GREEN BANK OBSERVATORY

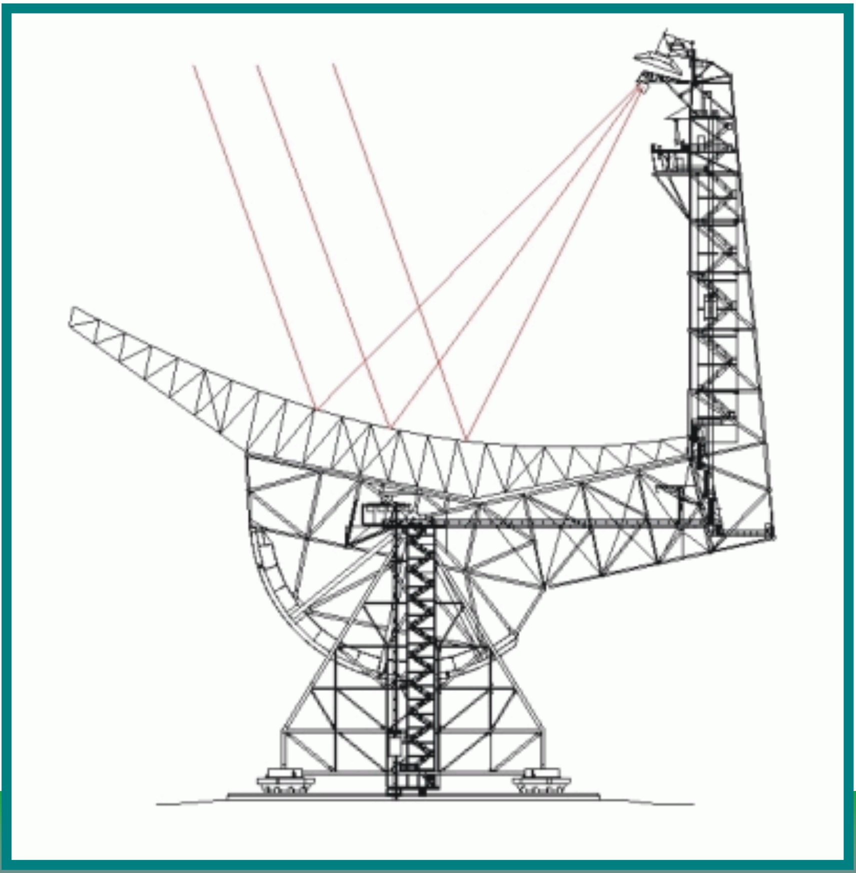
“Tracing the Signal”: Heterodyne Techniques and IF Systems in Radio Astronomy

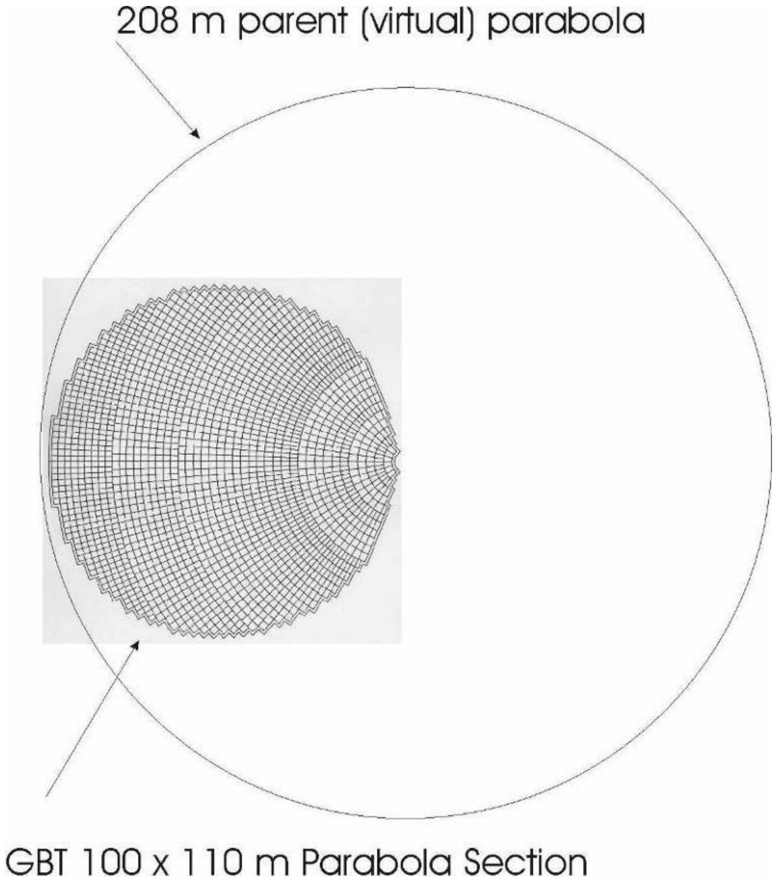
David Frayer

Tracing the signal --- Optics of the GBT

GBT Telescope Optics

- 110 m x 100 m of a 208 m parent paraboloid
  - Effective diameter: 100 m
  - Off axis - Clear/Unblocked Aperture

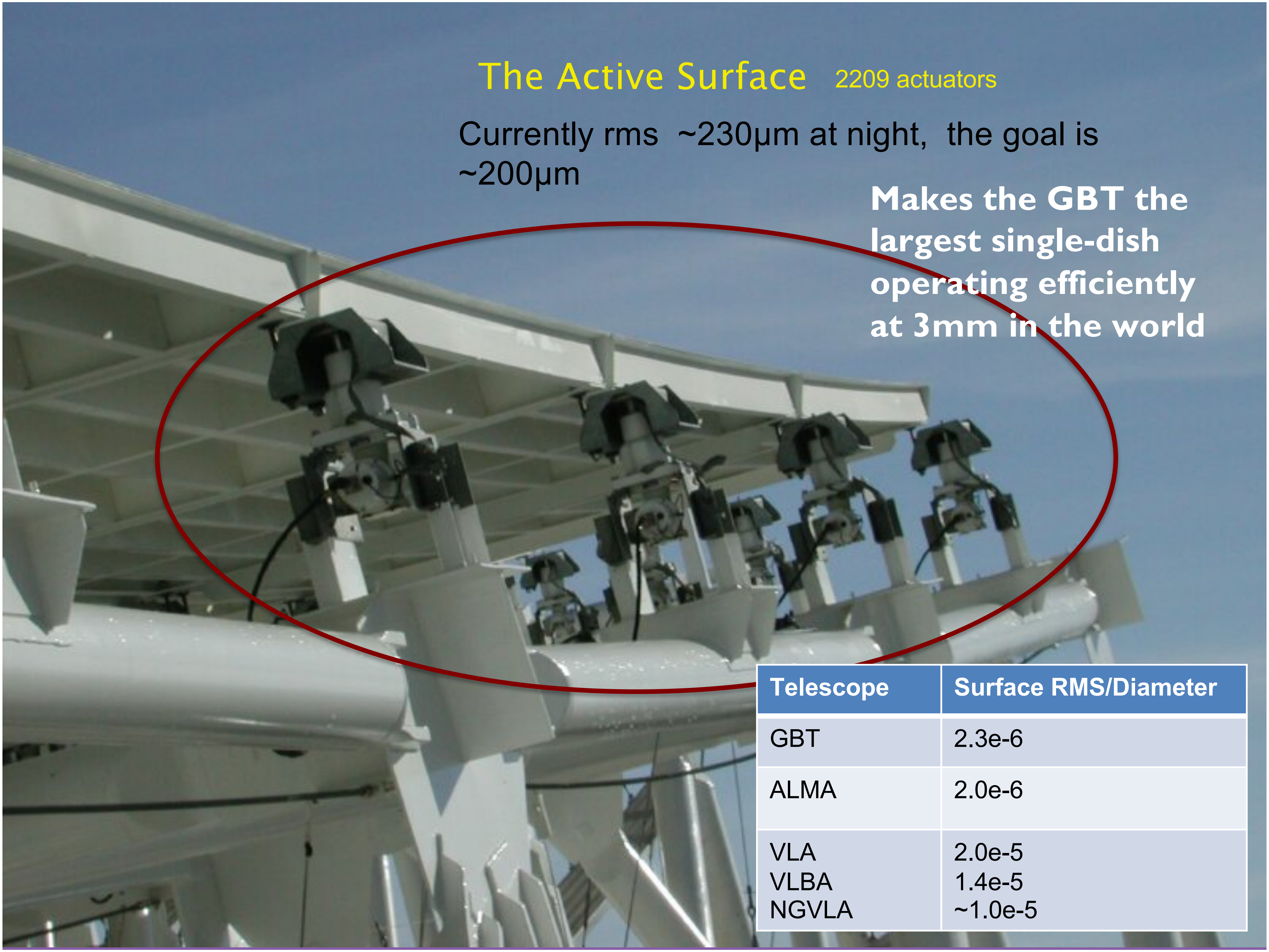




Prime Focus: Retractable boom

Gregorian Focus: 8-m subreflector - 6-degrees of freedom

Rotating Turret with 8 receiver bays



The Active Surface 2209 actuators

Currently rms ~230μm at night, the goal is ~200μm

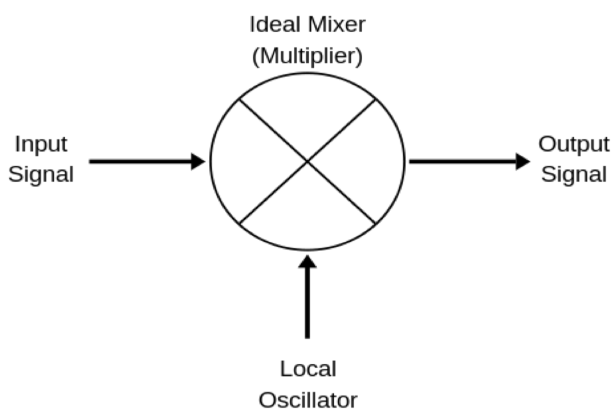
Makes the GBT the largest single-dish operating efficiently at 3mm in the world

Telescope	Surface RMS/Diameter
GBT	2.3e-6
ALMA	2.0e-6
VLA VLBA NGVLA	2.0e-5 1.4e-5 ~1.0e-5

