"Tracing the Signal": Heterodyne Techniques and IF Systems in Radio Astronomy

GREEN BANK OBSERVATORY

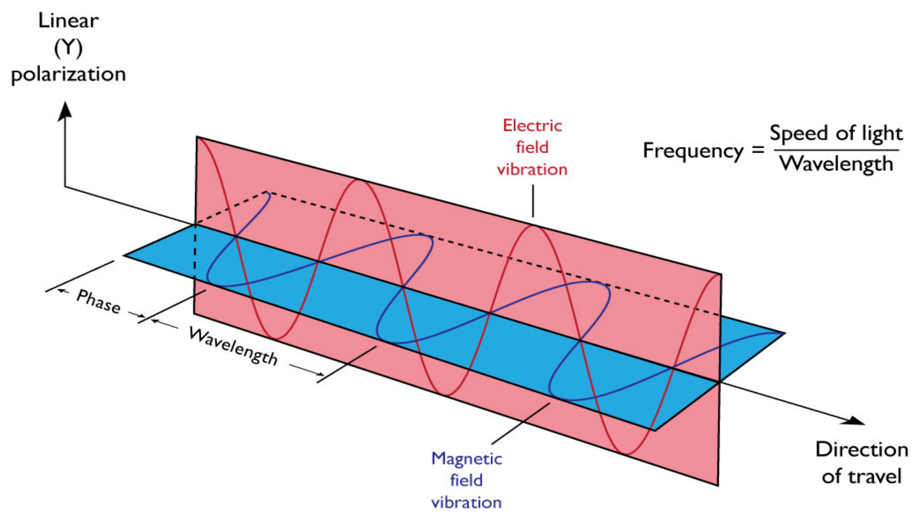
David Frayer

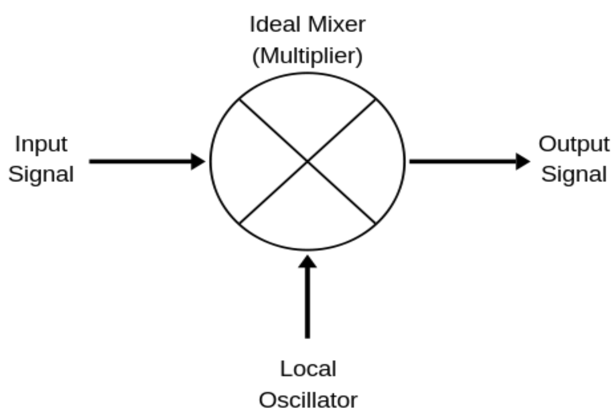
Radio Heterodyne Methods

Heterodyne radio receivers use the wave-like properties of the radio electromagnetic radiation by measuring both the amplitude and phase of the signal ("coherent"). This is different than most other astronomical techniques that treat incoming radiation as photons ("incoherent"), e.g., mm/sub-mm bolometers, IR Si/Ge detectors, optical/NIR CCDs, and X-ray and Gamma-ray detectors.

- Hetero – "other", dyne – "power"
- Combine ("mix") the signal of interest, with a second, precise frequency (the "***local oscillator (LO)***" to produce an output at a new frequency (the "***intermediate frequency (IF)***")

Electromagnetic Waves





Above only shows one polarization

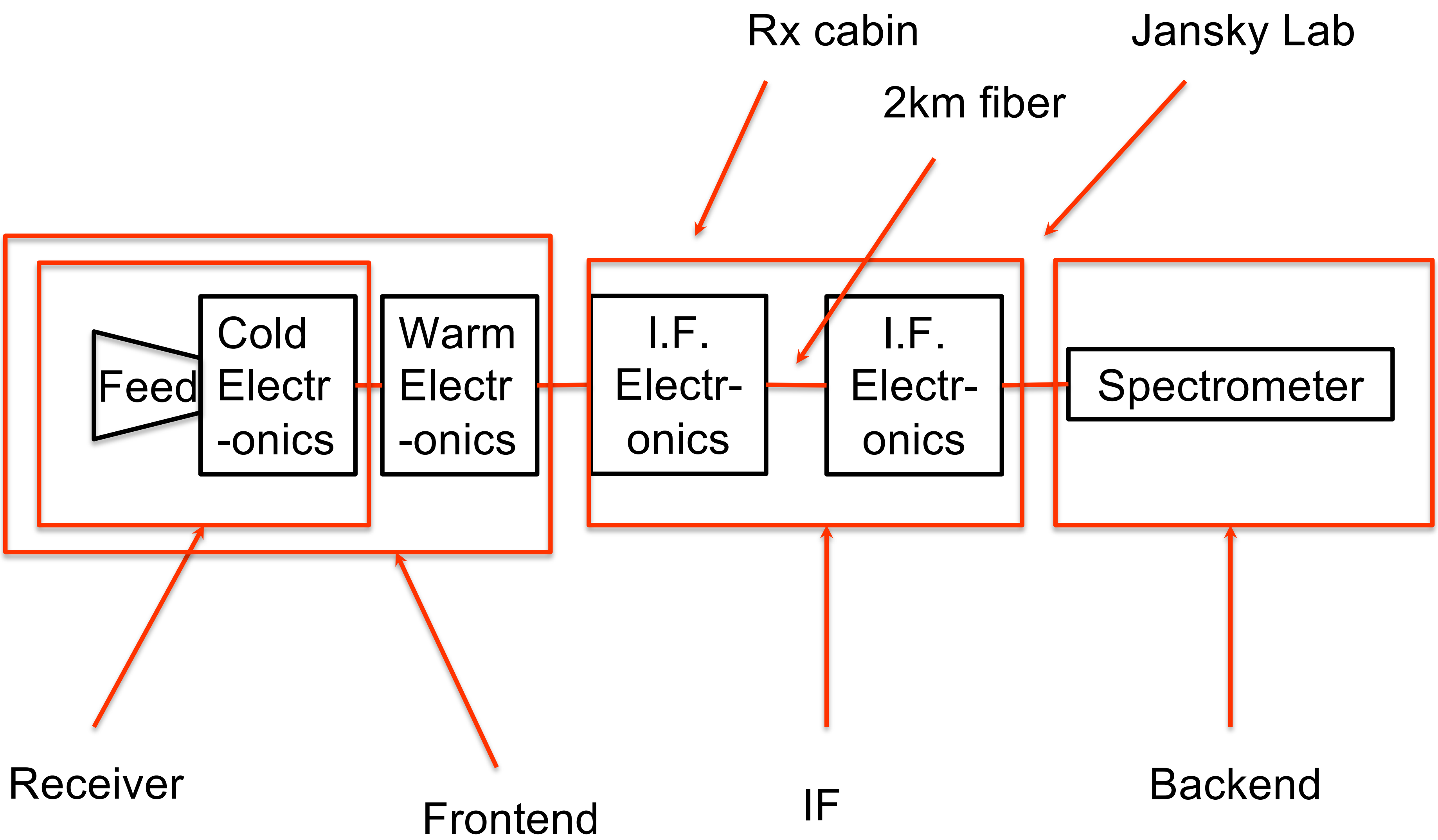
Stages in (Heterodyne) Detection / Analysis

- ***Gather*** the radiation — Antenna
- ***Convert*** the signal from free-space to electrical (feed horn)
- ***Amplify*** the signal (low noise amplifier – LNA)
- ***Mix*** the signal, or convert to a different frequency

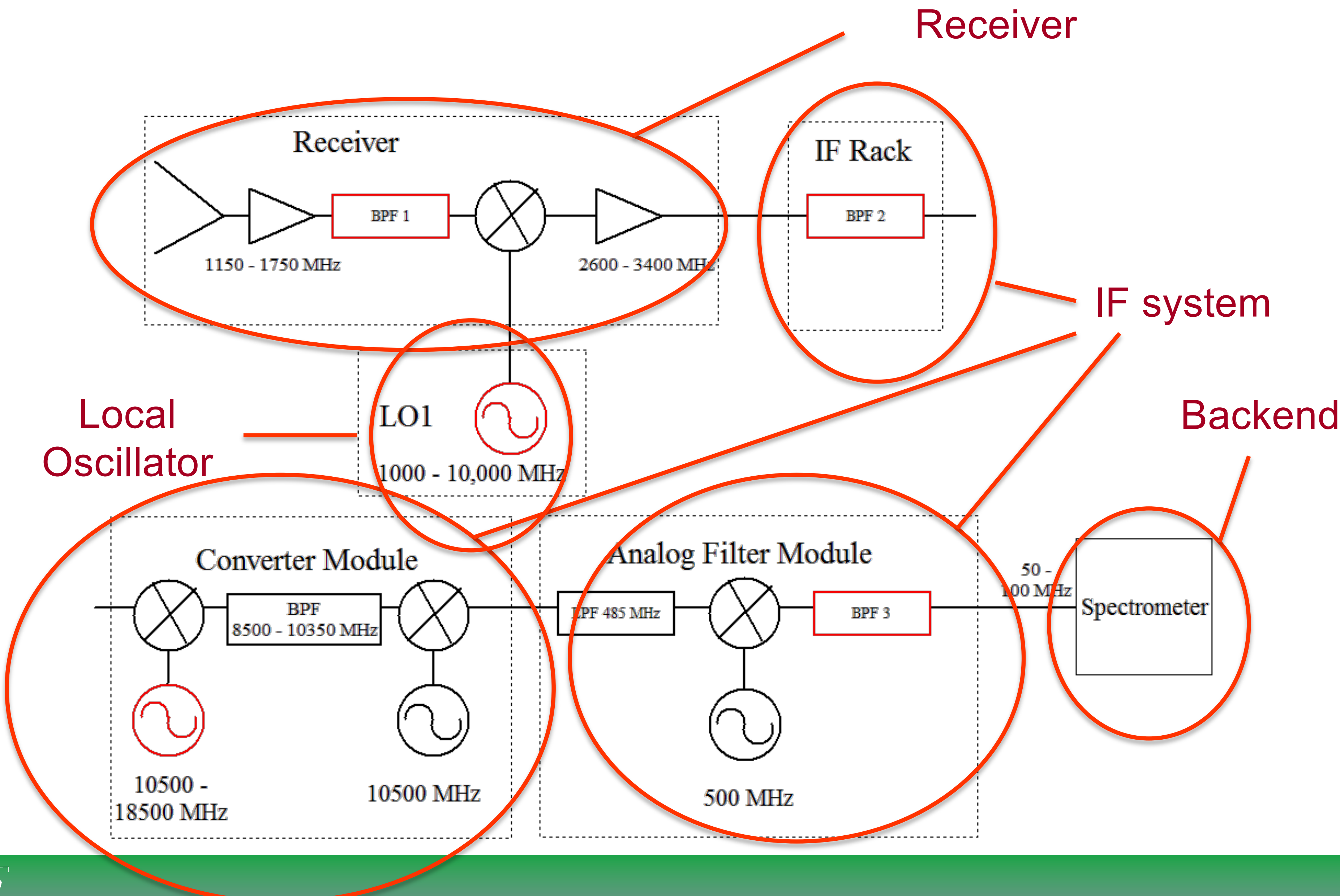
(Convert, Amplify, Mix: Frontend)

