=\int_{-\infty}^{\infty} R_{ff}(t)\exp(-2\pi ift)dt$$

$$R_{ff}(t)=f(t)\otimes f(t)=\int_{-\infty}^{\infty} f(\tau+t)f^*(\tau)d\tau=\int_{-\infty}^{\infty} f(\tau)f^*(\tau-t)d\tau$$

Backend: Correlator / Signal Processing

- For signal processing to get power spectrum, you must do correlation and Fourier transform. In digitized signal, the infinite integral is replaced by finite summation and multiplying over a certain range of discrete lag.

XF



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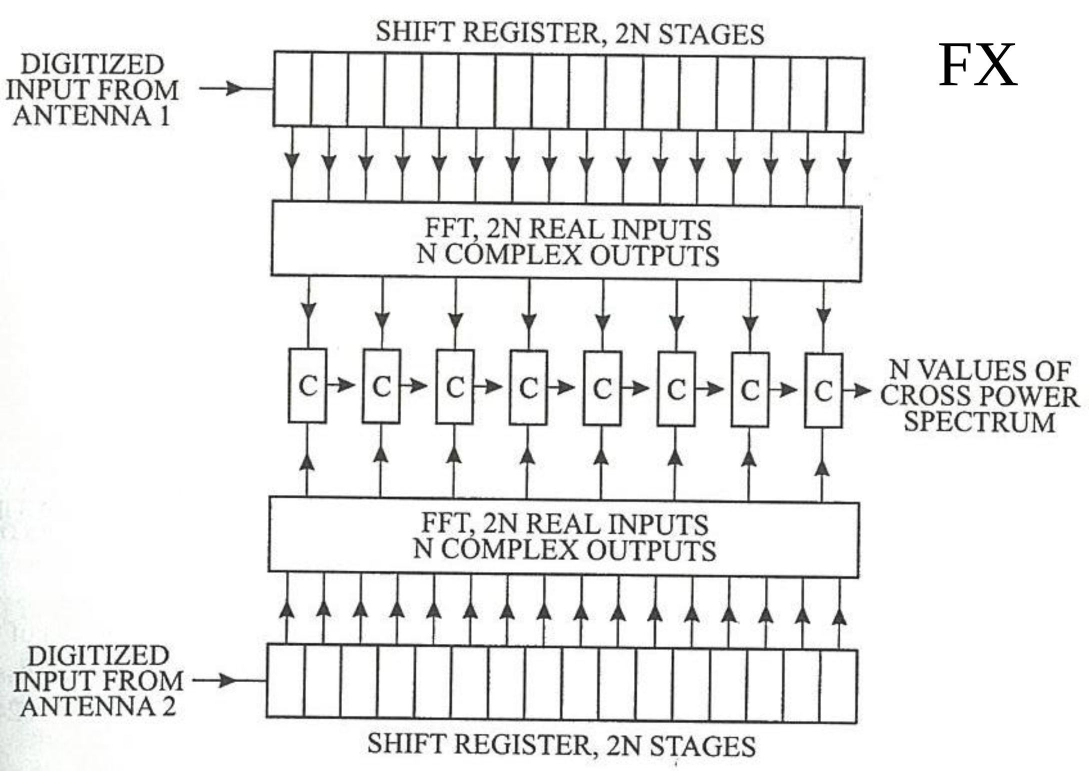

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