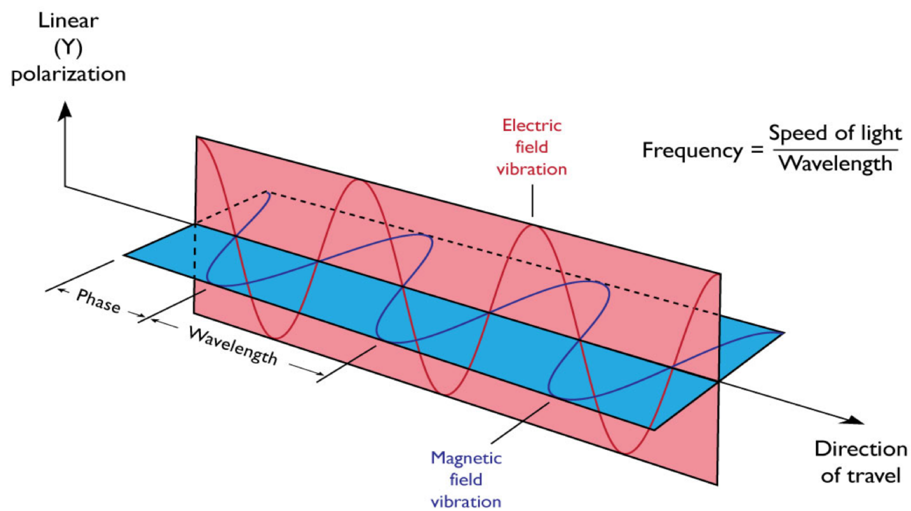
Radio Heterodyne Methods

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

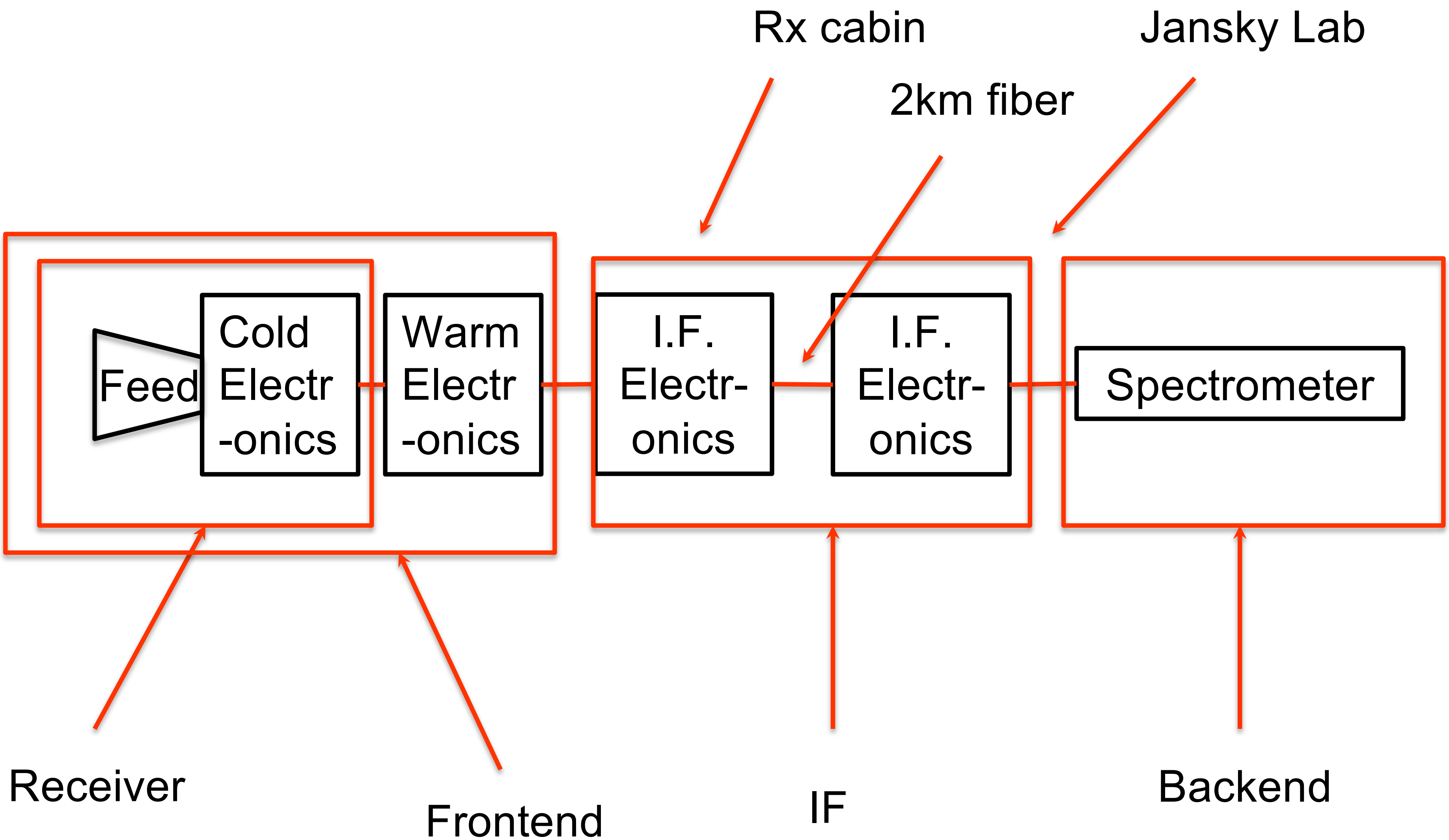
Stages in (Heterodyne) Detection / Analysis

- ***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

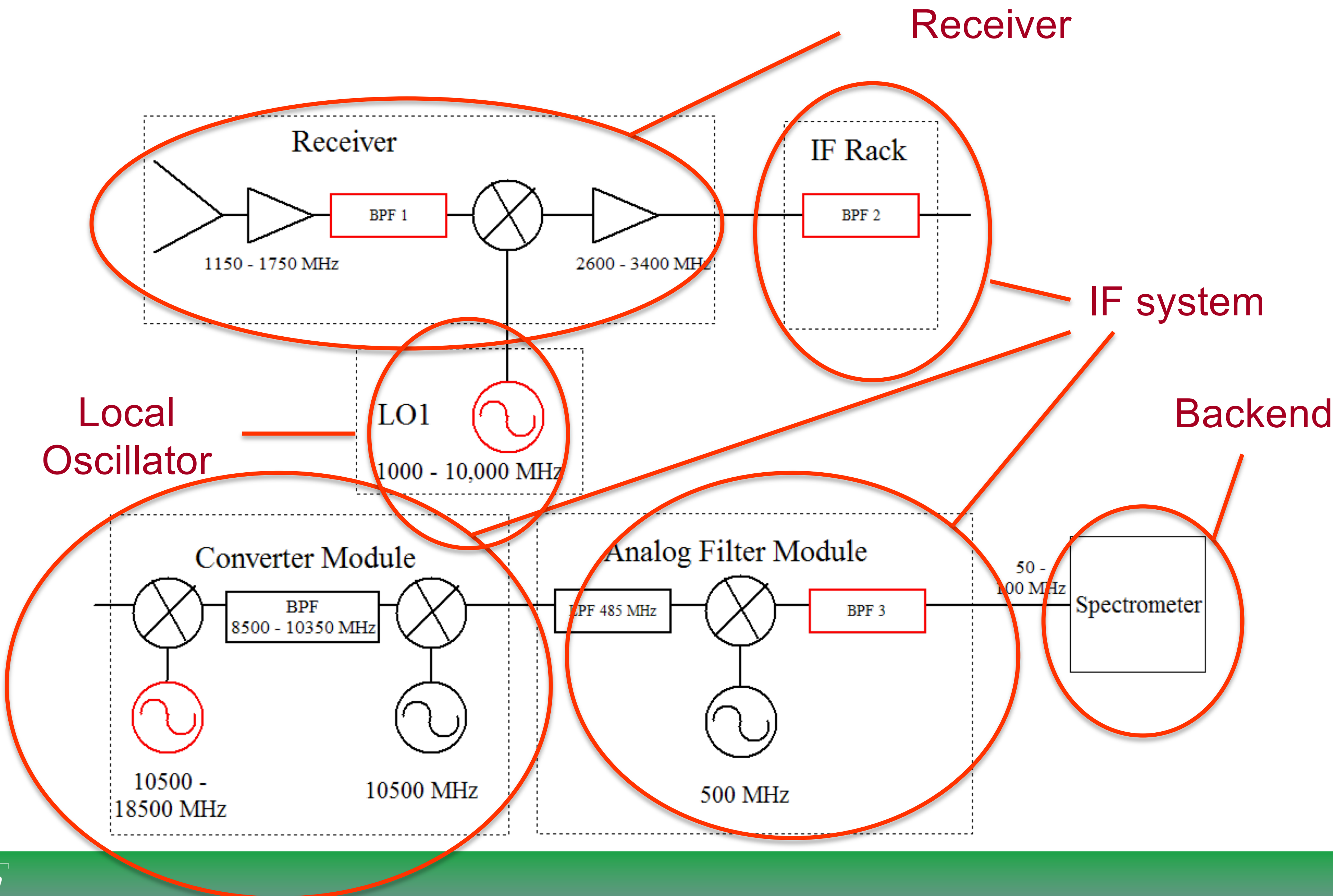
(Convert, Amplify, Mix: Frontend Receiver)

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

Parts of the system



Instrumentation Chain



IF System

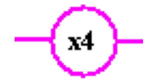
- “IF” – intermediate frequency
- The IF system is the part of the system that connects the “Front-end” (Receivers) with the “Back-end” (spectrometer/signal processors)

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

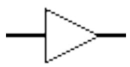
Available GBT Receivers

Receiver	Band	Frequency Range (GHz)	Focus	Polarization	Beams	Polarizations per Beam
PF1	342 MHz	.290-.395	Prime	Lin/Circ	1	2
	450 MHz*	.385-.520	Prime	Lin/Circ	1	2
	600 MHz*	.510-.690	Prime	Lin/Circ	1	2
	800 MHz	.680-.920	Prime	Lin/Circ	1	2
PF2*	——	.910-1.23	Prime	Lin/Circ	1	2
L-Band	——	1.15-1.73	Greg.	Lin/Circ	1	2
S-Band	——	1.73-2.60	Greg.	Lin/Circ	1	2
C-Band	——	3.95-8.0	Greg.	Lin/Circ	1	2
X-Band	——	8.00-11.6	Greg.	Circ	1	2
Ku-Band	——	12.0-15.4	Greg.	Circ	2	2
KFPA	——	18.0-27.5	Greg.	Circ	7	2
Ka-Band	MM-F1	26.0-31.0	Greg.	Circ	2	1
	MM-F2	30.5-37.0				
	MM-F3	36.0-39.5				
Q-Band	——	38.2-49.8	Greg.	Circ	2	2
W-Band 4mm	MM-F1	67-74	Greg.	Circ	2	2
	MM-F2	73-80	Greg.	Circ	2	2
	MM-F3	79-86	Greg.	Circ	2	2
	MM-F4	85-93.3	Greg.	Circ	2	2
Mustang2	——	80-100	Greg.	—-	200	—-
ARGUS	——	80-115.3	Greg.	Circ	16	1

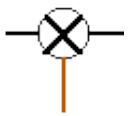
Typical Components in System Block Diagrams:



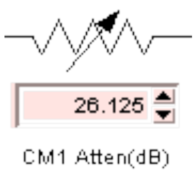
Multipliers



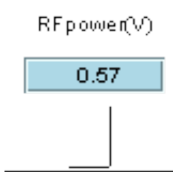
Amplifiers



Mixers



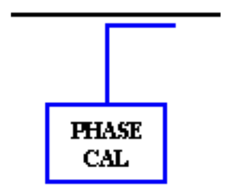
Attenuators



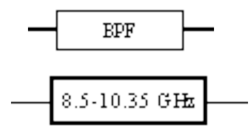
Power Detectors

Synthesizers

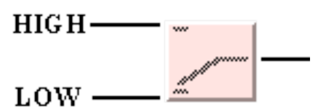
Splitters



Couplers

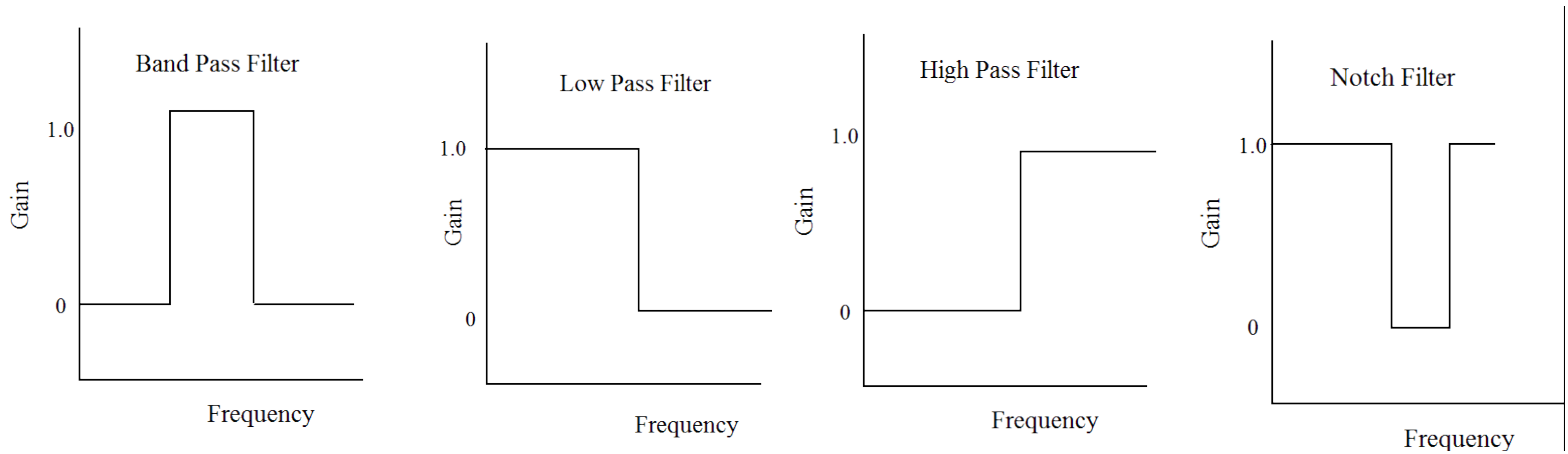


Filters



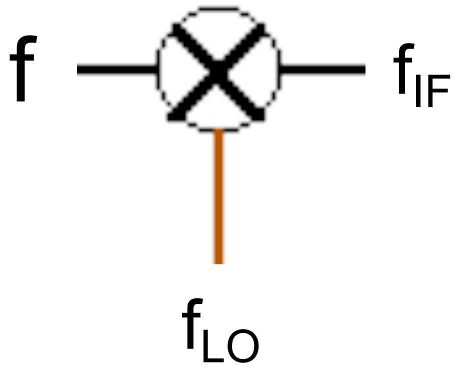
Switches

Types of Filters

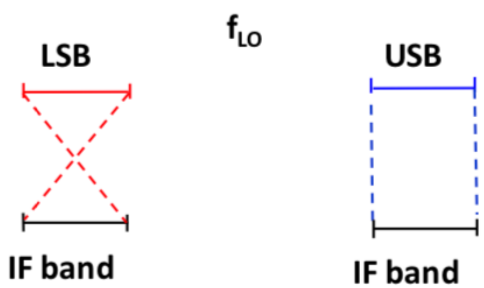


Edges are smoother than illustrated

Types of Mixers



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

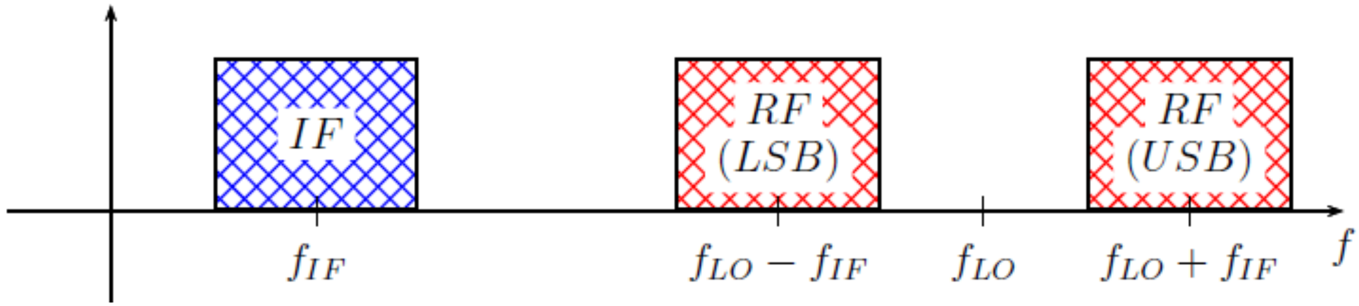


- n and m are positive or negative integers, usually 1 or -1

- 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

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

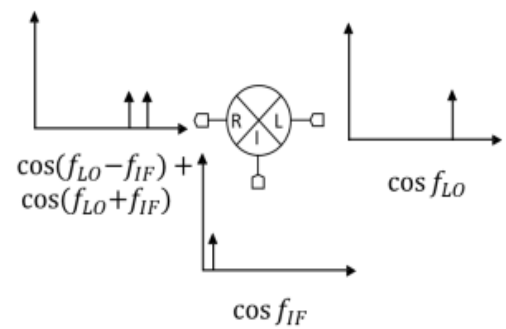
USB= LO + IF

LSB = LO - IF

$f = frequency$

$2\pi f = \omega$

$dropping \;\; 2\pi t$

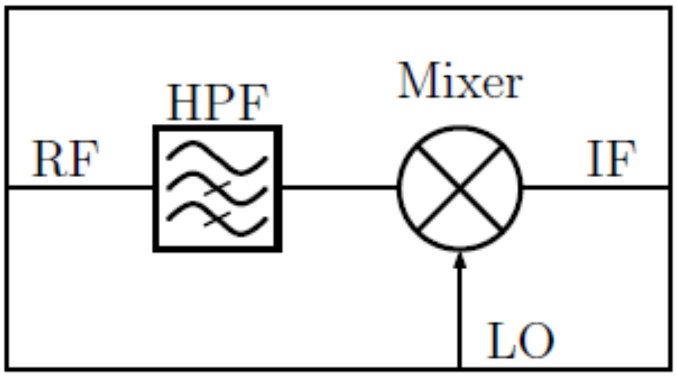


$$v(t) = A_o \cos(\omega t + \phi)$$

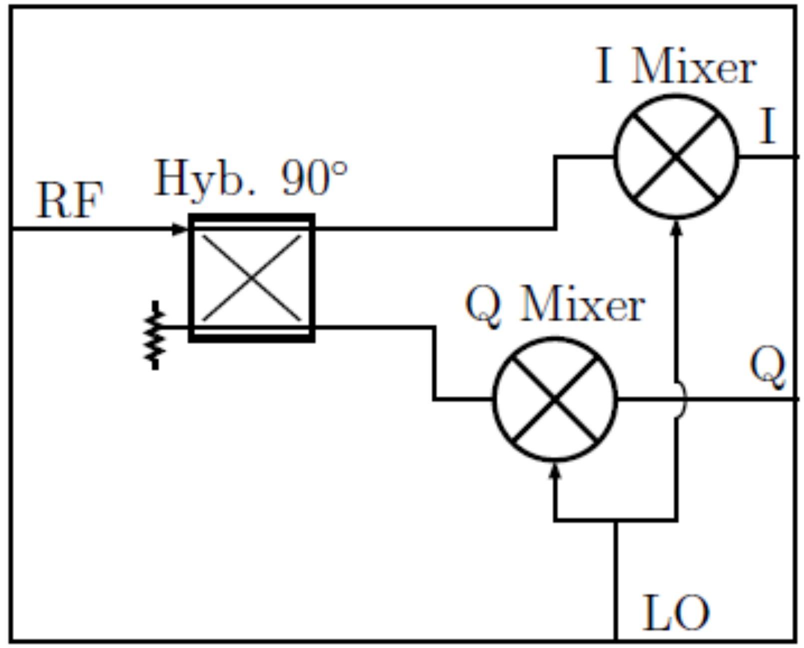
$$\cos(\omega_a t)\cos(\omega_b t) = \frac{1}{2}\cos(\omega_a - \omega_b)t + \frac{1}{2}\cos(\omega_a + \omega_b)t$$

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.

Mixer Examples/Side-band Rejection



(a) A single sideband mixer.

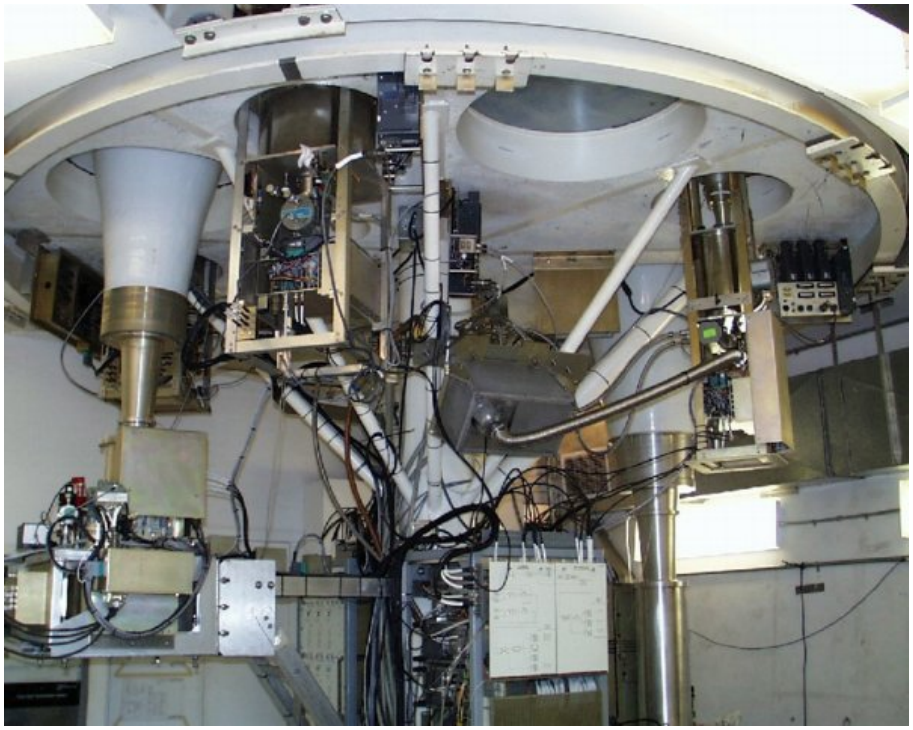


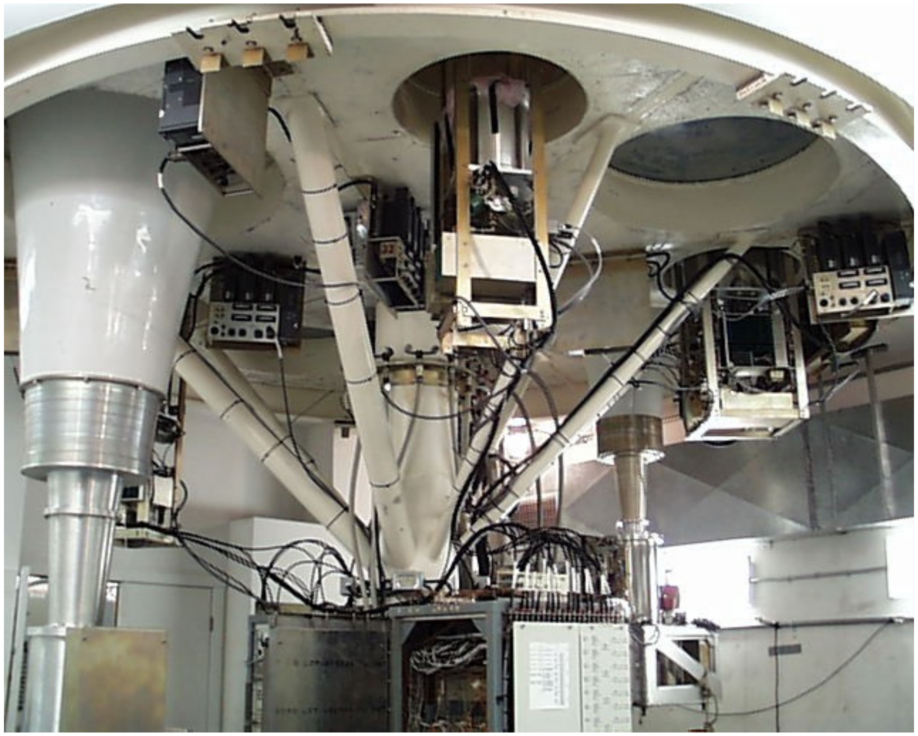
(b) A double sideband I/Q mixer.

(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.

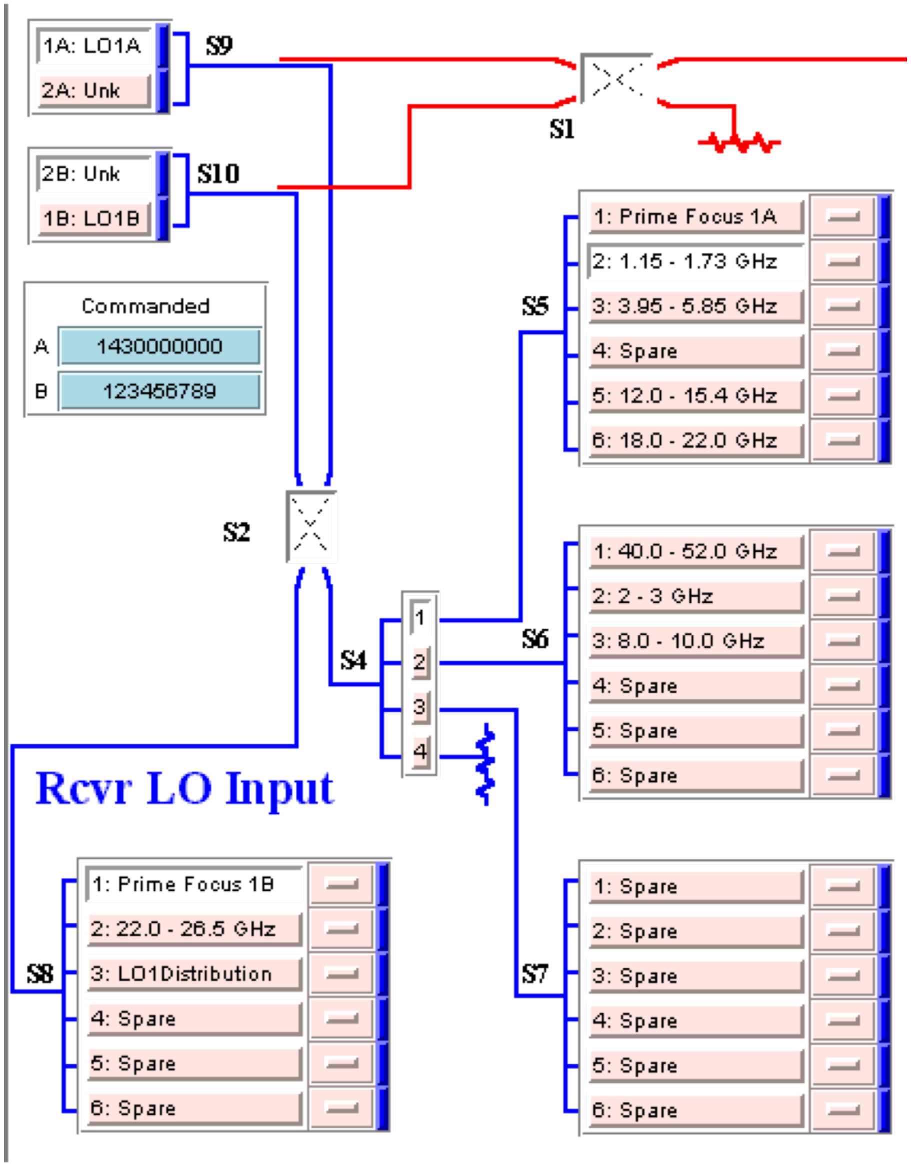
Receiver Room (on telescope)