- ***Transmit*** the signal to the "backend" — I.F. (Intermediate Frequency) System
- ***Analyze*** the signal in the backend — Backend

Parts of the system



Instrumentation Chain



IF System

- “IF” – intermediate frequency
- The IF system is the part of the system that connects the “Front-end” (Receivers) with the “Back-end” (spectrometer/signal processors)

➔ Allows the connection of receivers covering wide-range of different frequencies to the same backend hardware

Available GBT receivers

Table 1: GBT Receivers

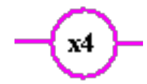
Receiver	Frequency Range
Prime Focus 1	290-920 MHz
Prime Focus 2	910-1230 MHz
L-band	1.15-1.73 GHz
S-band	1.73-2.60 GHz
C-band	3.8-8.0 GHz
X-band	8.0-11.6 GHz
Ku-band	12.0-15.4 GHz
K-band Focal Plane Array (7 pixels)	18.0-26.0 GHz
Ka-band	26.0-39.5 GHz
Q-band	38.2-49.8 GHz
W-band	67-93.3 GHz
MUSTANG 2 bolometer array (shared risk)	80-100 GHz
ARGUS (shared risk)	75-115.3 GHz, Private PI instrument

Available GBT Backends

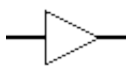
Table 2: GBT Backends and Observing Modes

Backend	Observing Modes
Versatile Green Bank Astronomical Spectrometer (VEGAS)	Continuum, pulsar, spectral line
Digital Continuum Receiver (DCR)	Continuum
Green Bank Ultimate Pulsar Processing Instrument (GUPPI)	Pulsar
Mark V Very Long Baseline Array Disk Recorder	Very Long Baseline Interferometry
Caltech Continuum Backend (CCB) (Ka-band)	Continuum
Zpectrometer (Ka-band)	Private PI instrument
Radar	Private PI instrument

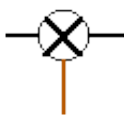
Typical Components in System Block Diagrams:



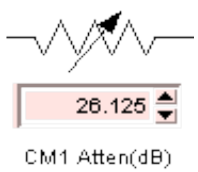
Multipliers



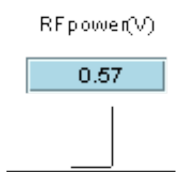
Amplifiers



Mixers



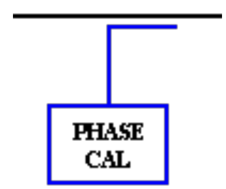
Attenuators



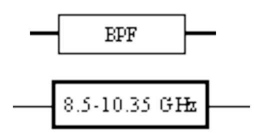
Power Detectors

Synthesizers

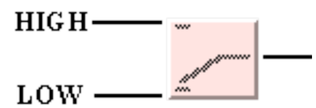
Splitters



Couplers

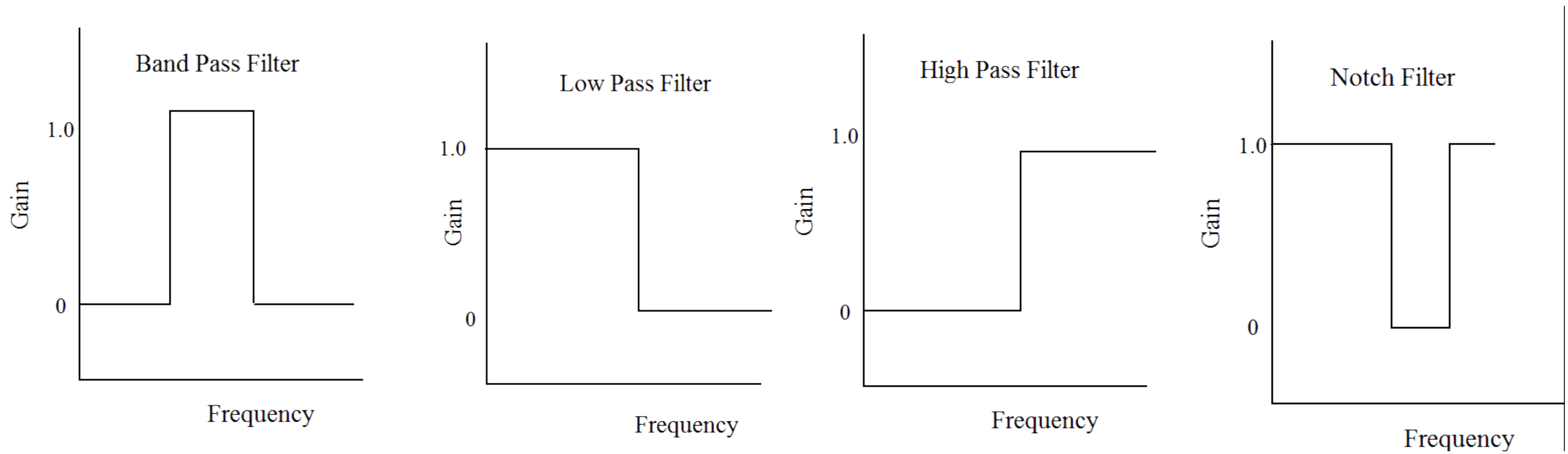


Filters



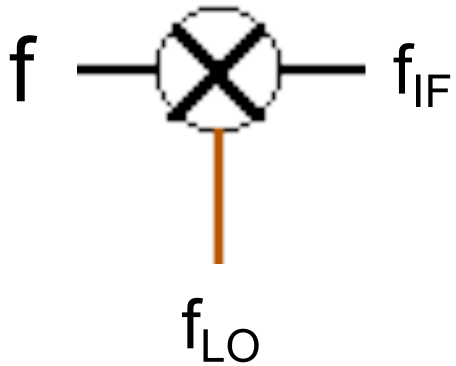
Switches

Types of Filters

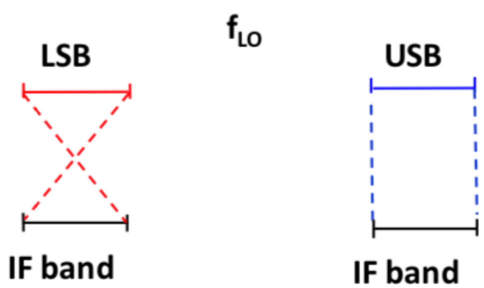


Edges are smoother than illustrated

Types of Mixers



$$f_{IF} = n*f_{LO} + m*f$$

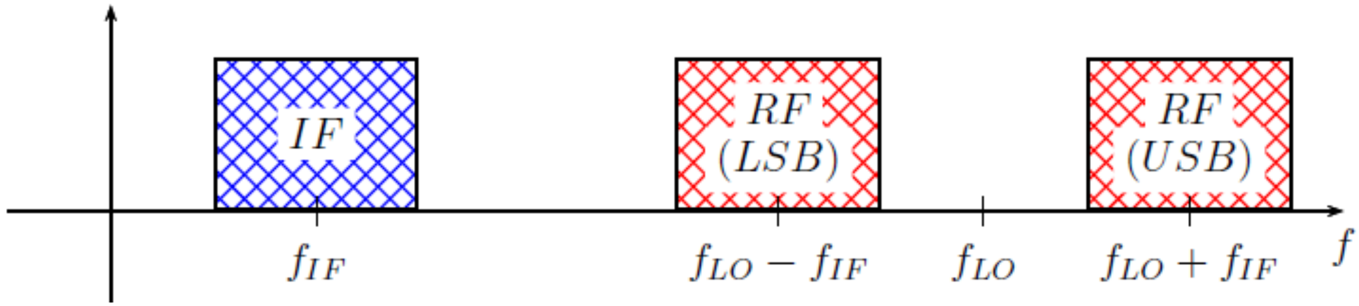


- n and m are positive or negative integers, usually 1 or -1

- Up Conversion : $f_{IF} > f$
- Down Conversion : $f_{IF} < f$

- Lower Side Band : $f_{LO} > f$
- Sense of frequency flips
- Upper Side Band : $f_{LO} < f$

Example "Down Conversion" Mixing

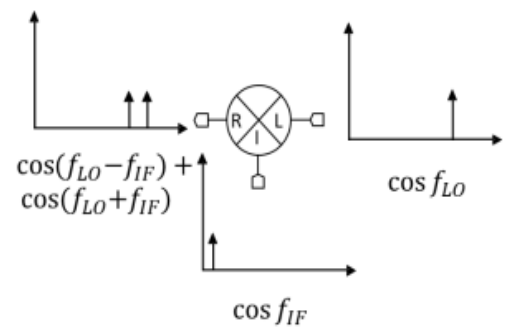


USB / LSB

$$\cos f_{LO} \cos f_{IF} = \frac{1}{2}\left(\cos(f_{LO} + f_{IF}) + \cos(f_{LO} - f_{IF})\right)$$

USB= LO + IF
LSB = LO - IF

$f = frequency$
$2\pi f = \omega$
$dropping \;\; 2\pi t$

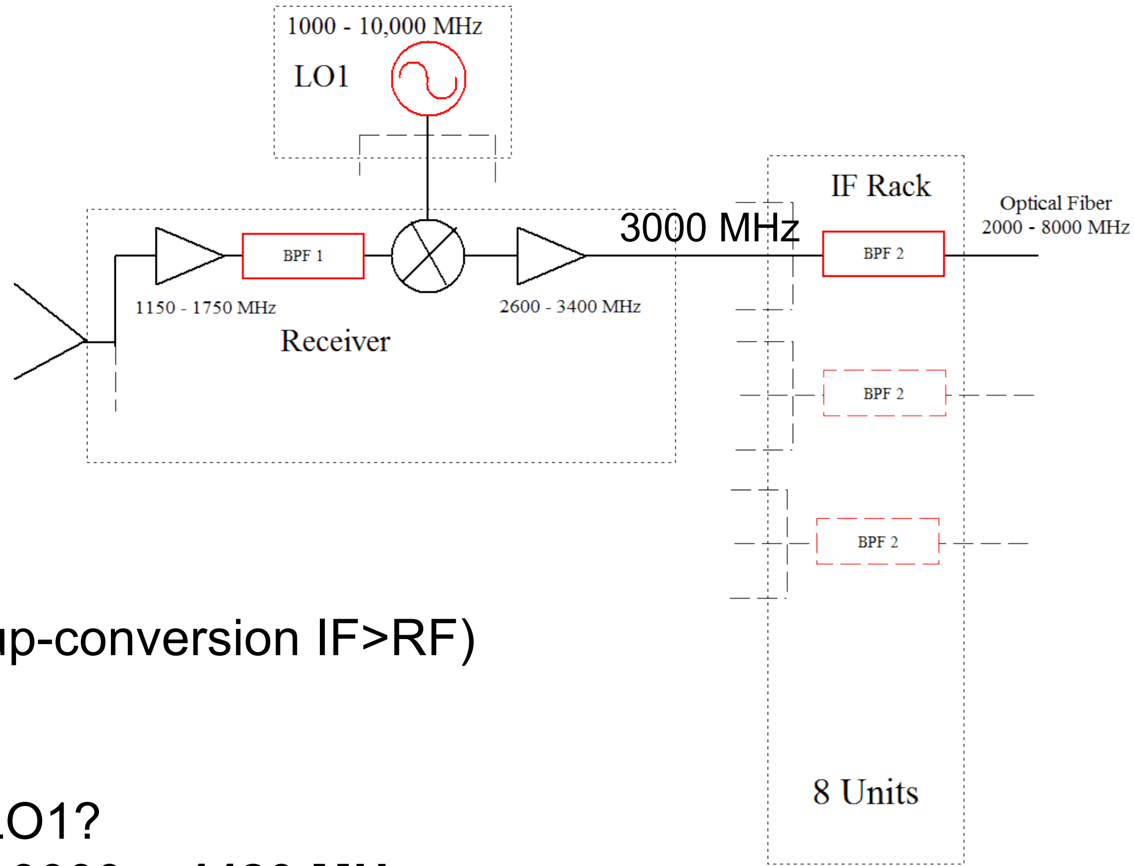


$$v(t) = A_o \cos(\omega t + \phi)$$

$$\cos(\omega_a t)\cos(\omega_b t) = \frac{1}{2}\cos(\omega_a - \omega_b)t + \frac{1}{2}\cos(\omega_a + \omega_b)t$$

IF signal includes both lower (LSB) and upper (USB) side-bands. For typical single-side band (SSB) systems, the image side band is rejected, while double-side band (DSB) systems keeps both side-bands.

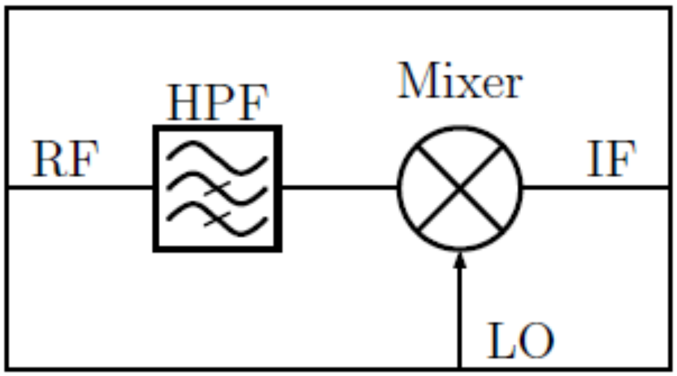
GBT L-band Example



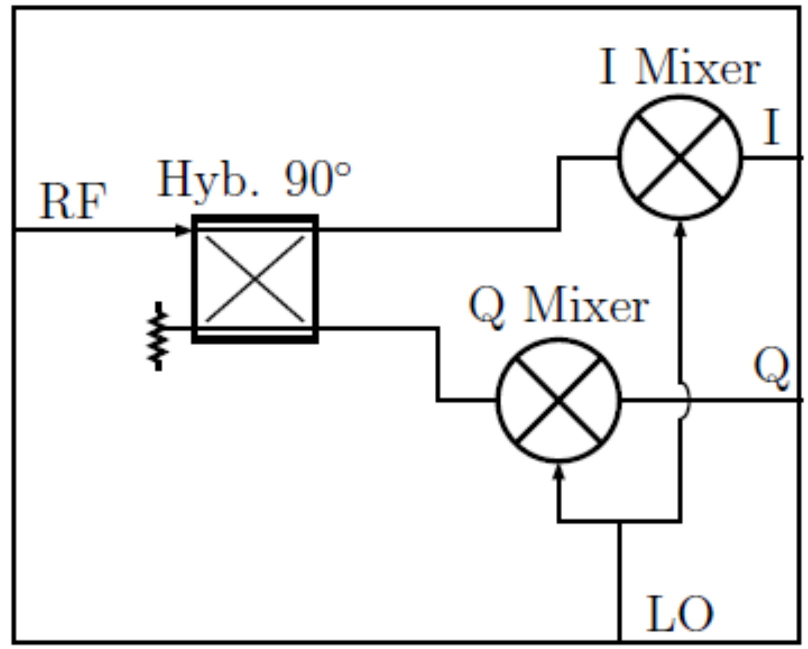
RF=1420 MHz
IF centered on 3000 MHz (up-conversion IF>RF)
Mixer is LSB (LO>RF)

Quiz: What is the value of LO1?
LSB =LO - IF ➔ LO = 1420+3000 = **4420 MHz**
USB mix does not work: RF(USB) =1420 MHz= LO + IF ➔ LO=-1580 MHz not possible
For LSB mix, RF(LSB)=1420 MHz, IF=3000 MHz, LO=4420 MHz;
RF(USB)=7420 MHz which is out of the Rx band and is filtered out.

Mixer Examples/Side-band Rejection



(a) A single sideband mixer.