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

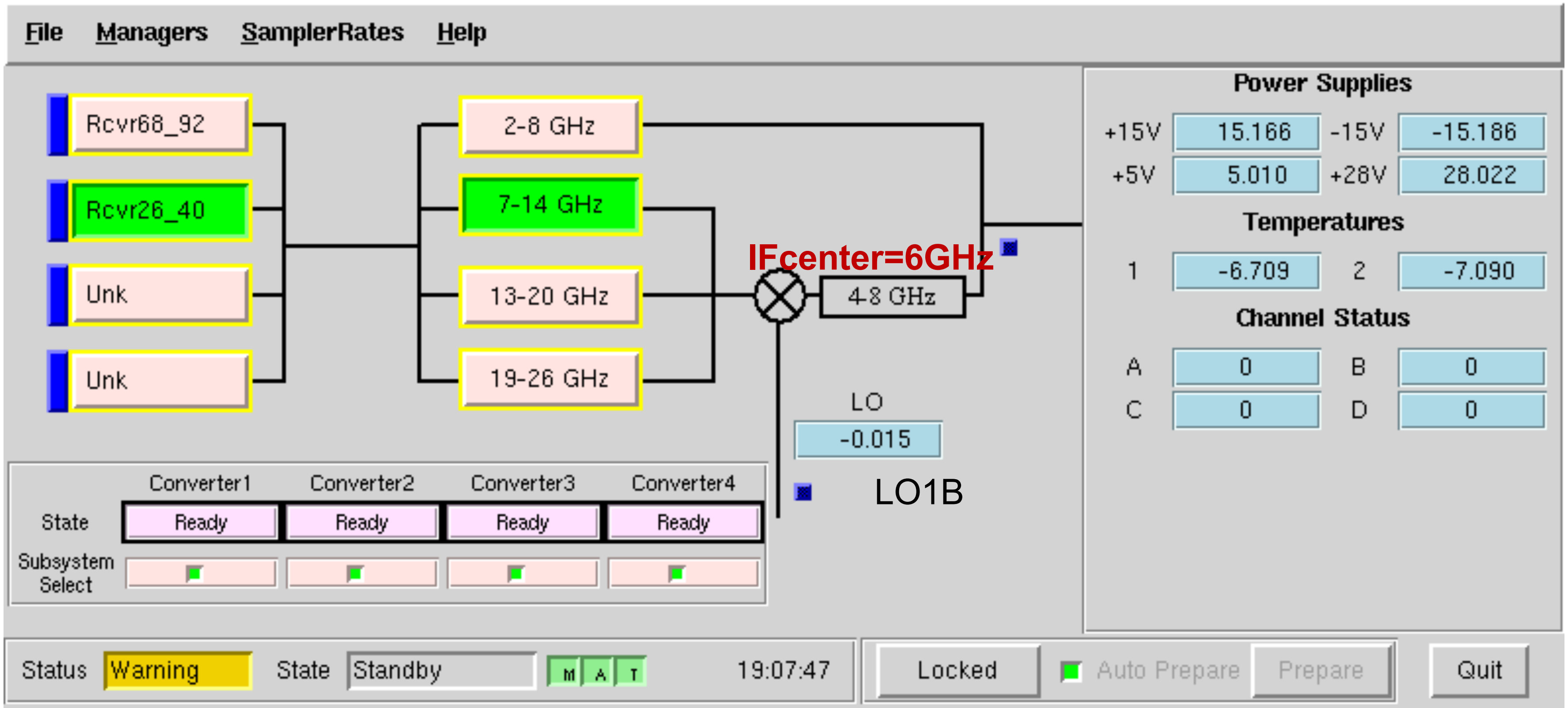
GBT Local Oscillator and Switching Matrix



LO also used for:

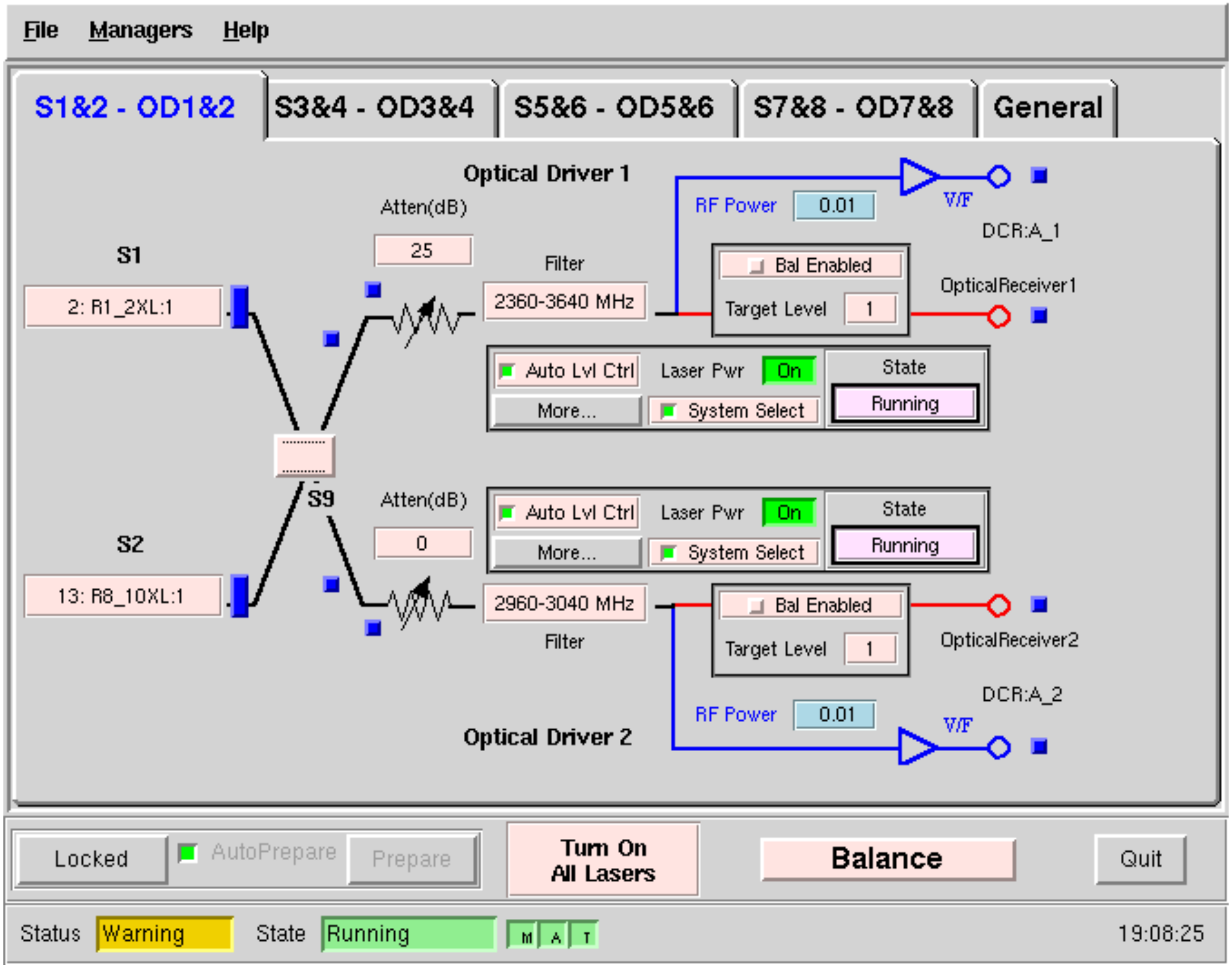
- Correcting for source velocity
  - wrt a chosen frame of rest
    - Heliocentric
    - LSR
    - Galactocentric
    - Topocentric
  - And chosen approximation of Doppler shift
    - Relativistic
    - Radio
    - Optical
- Frequency Switching (optional tactic for removal of instrumental bandpass)
-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

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



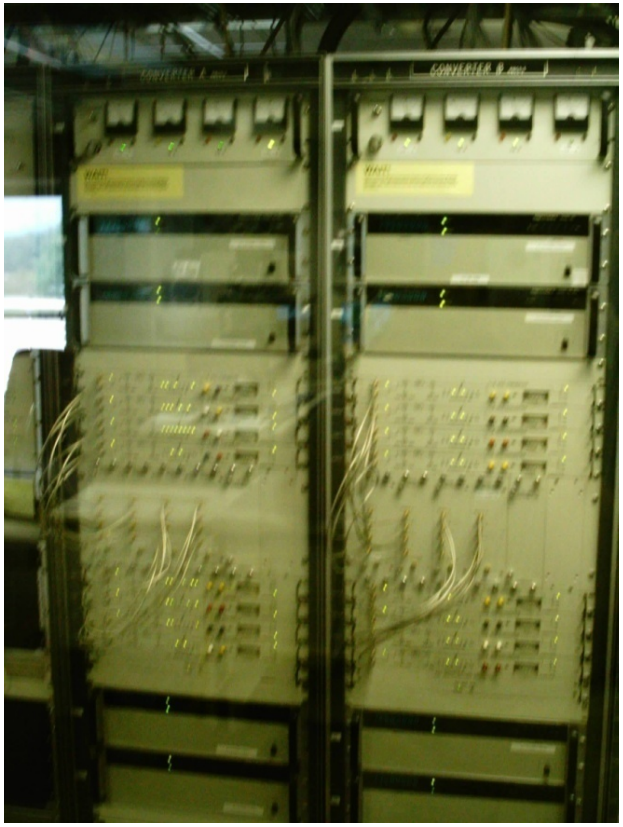
Example: 4mm/Rcvr68_92:
Observing 89.0 GHz = RF in USB.
LO1A=66GHz (4x16.5GHz), IF1=23 GHz input to Mmcoverter filter FL4 subband (19-26GHz). LO1B=RF-66GHz -6GHz= 17GHz to produce output IF centered on 6 GHz that goes to the IFrack.

IF-Rack (8 channels)

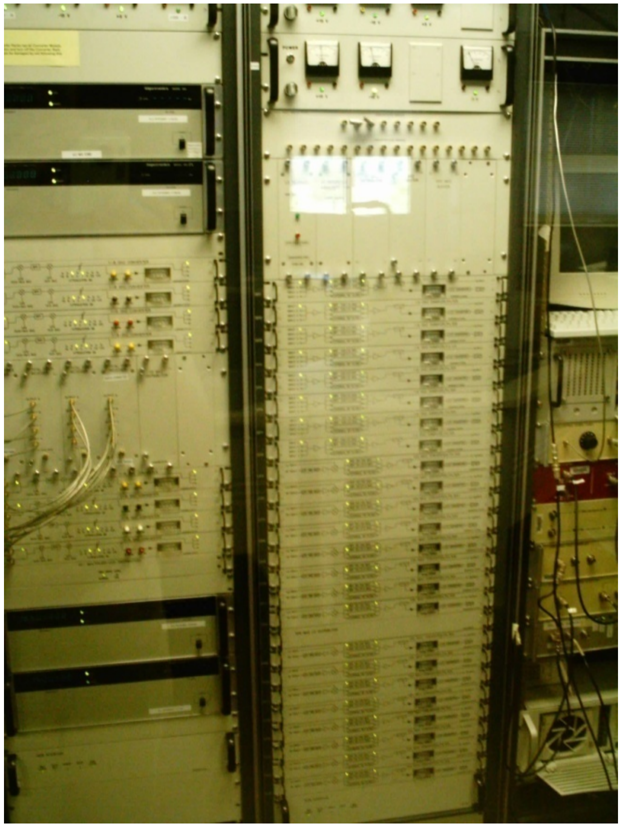


Equipment Room (Jy-Lab)