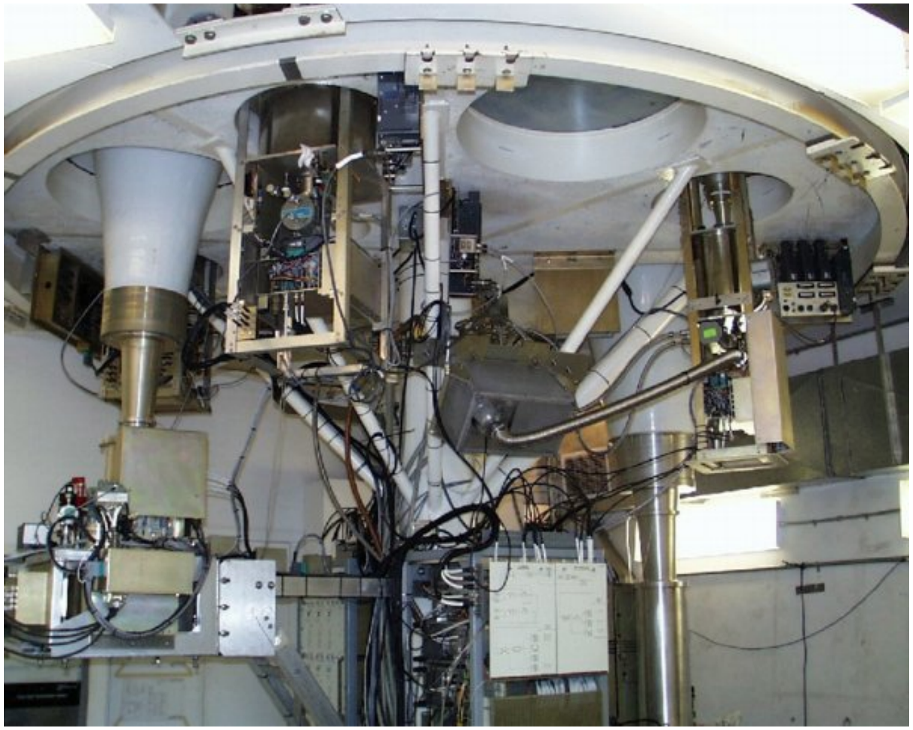


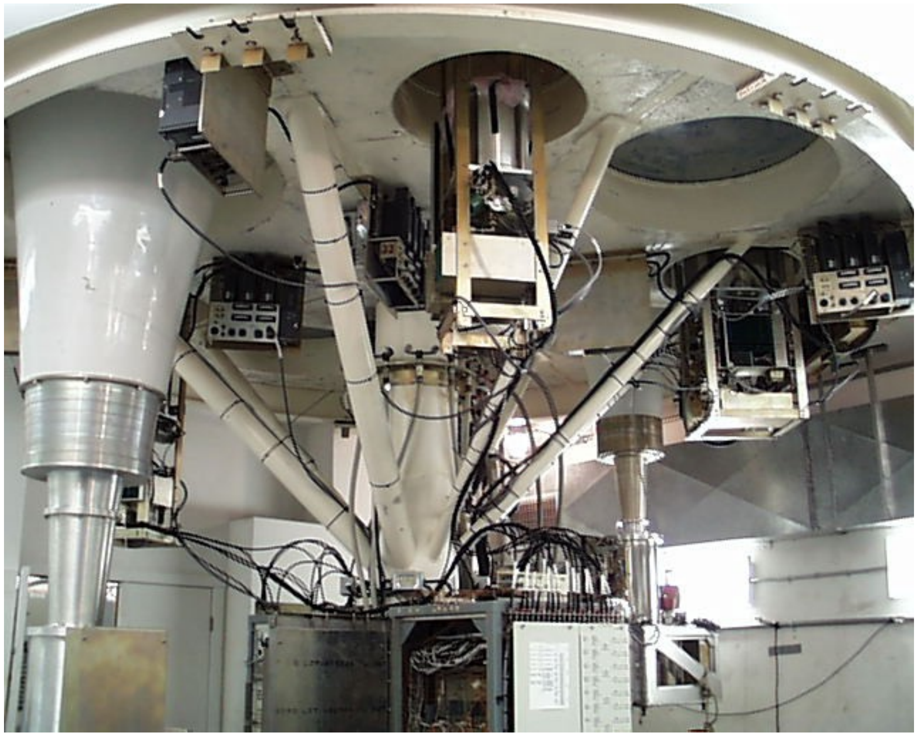
(b) A double sideband I/Q mixer.

(a) Simple mixer where LSB is filtered with high-pass filter

(b) I=in phase, Q=quadrature phase I/Q mixer can be used for sideband rejection. Only Argus on the GBT uses this method.

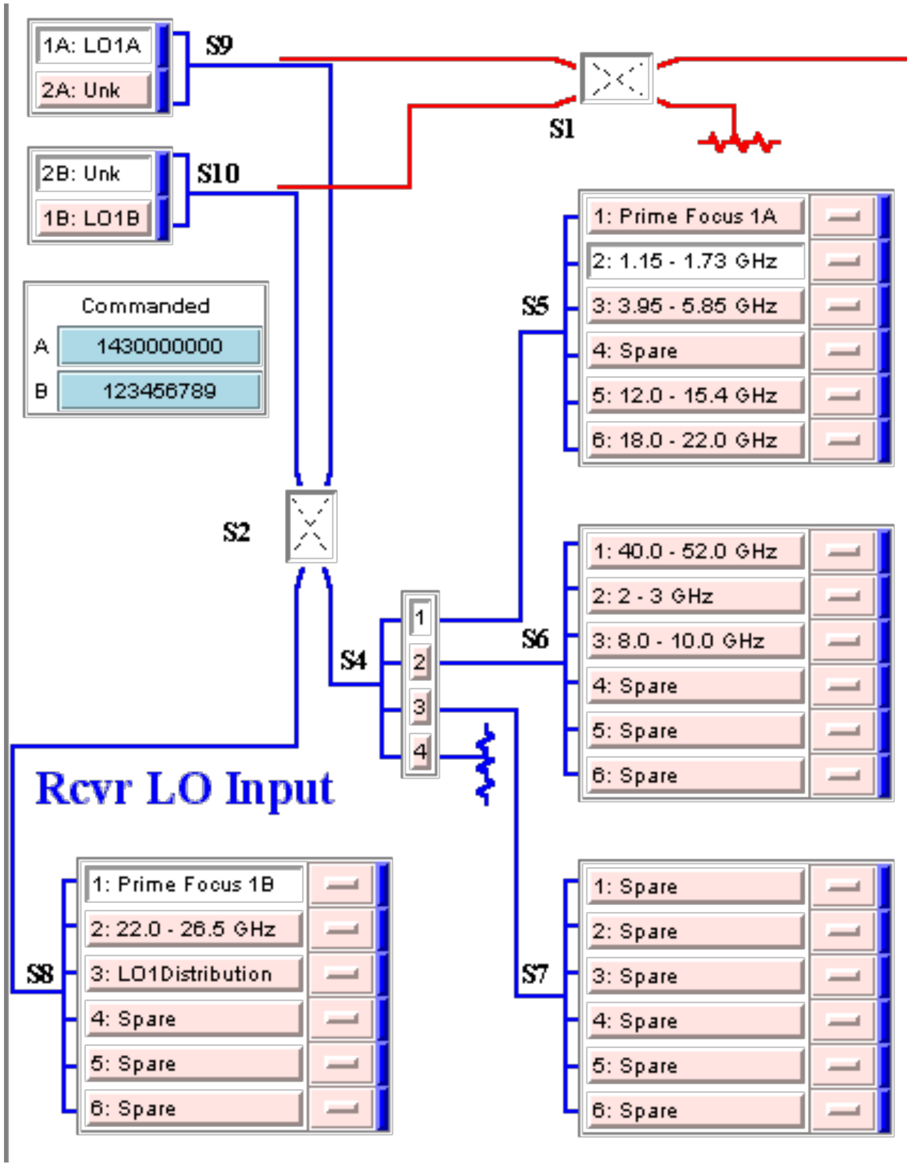
Receiver Room (on telescope)





In addition to the installed receivers, room includes LO, IFRack, MM-converters, and conversion to optical-fibers.

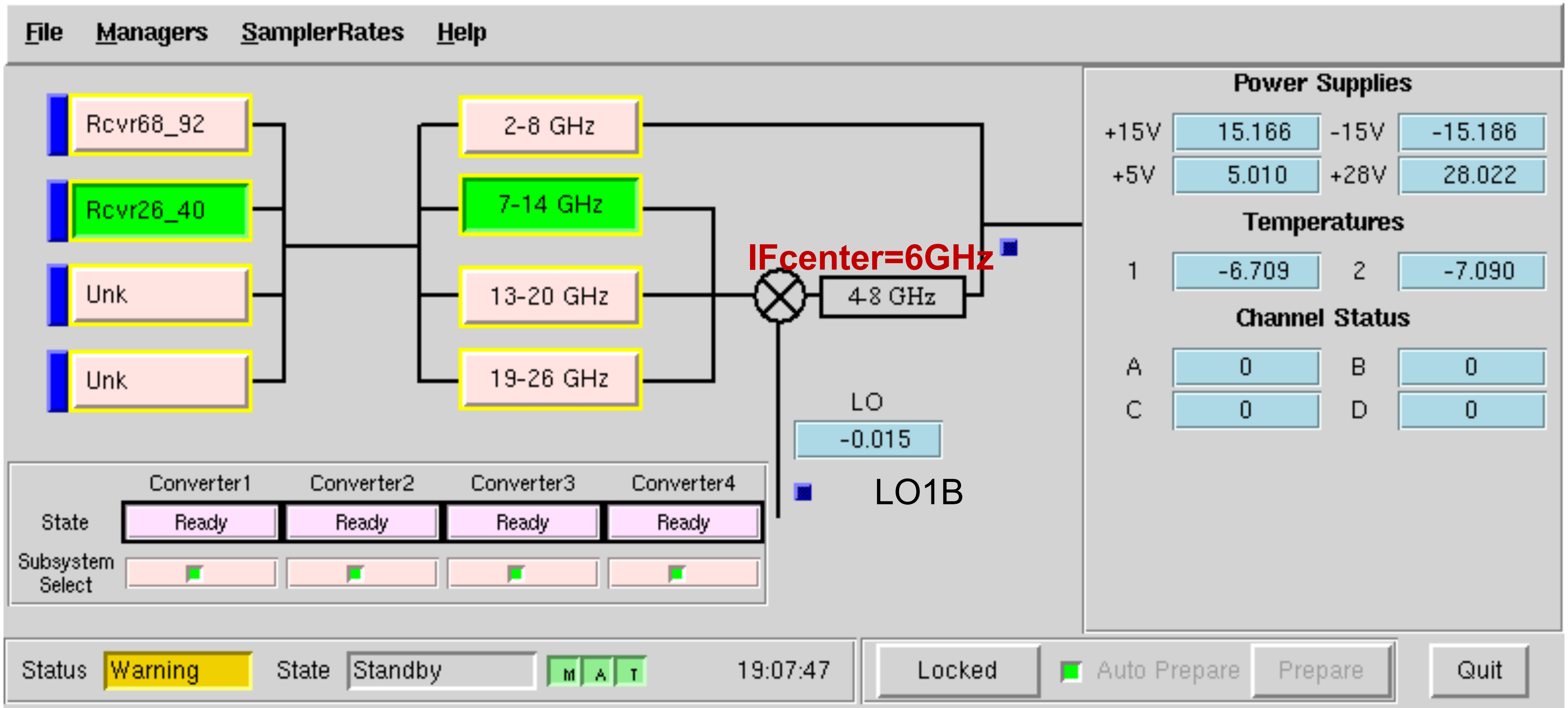
GBT Local Oscillator and Switching Matrix



LO also used for:

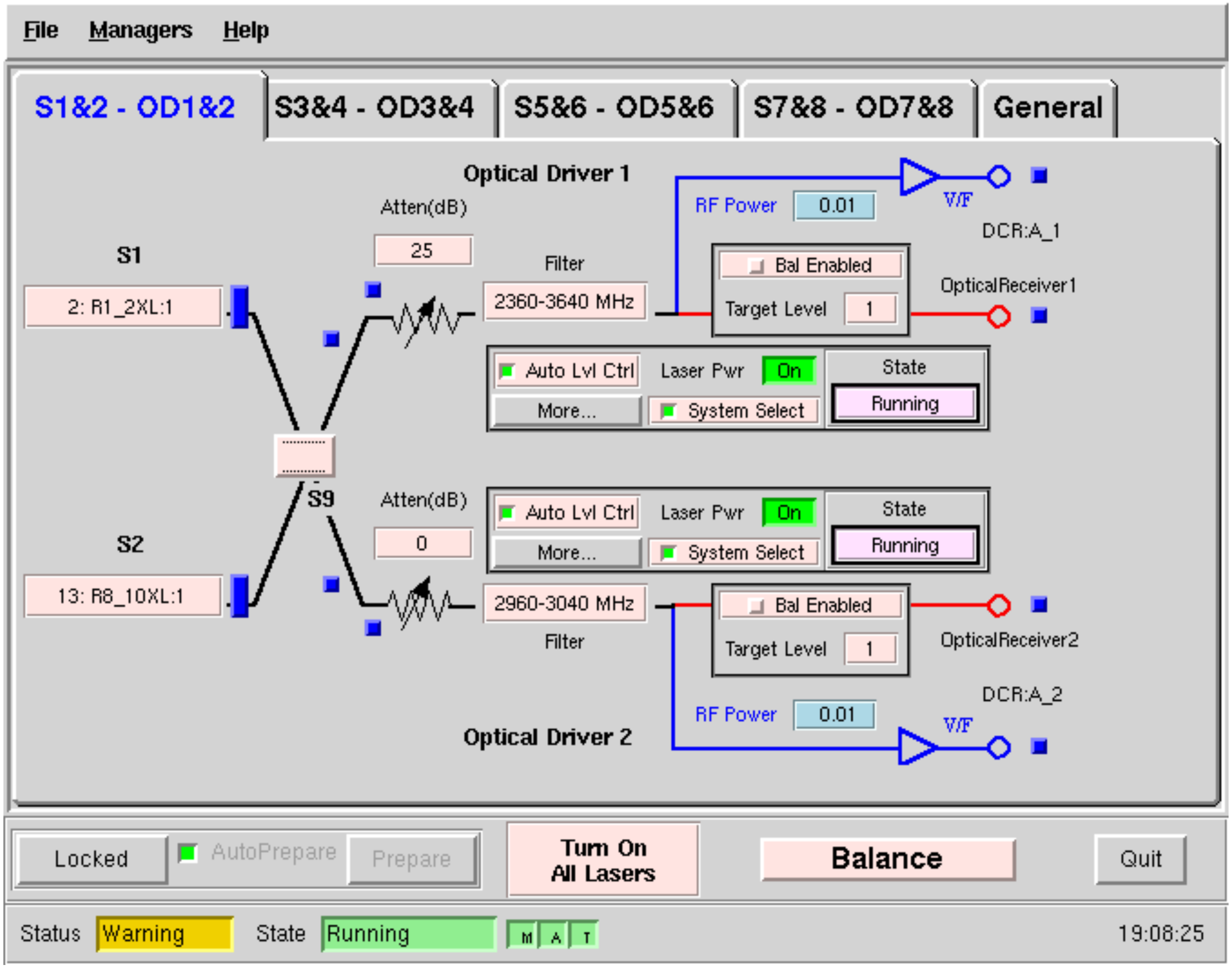
- Correcting for source velocity
  - wrt a chosen frame of rest
    - Heliocentric
    - LSR
    - Galactocentric
    - Topocentric
  - And chosen approximation of Doppler shift
    - Relativistic
    - Radio
    - Optical
- Frequency Switching (optional tactic for removal of instrumental bandpass)
- Doppler Tracking for Earth rotation and revolution

MM Converter (used by 4mm and Ka-band)



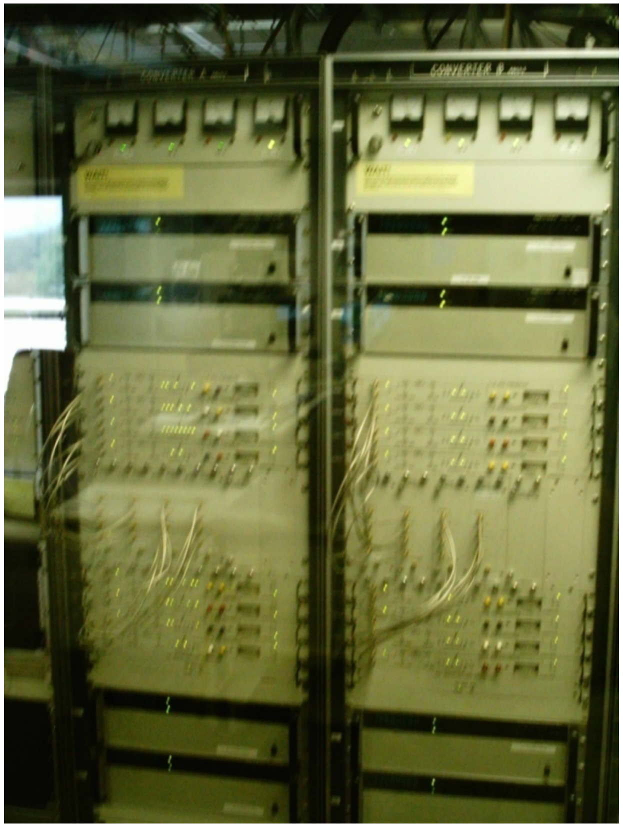
Example: 4mm/Rcvr68_92:
Observing 89.0 GHz = RF in USB.
LO1A=66GHz (4x16.5GHz), IF1=23 GHz input to Mmcoverter filter FL4 subband (19-26GHz). LO1B=RF-66GHz -6GHz= 17GHz to produce output IF centered on 6 GHz that goes to the IFrack.

IF-Rack (8 channels)

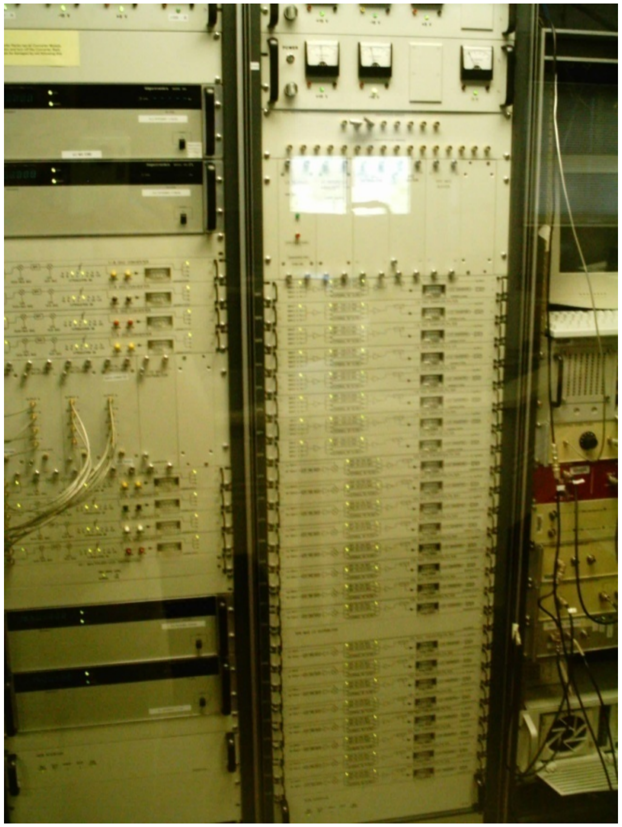


Equipment Room (Jy-Lab)

Converter Racks

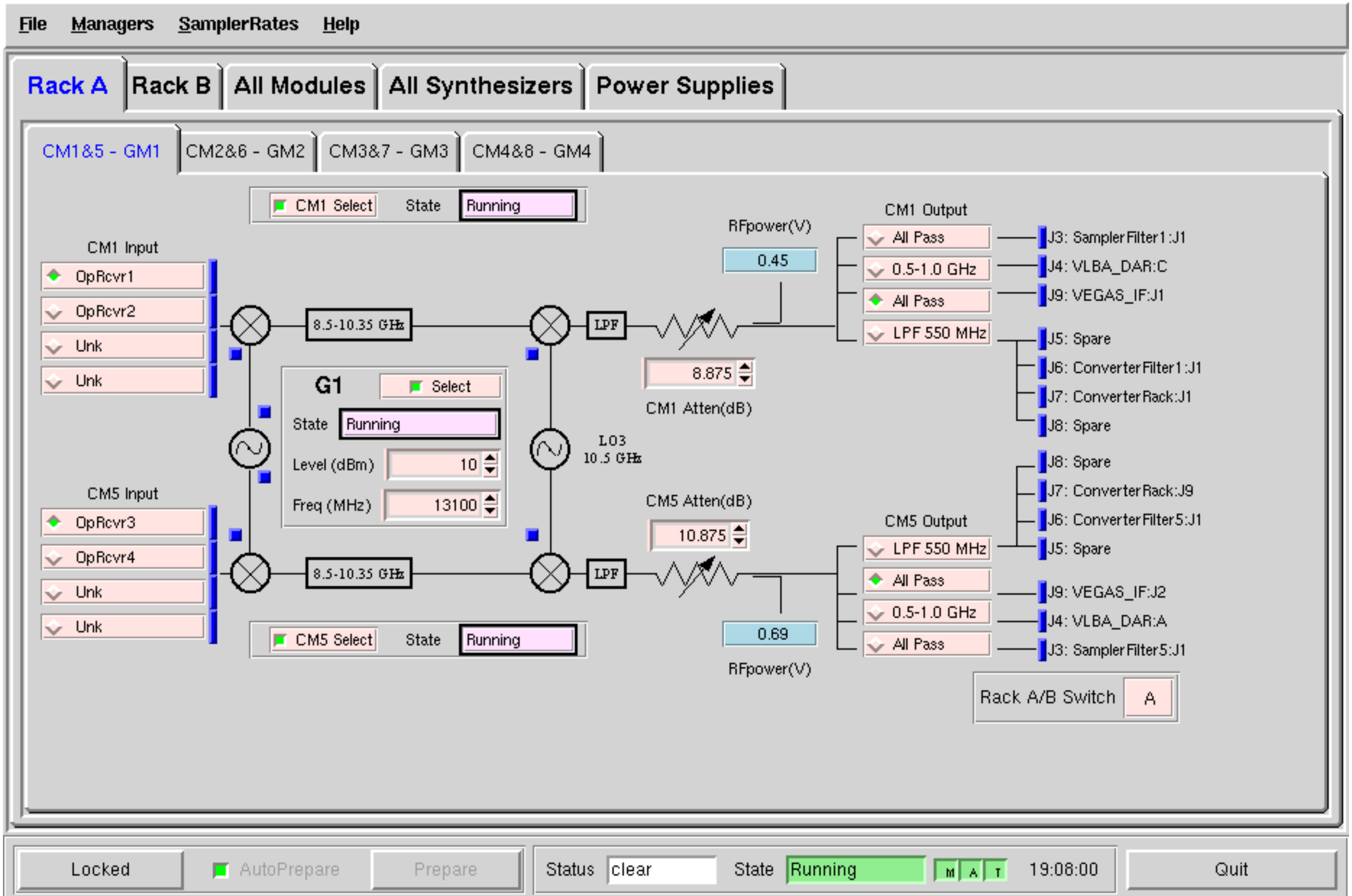


Analog
Filter rack

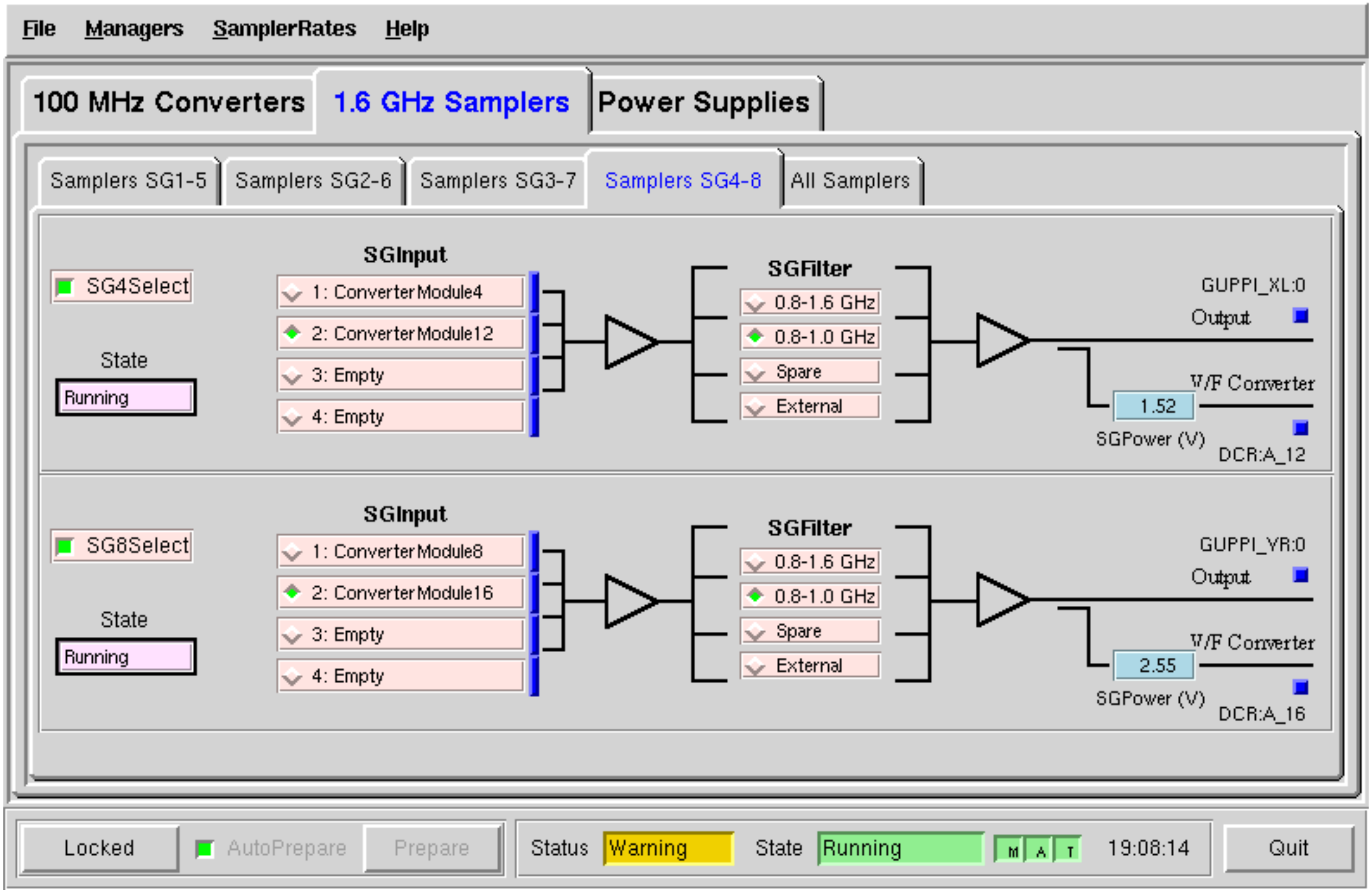


VEGAS

Converter Rack (16 channels)



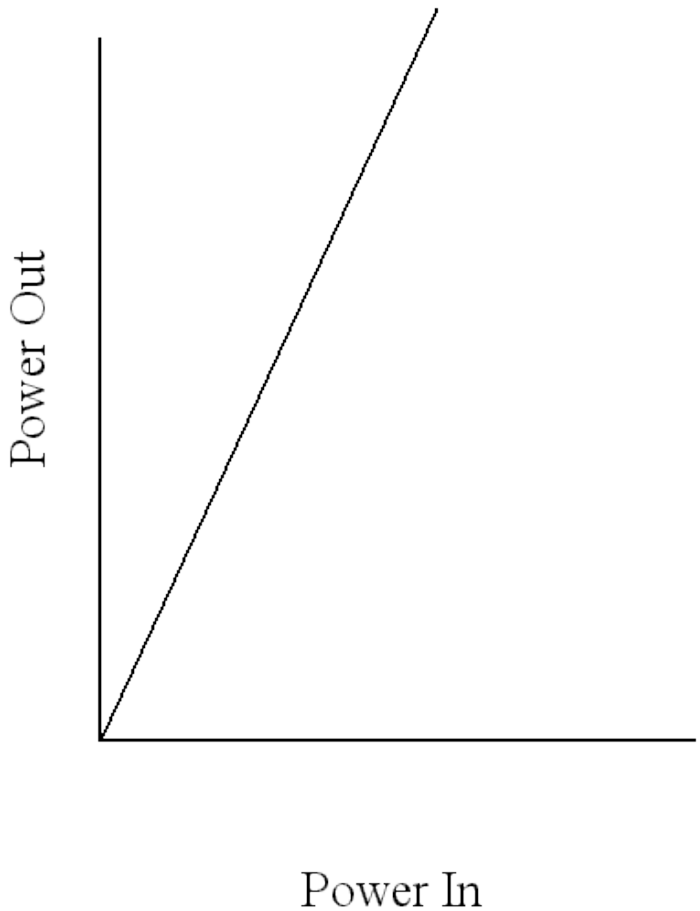
Analog Filter Rack (used with GUPPI and old Spectrometer)