Converter Racks

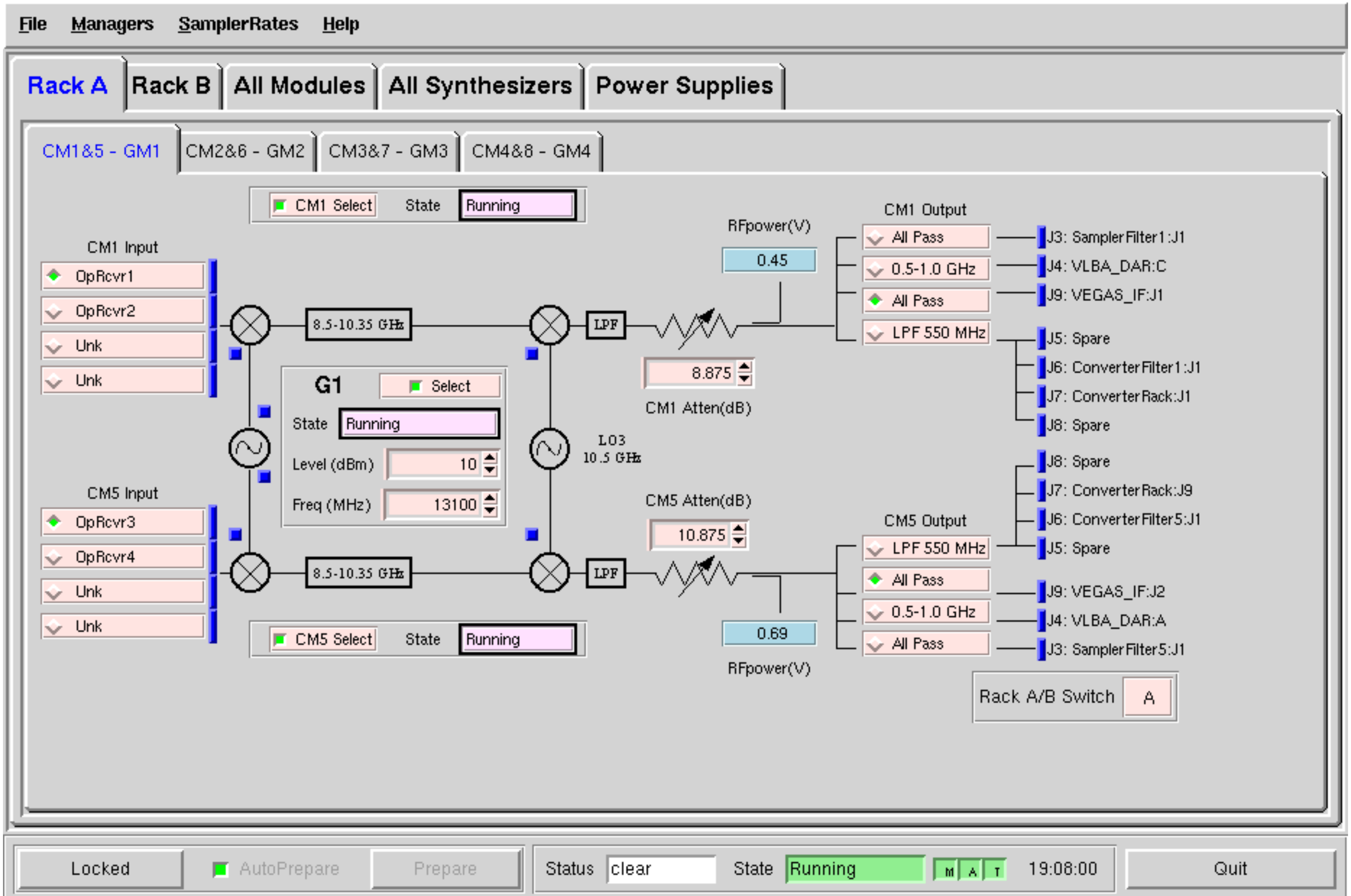


Analog
Filter rack

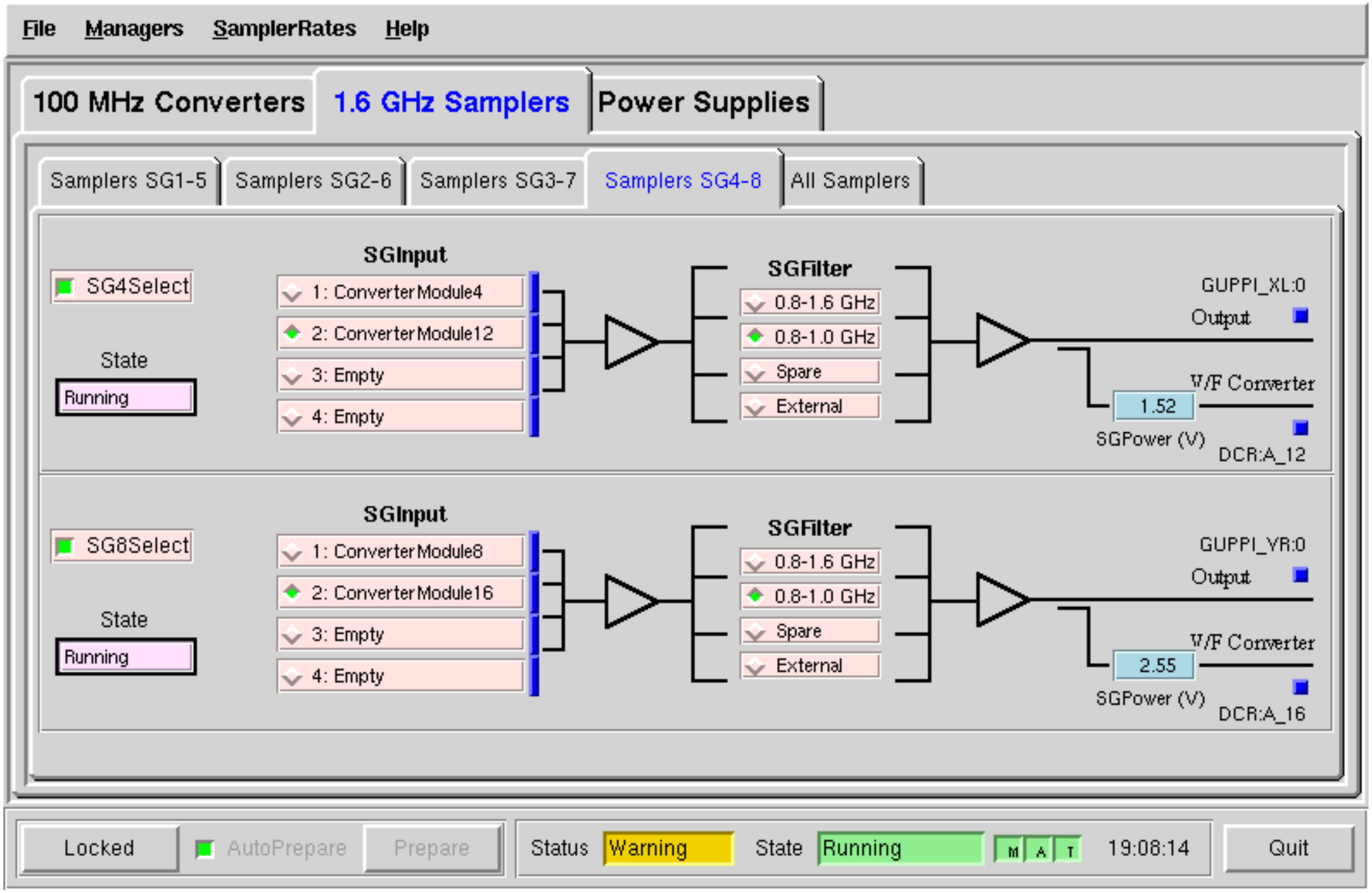


VEGAS

Converter Rack (16 channels)



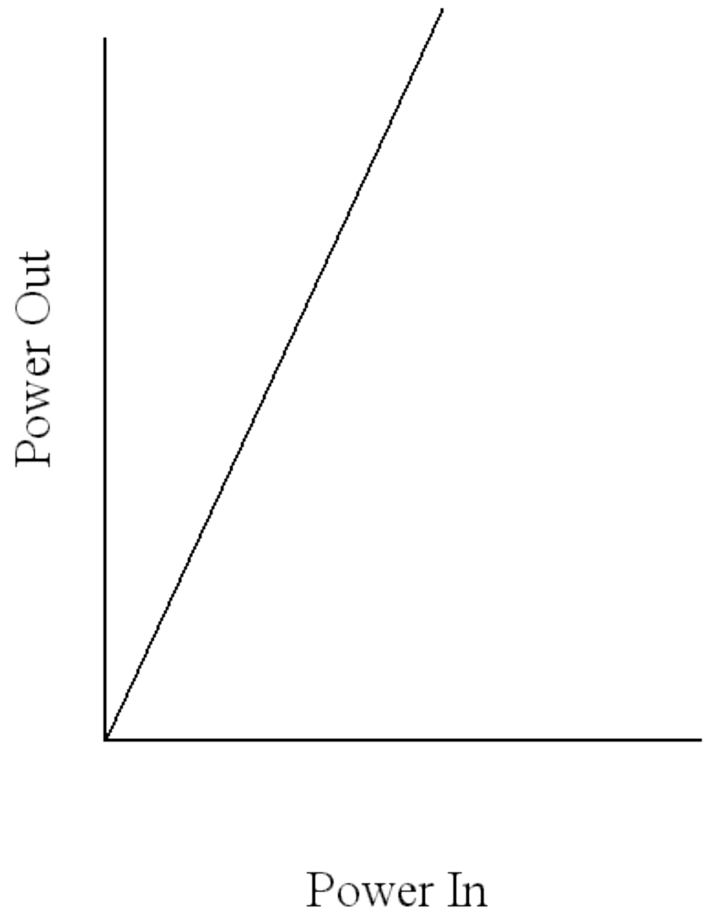
Analog Filter Rack (used with GUPPI and old Spectrometer)

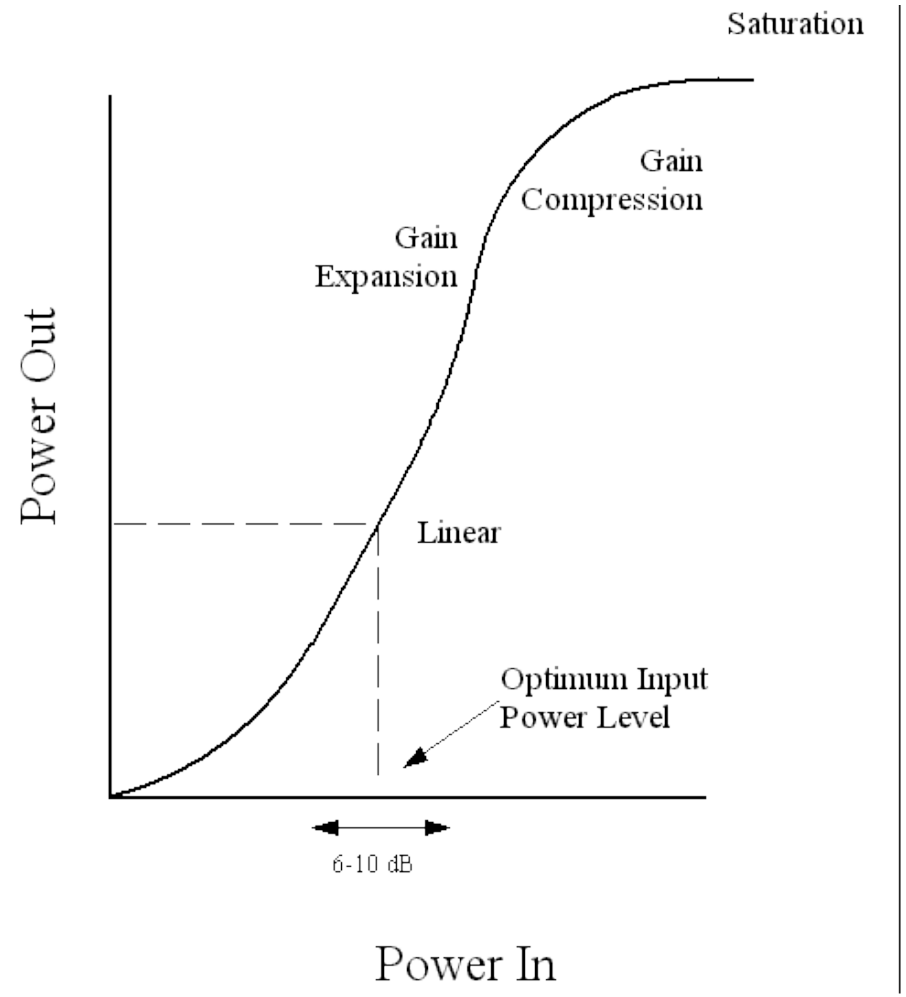


Power Balancing/Leveling

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.

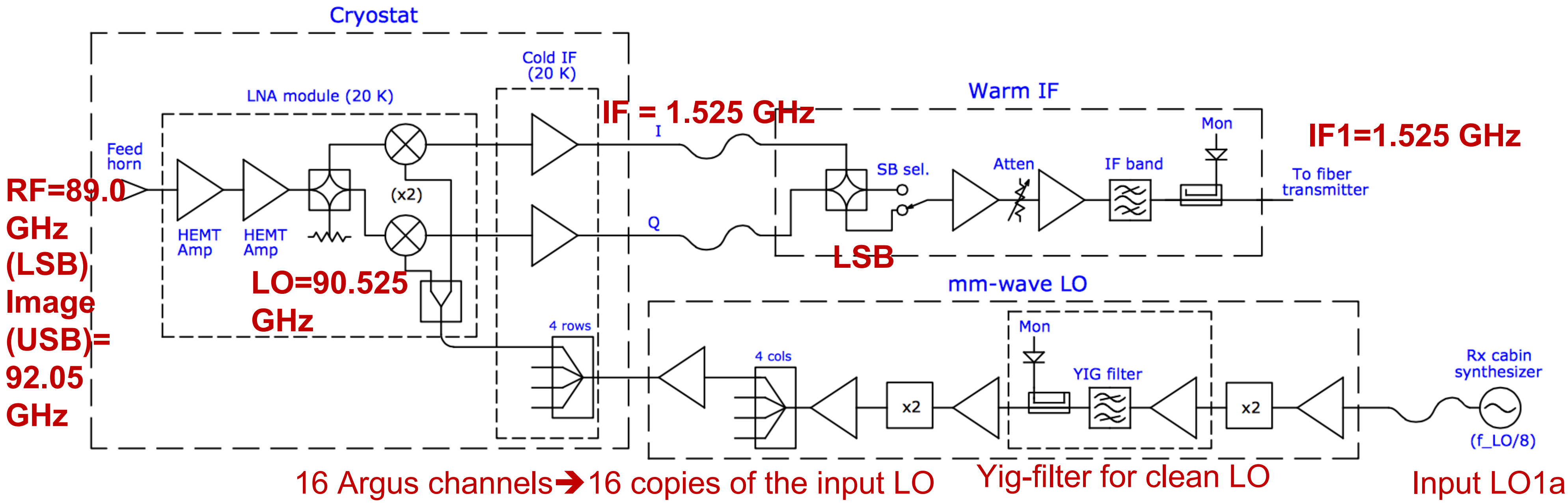
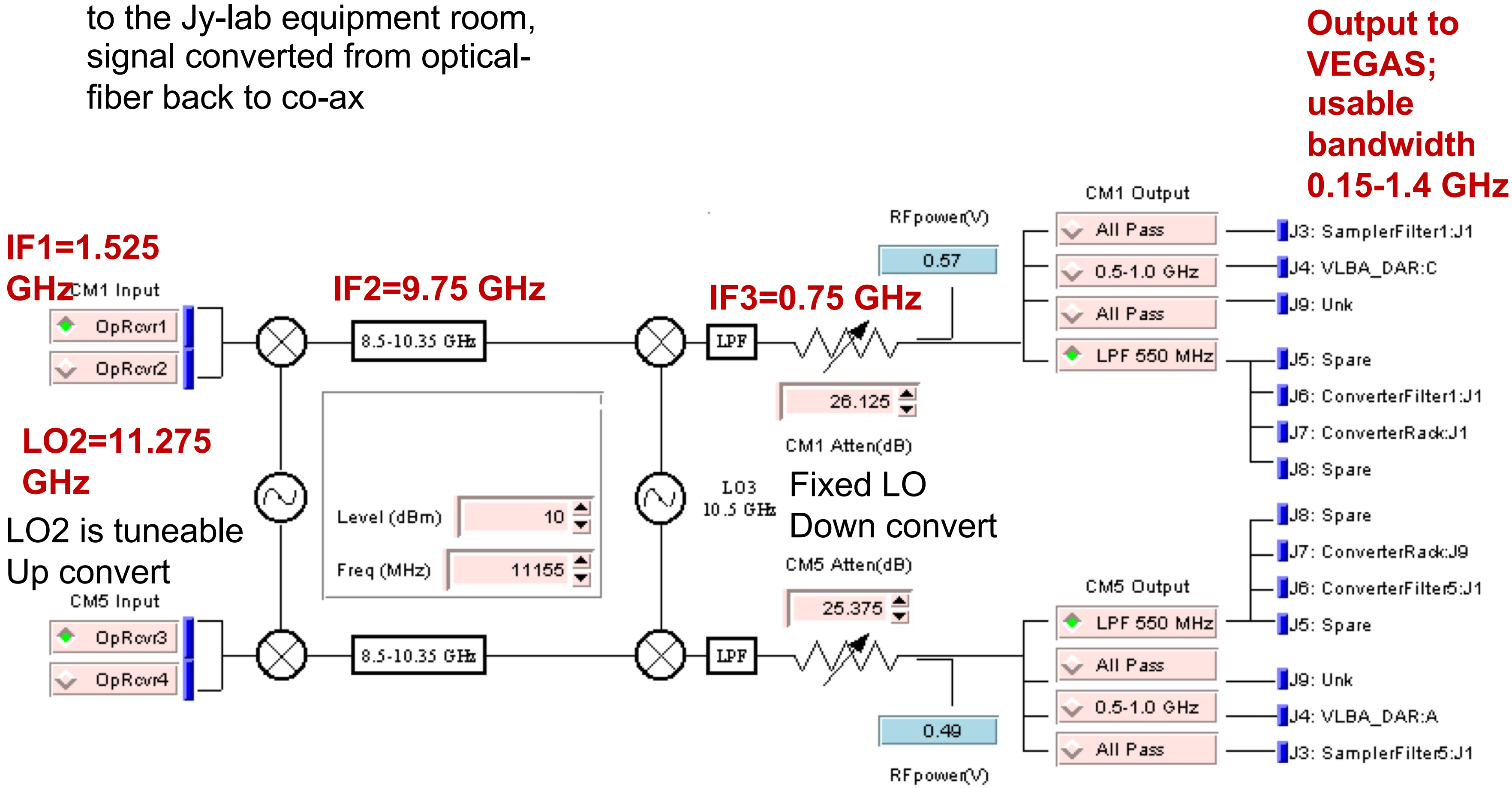