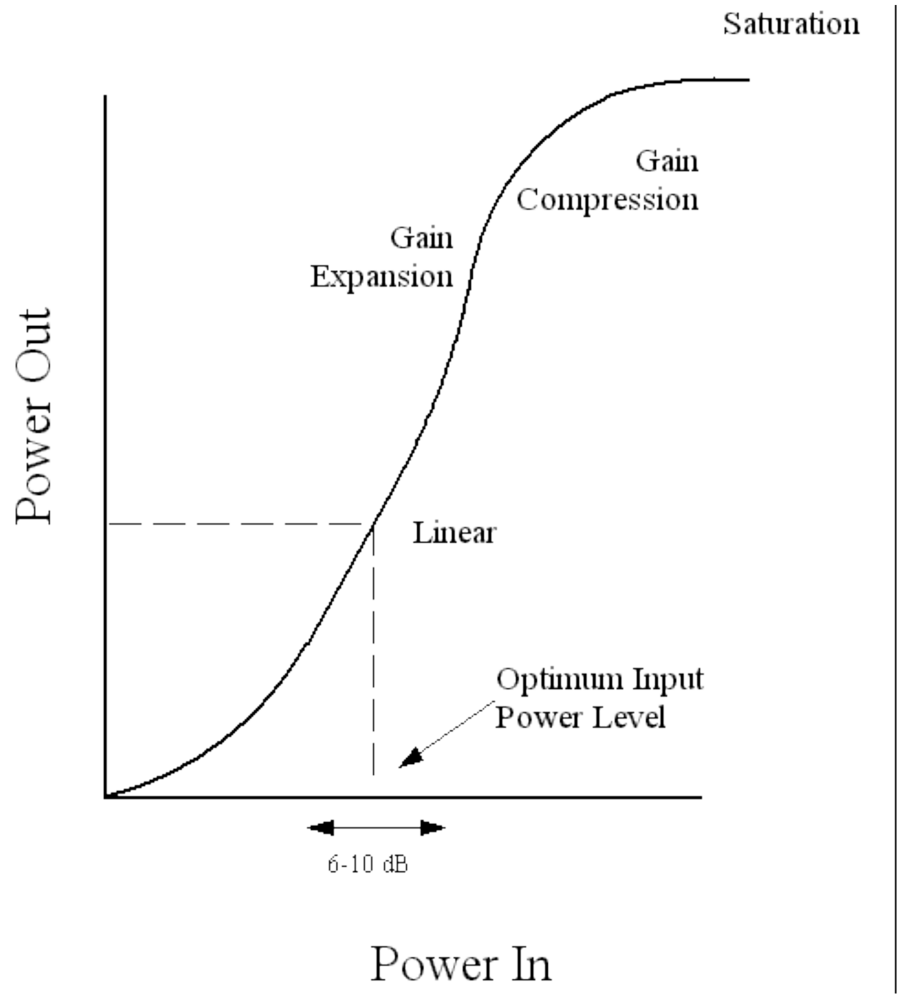


Power Balancing/Leveling

Key point: Need all parts of the IF system to be linear

e.g., when observing on the GBT confirm levels after the “Balance” at the IFrack after receiver, the Converter Modules (before VEGAS), and the VEGAS levels.





Tracing the Signal:
Example Argus on the GBT (page 1)

Goal: Observe HCN/HCO+ at 89 GHz in LSB.

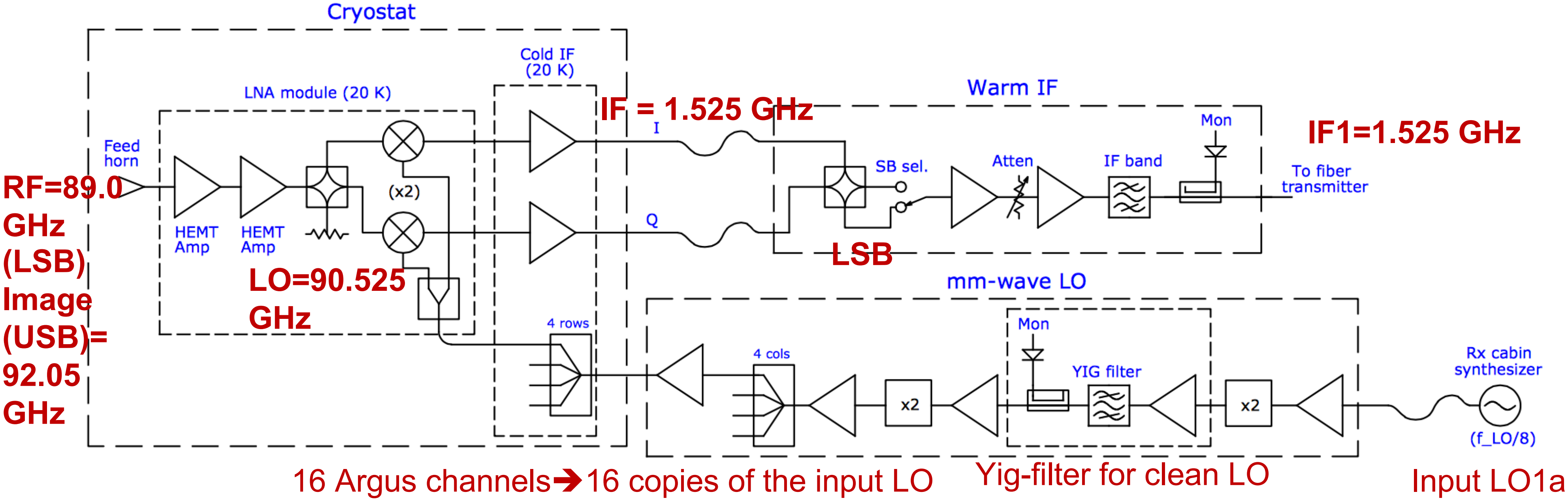


Figure 1: Schematic block diagram of Argus' signal path for a single receiver.

Argus has 16 beams/channels. 8 channels go to IF rack after the instrument and are then transmitted to the equipment room via optical fibers and 8 channels go directly to fibers from the instrument.

Tracing the Signal, Argus (page 2)

After transmission from the GBT to the Jy-lab equipment room, signal converted from optical-fiber back to co-ax