Figure 1: Schematic block diagram of Argus' signal path for a single receiver.

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.

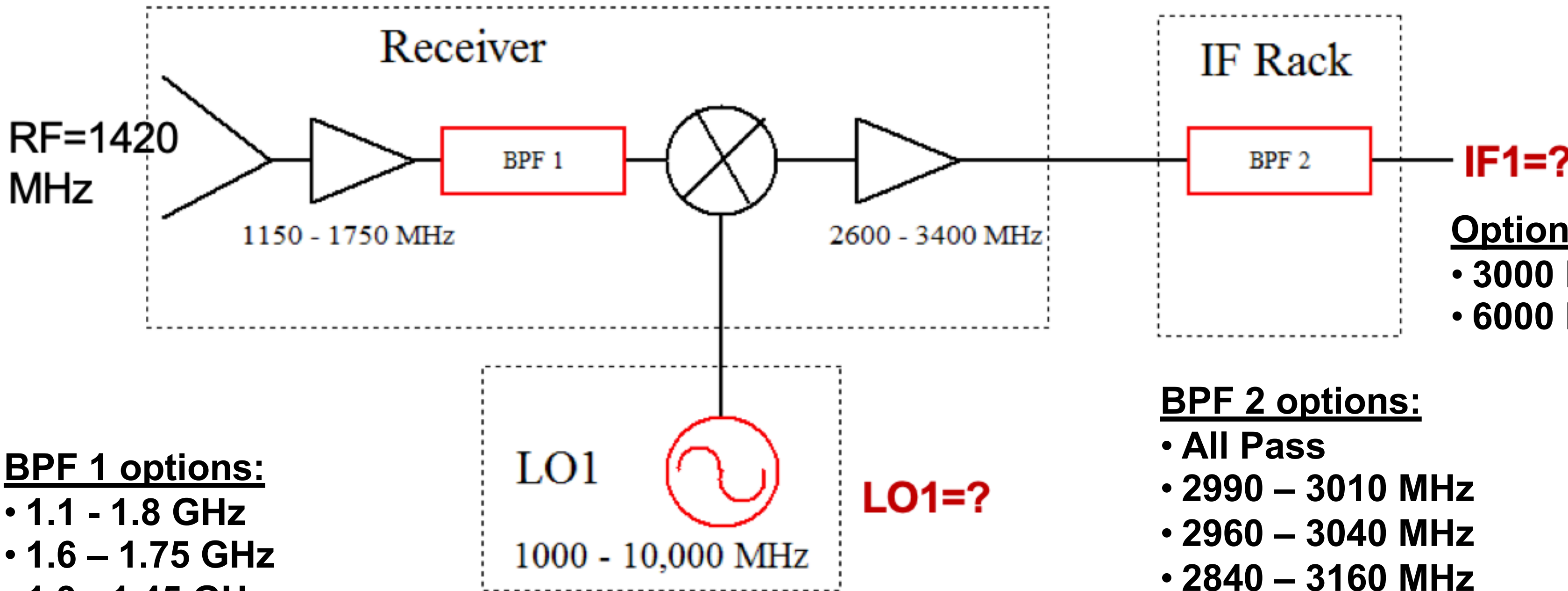
Tracing the Signal, Argus (page 2)

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



Tracing the Signal Quiz

An observer wants to use the L-band Receiver to measure HI (1420 MHz) using the narrowest possible output bandwidth of VEGAS (11.72 MHz) to minimize the effects of RFI. For an input sky frequency (RF) of 1420 MHz, what is the required LO1 frequency, the center output IF1 frequency, and the appropriate choice of filters for the observations based on the block diagram below?



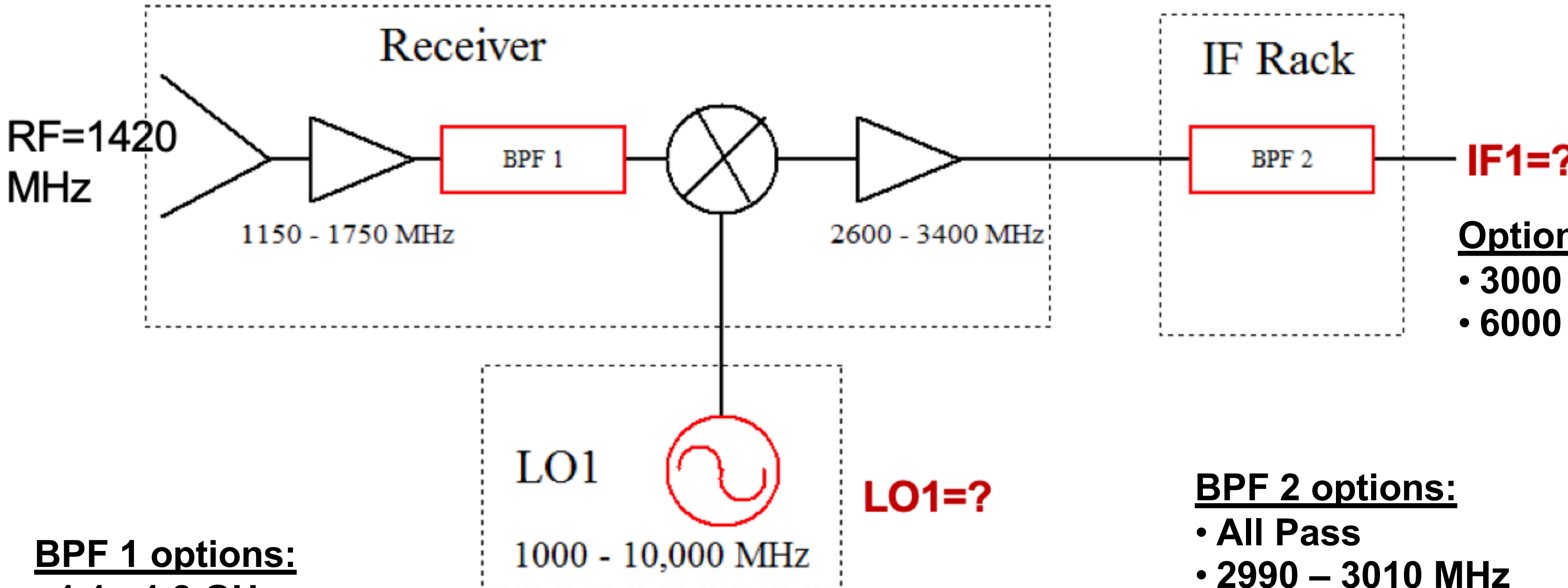
Options
- 3000 MHz
- 6000 MHz

BPF 1 options:
- 1.1 - 1.8 GHz
- 1.6 – 1.75 GHz
- 1.3 - 1.45 GHz
- 1.1 – 1.45 GHz

BPF 2 options:
- All Pass
- 2990 – 3010 MHz
- 2960 – 3040 MHz
- 2840 – 3160 MHz
- 2360 – 3640 MHz
- 5960 – 6040 MHz
- 5840 – 6160 MHz
- 5360 – 6640 MHz

Answers (BPF 1)

➔ 1.3-1.45 GHz which is the smallest bandwidth allowing the 1420 MHz signal to pass through



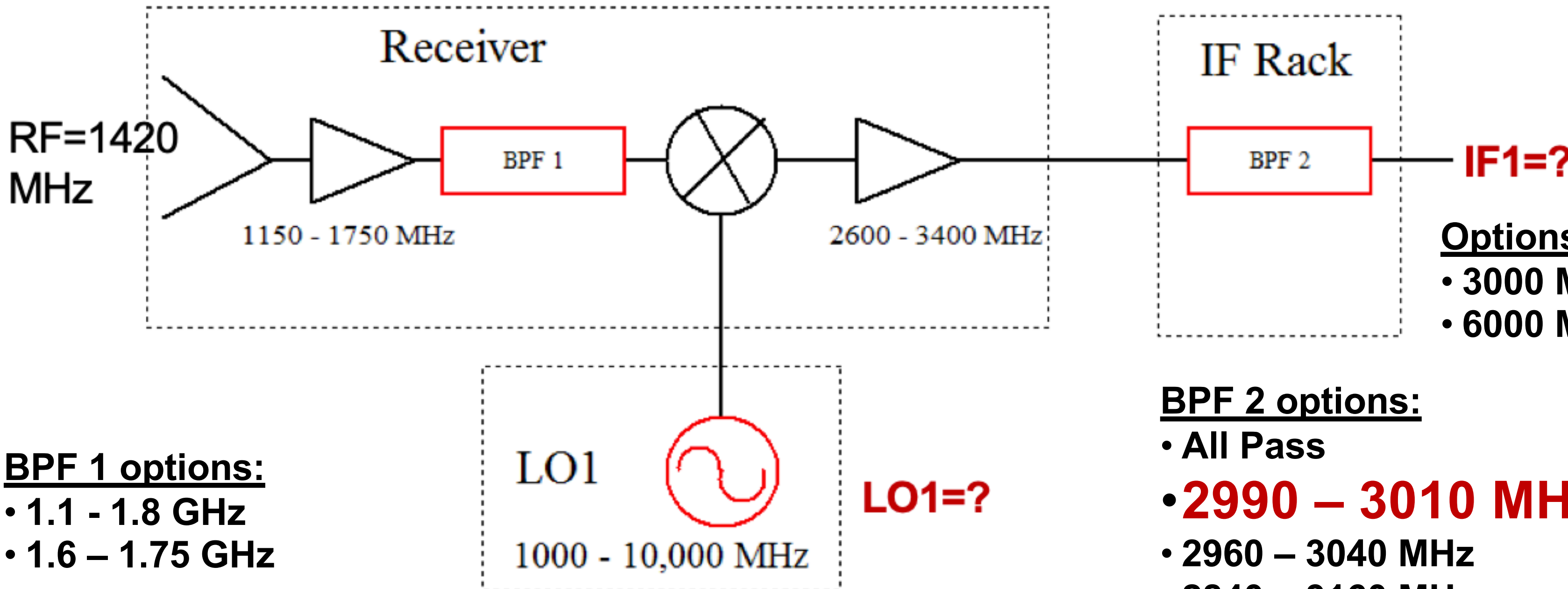
Options
- 3000 MHz
- 6000 MHz

BPF 1 options:
- 1.1 - 1.8 GHz
- 1.6 – 1.75 GHz
- **1.3 - 1.45 GHz**
- 1.1 – 1.45 GHz

BPF 2 options:
- All Pass
- 2990 – 3010 MHz
- 2960 – 3040 MHz
- 2840 – 3160 MHz
- 2360 – 3640 MHz
- 5960 – 6040 MHz
- 5840 – 6160 MHz
- 5360 – 6640 MHz

Answers (BPF 2)

➔ 2990 – 3010 MHz which is the smallest bandwidth associated with the 3000 MHz amplifier in front of the filter. The GBT IF Rack filters are centered around either 3000 MHz or 6000 MHz.



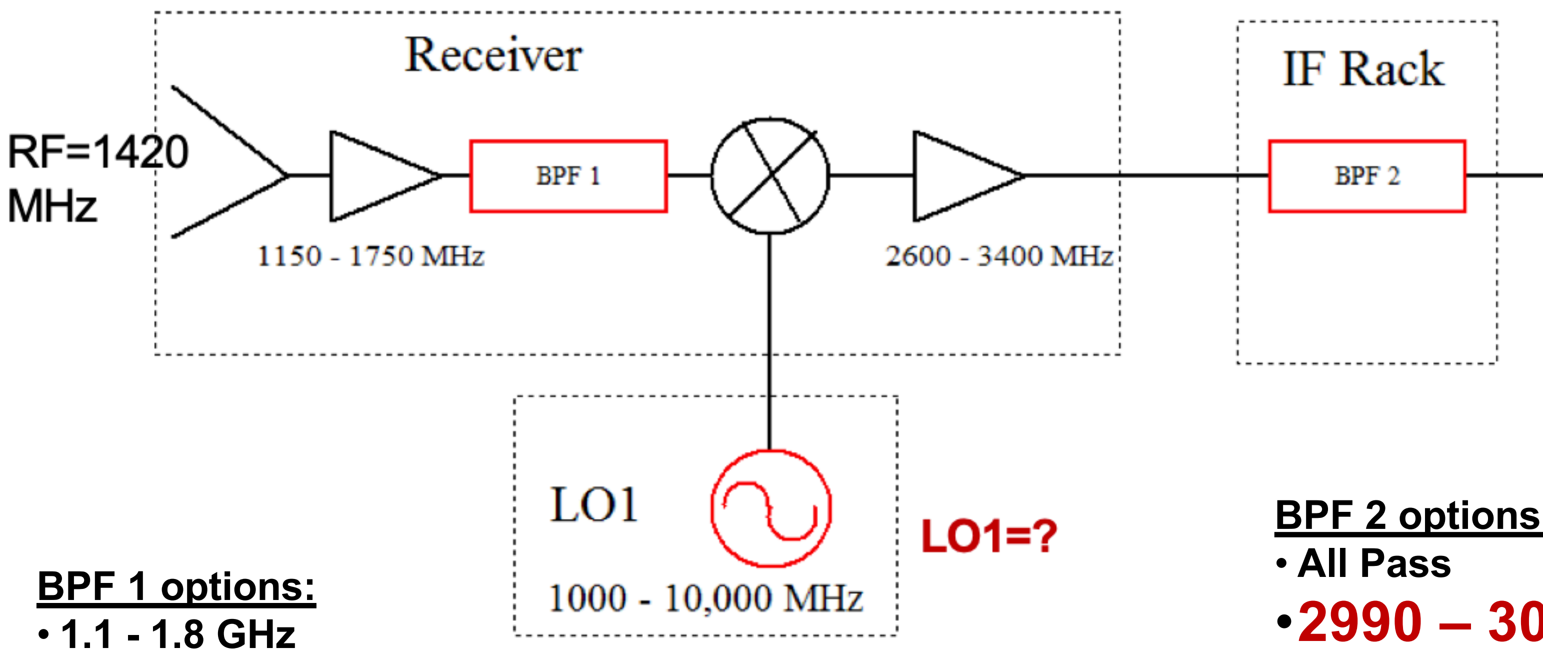
Options
- **3000 MHz**
- **6000 MHz**

BPF 1 options:
- **1.1 - 1.8 GHz**
- **1.6 – 1.75 GHz**
- **1.3 - 1.45 GHz**
- **1.1 – 1.45 GHz**

BPF 2 options:
- **All Pass**
- **2990 – 3010 MHz**
- **2960 – 3040 MHz**
- **2840 – 3160 MHz**
- **2360 – 3640 MHz**
- **5960 – 6040 MHz**
- **5840 – 6160 MHz**
- **5360 – 6640 MHz**

Answers (IF1)

➔ The optimal IF1 frequency is 3000 MHz which is compatible with the IF amplifier of the L-band receiver and the IF Rack bandpass filter.



Options
- **3000 MHz**
- **6000 MHz**

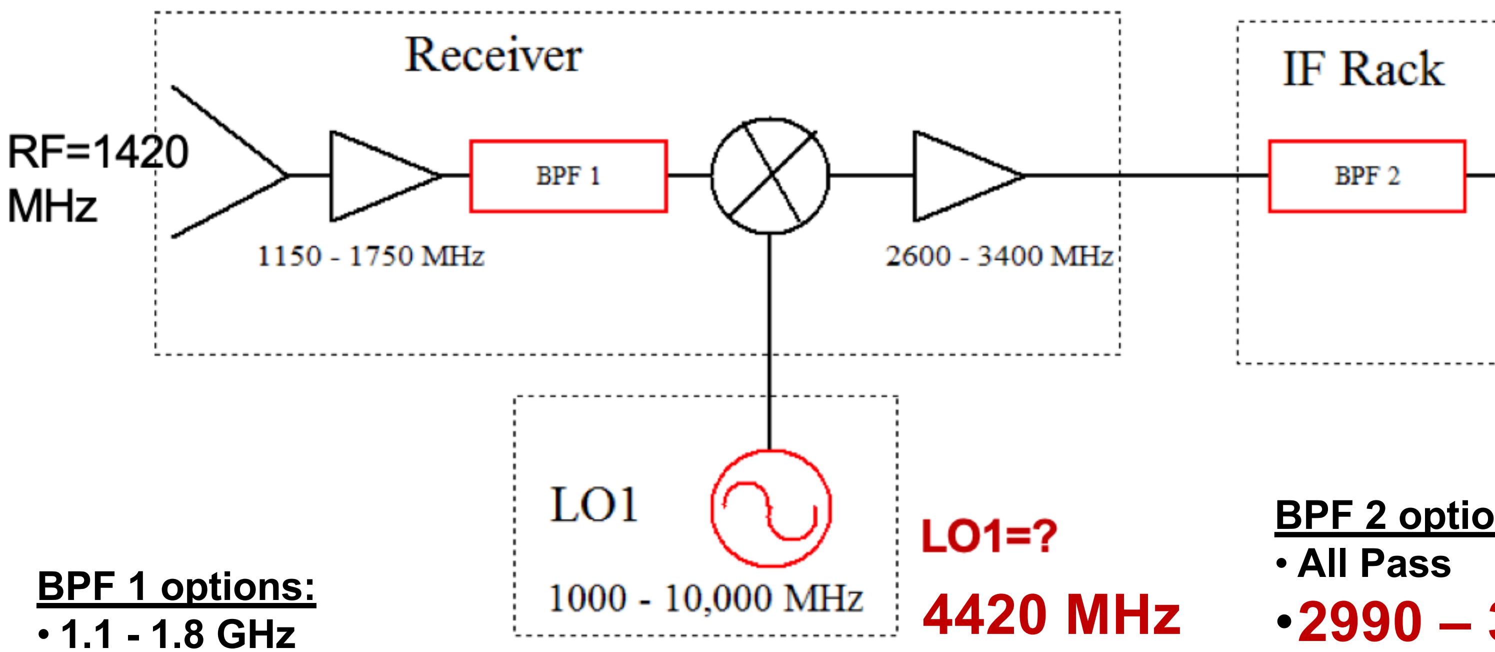
BPF 1 options:
- **1.1 - 1.8 GHz**
- **1.6 – 1.75 GHz**
- **1.3 - 1.45 GHz**
- **1.1 – 1.45 GHz**

BPF 2 options:
- **All Pass**
- **2990 – 3010 MHz**
- **2960 – 3040 MHz**
- **2840 – 3160 MHz**
- **2360 – 3640 MHz**
- **5960 – 6040 MHz**
- **5840 – 6160 MHz**
- **5360 – 6640 MHz**

Answers (LO1)

- RF(USB/LSB) = LO +/- IF
- If RF is in the USB➔ USB=LO + IF ➔ LO = USB - IF = 1420 MHz – 3000 MHz = -1580 MHz (X)
- Must be LSB mix; LSB = LO – IF ➔ LO = LSB + IF = 1420 MHz + 3000 MHz = **4420 MHz** (Yes, within LO1 operational range).

Note, with L-band LSB system the associated USB is 7420 MHz which is outside the Rx range and is filtered out.



IF1=?

Options

- **3000 MHz**
- **6000 MHz**

LO1=?

4420 MHz

BPF 1 options:

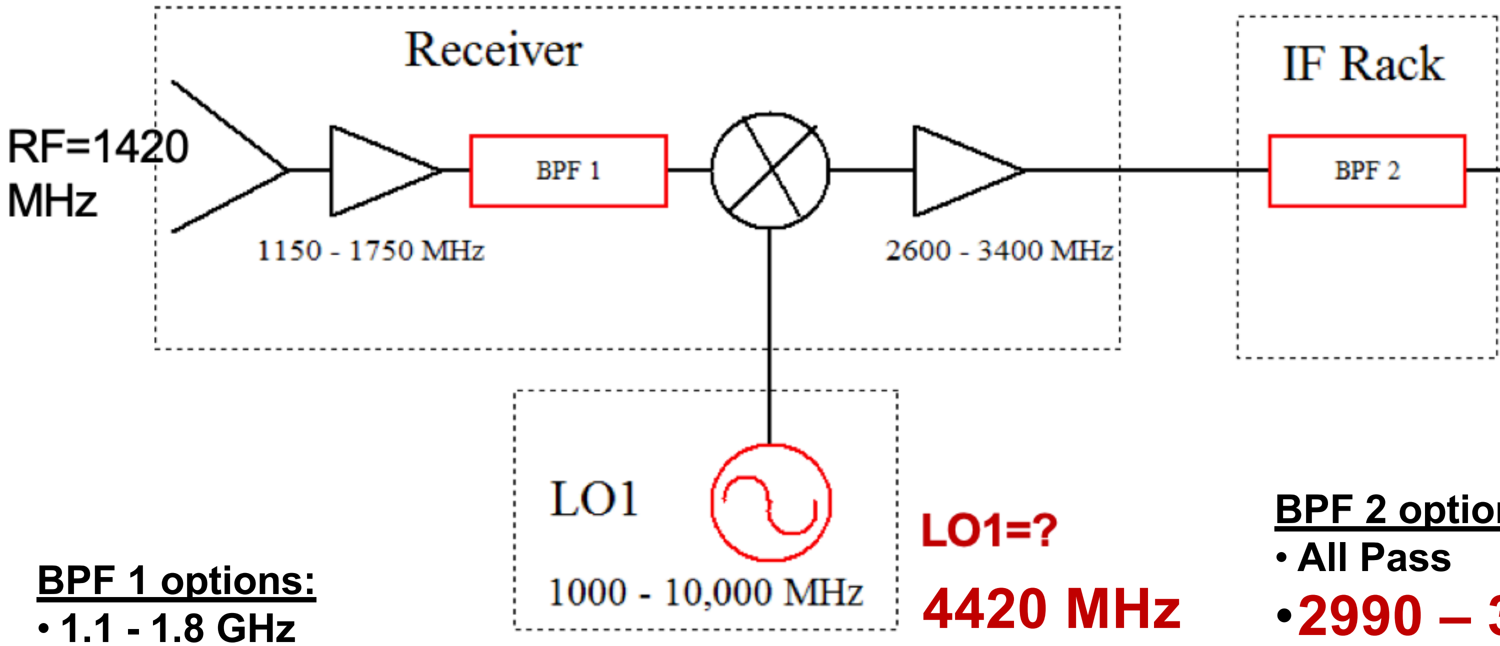
- **1.1 - 1.8 GHz**
- **1.6 – 1.75 GHz**
- **1.3 - 1.45 GHz**
- **1.1 – 1.45 GHz**

BPF 2 options:

- **All Pass**
- **2990 – 3010 MHz**
- **2960 – 3040 MHz**
- **2840 – 3160 MHz**
- **2360 – 3640 MHz**
- **5960 – 6040 MHz**
- **5840 – 6160 MHz**
- **5360 – 6640 MHz**

Answers Summary

Questions?



Options
- **3000 MHz**
- 6000 MHz

LO1=?