Output to VEGAS; usable bandwidth 0.15-1.4 GHz

IF1=1.525 GHz

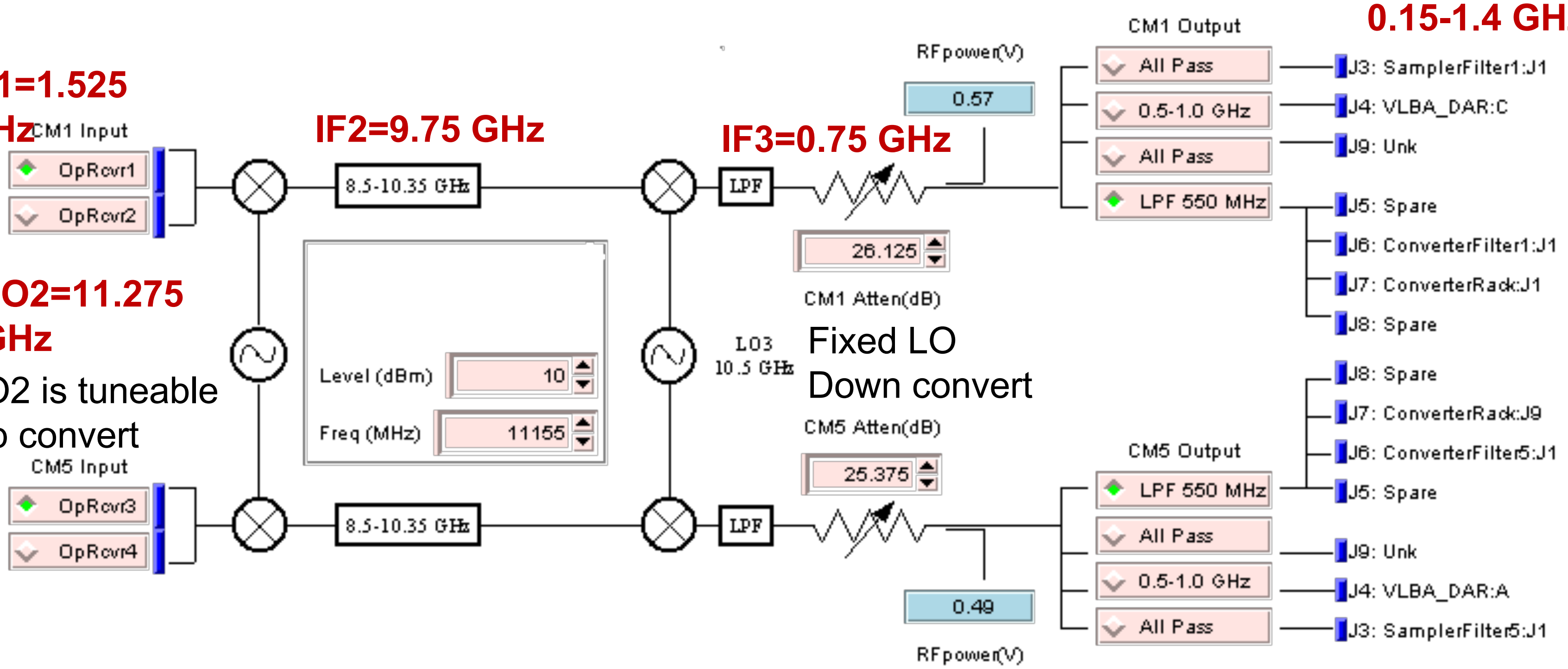
IF2=9.75 GHz

IF3=0.75 GHz

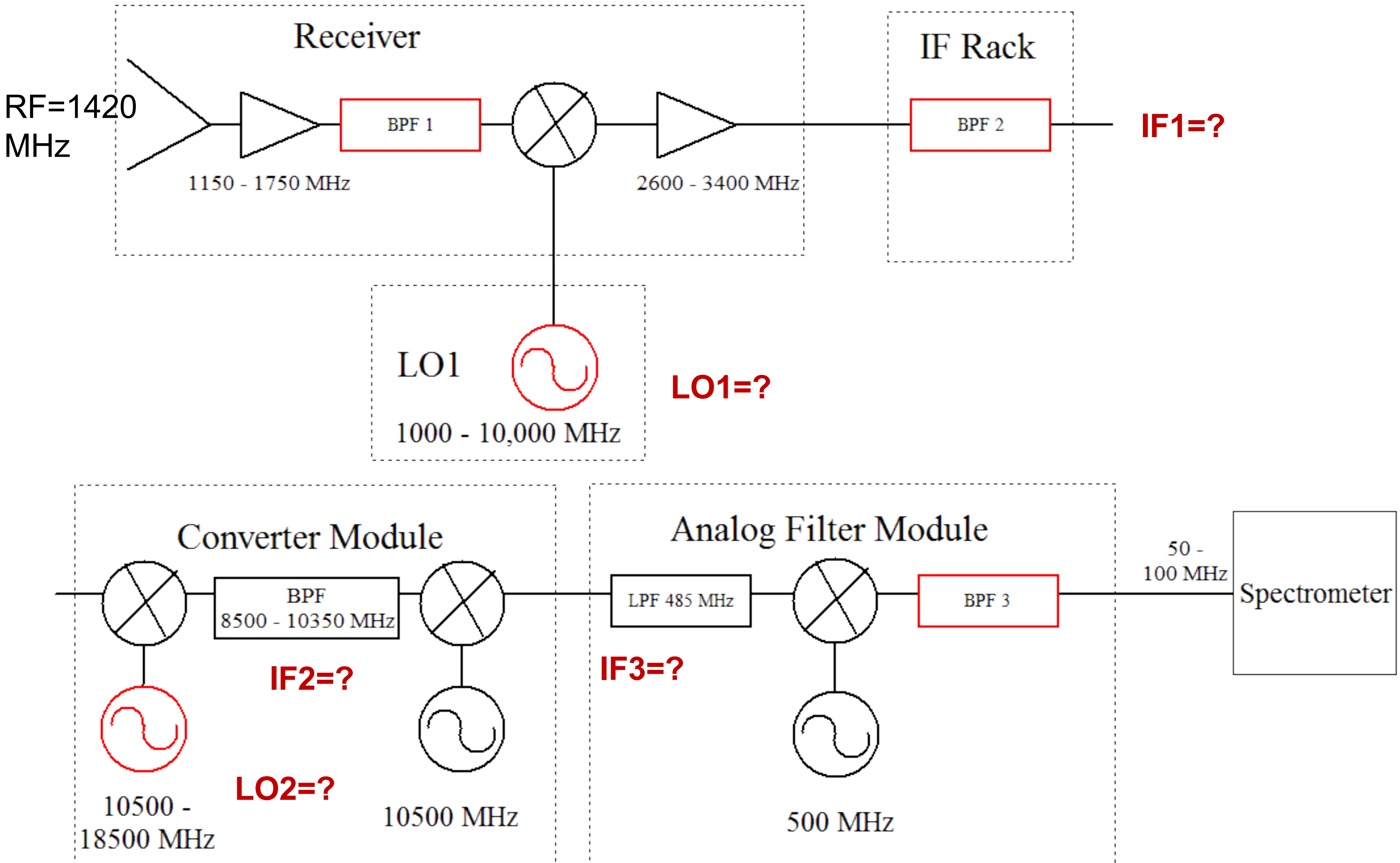
LO2=11.275 GHz

LO2 is tuneable
Up convert

Fixed LO
Down convert



"Ron's" Famous Tracing the Signal Quiz:
Derive the values for the Red Components



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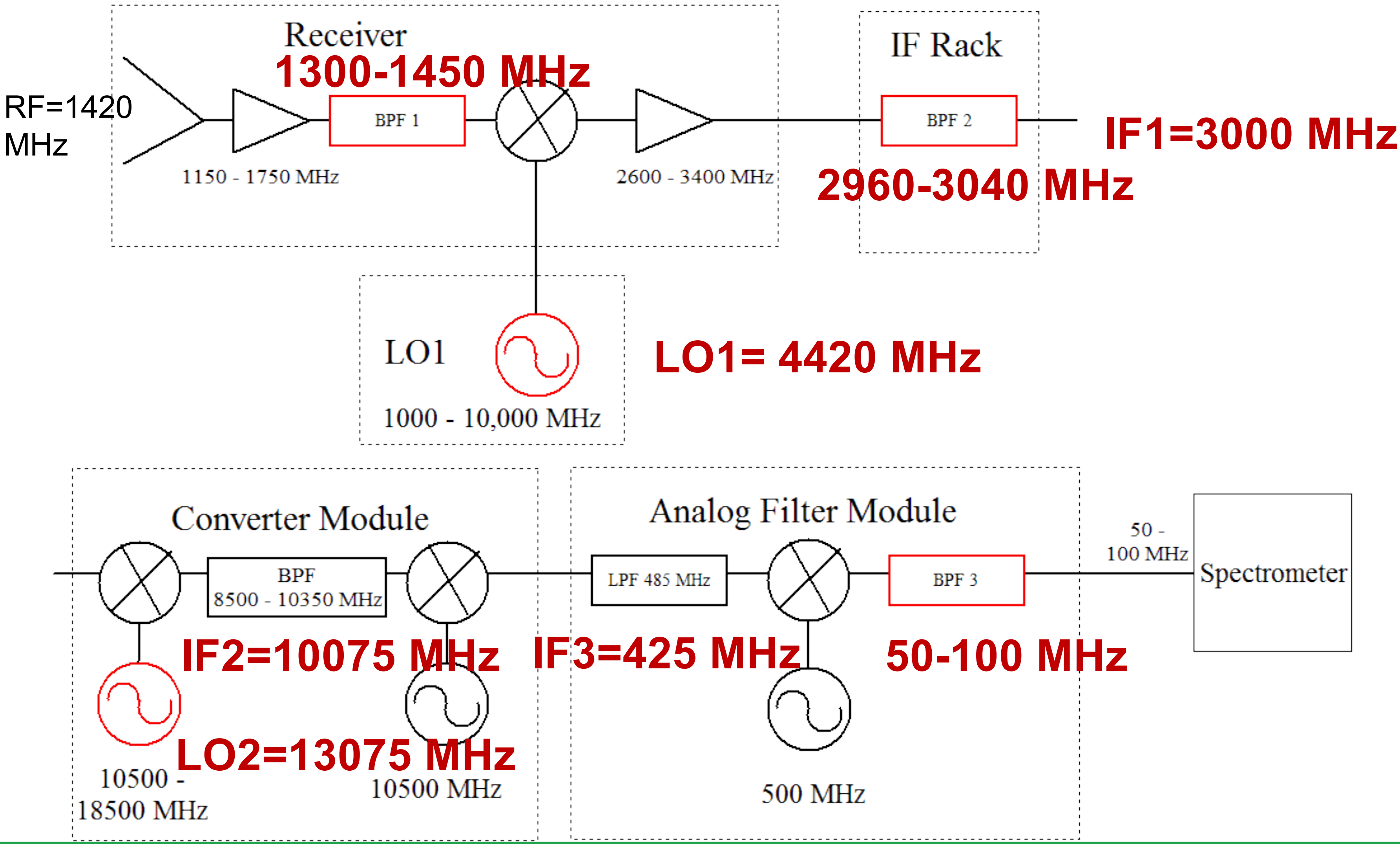
Quiz

- Goal : Observe 1420 MHz with the 50 MHz mode of the Spectrometer (spectrometer does not exist now)
- **Parameters:**
  - BPF1 can be: 1100–1800, 1600-1750, 1300-1450, or 1100-1450 MHz
  - All mixers are Lower Side Band. Hint: first two mixers up convert, the last two down convert.
  - BPF2 can be : 2990-3010, 2960-3040, 2840-3160, 2360-3640, 5960-6040, 5840-6160, or 5360-6640 MHz
  - BPF3 can be : 50-100 or 25-37.5 MHz
  - See block diagram for other parameters
- Hint: Work from the receiver down the chain until you get stuck, then from Spectrometer up
- Record values for LO1 and LO2; settings for BPF1, 2, and 3; and center values for all Intermediate Frequencies

Answers (Note: most folks regardless of experience will mess this up which is why the configuration choices are done in software for our users....):



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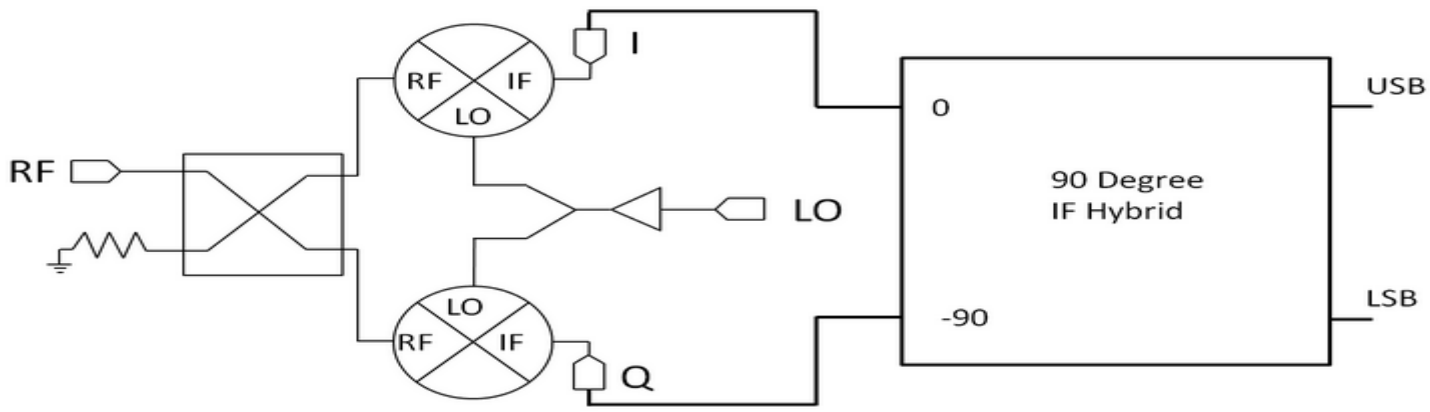
I-Q Mixer

Image-Reject Mixer Application



By connecting an IF 90 degree hybrid to the I and Q mixer outputs, the IF combines into either the upper sideband (USB) or lower sideband (LSB) IF signal.

$$I=\frac{1}{2}[\cos(f_{usb})+\cos(f_{lsb})]$$

$$Q=\frac{1}{2}[\sin(f_{usb})+\sin(f_{lsb})]$$

$$USB = I+Q(f_{usb}+\pi/2, f_{lsb}-\pi/2) = \cos(f_{usb})$$

$$LSB = I(f_{usb}+\pi/2, f_{lsb}-\pi/2)+Q = \sin(f_{lsb})$$