4420 MHz

BPF 1 options:
- 1.1 - 1.8 GHz
- 1.6 – 1.75 GHz
- **1.3 - 1.45 GHz**
- 1.1 – 1.45 GHz

BPF 2 options:
- All Pass
- **2990 – 3010 MHz**
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- 5840 – 6160 MHz
- 5360 – 6640 MHz

GREEN BANK OBSERVATORY

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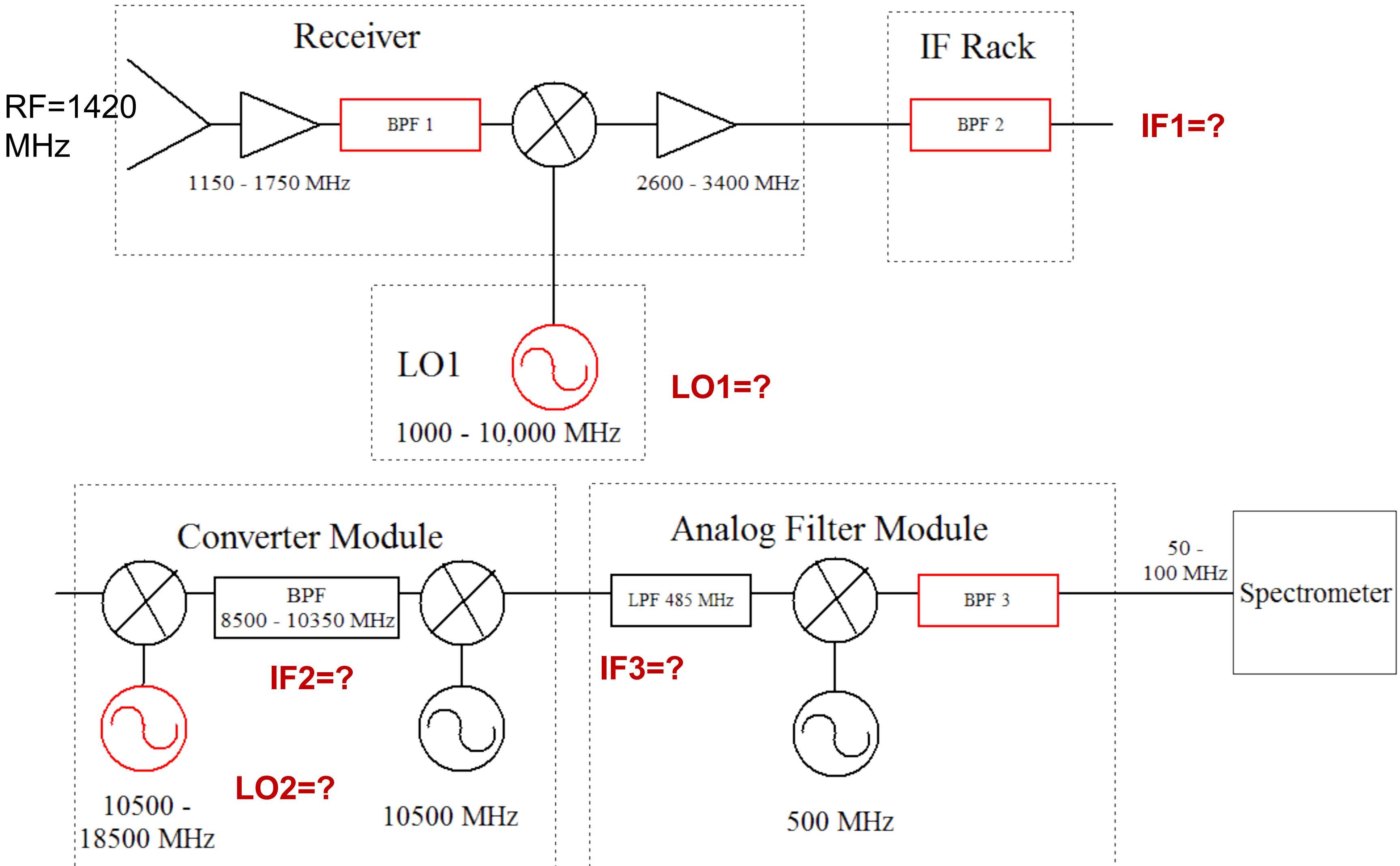
Previous Harder Quiz

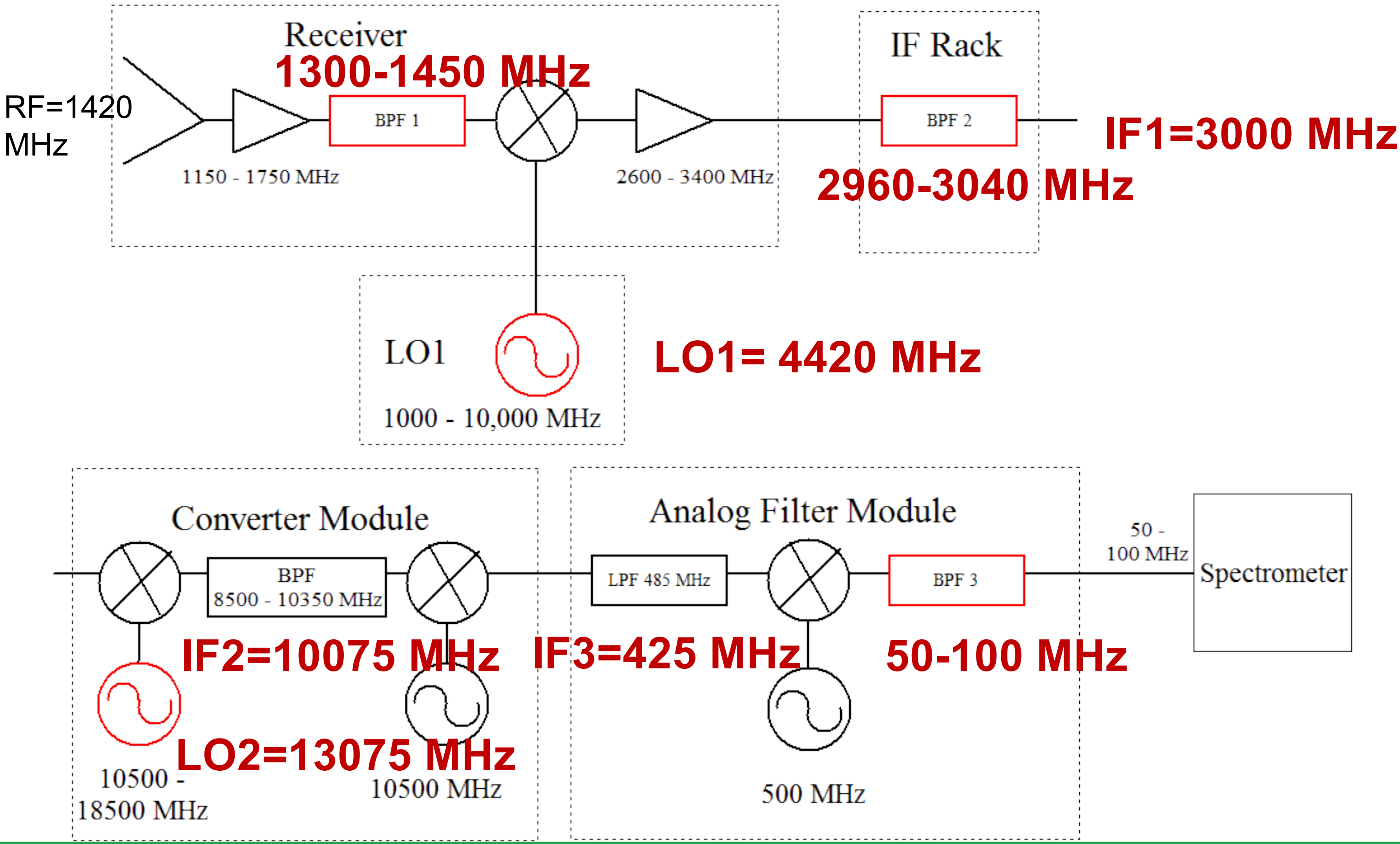
Quiz

- 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

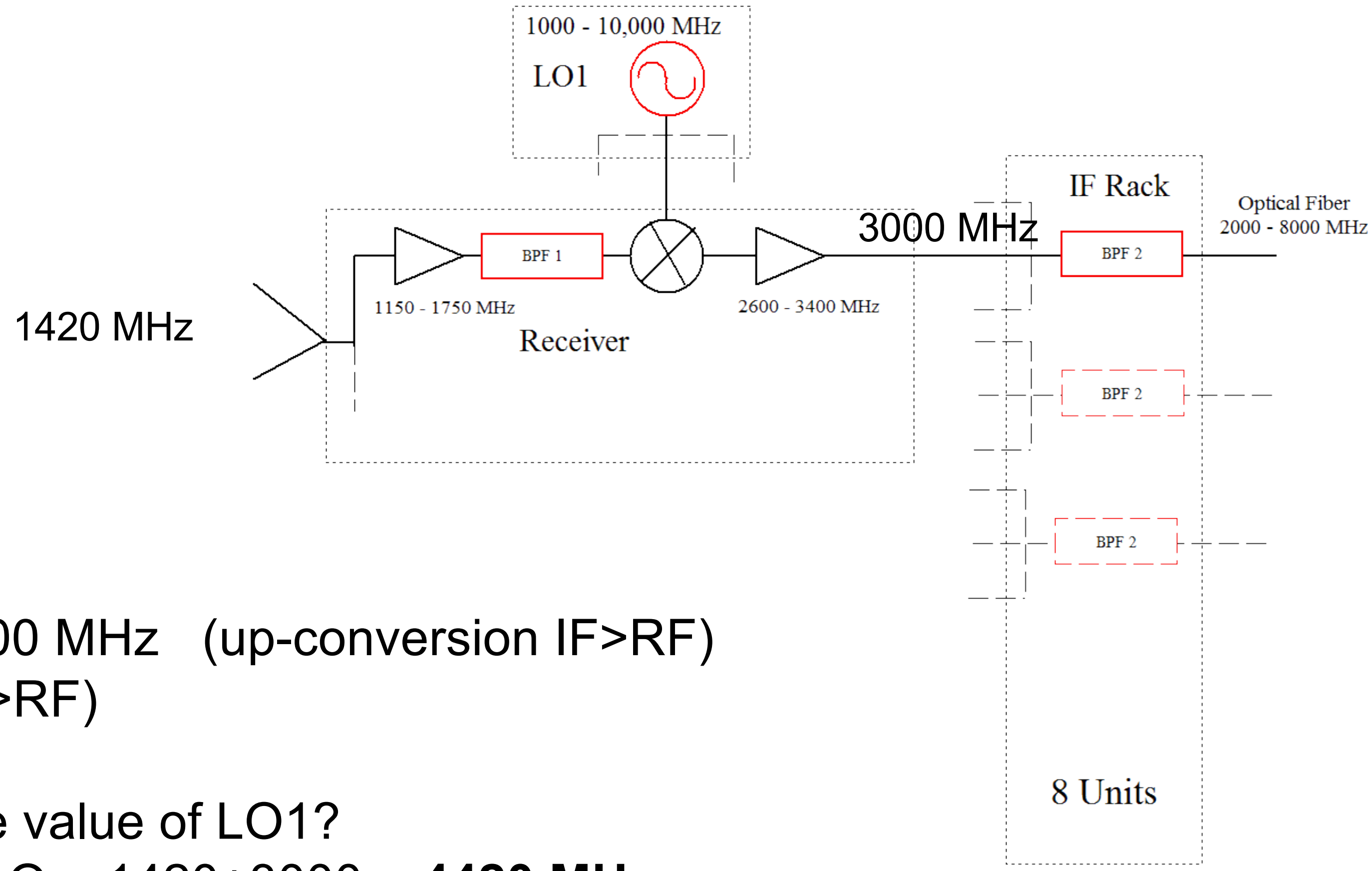
"Ron's" Famous Tracing the Signal Quiz:
Derive the values for the Red Components



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



GBT L-band Example

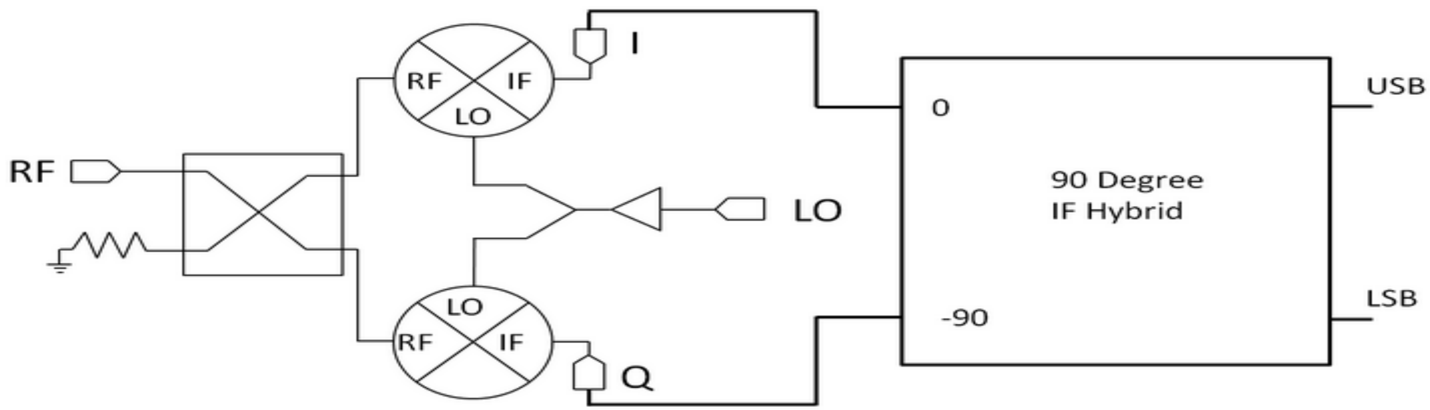


RF=1420 MHz
IF centered on 3000 MHz (up-conversion IF>RF)
Mixer is LSB (LO>RF)

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.

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.

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

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

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

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