“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

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Surface RMS/Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>GBT</td>
<td>2.3e-6</td>
</tr>
<tr>
<td>ALMA</td>
<td>2.0e-6</td>
</tr>
<tr>
<td>VLA</td>
<td>2.0e-5</td>
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<tr>
<td>VLBA</td>
<td>1.4e-5</td>
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<tr>
<td>NGVLA</td>
<td>~1.0e-5</td>
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</table>
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)”)
Stages in (Heterodyne) Detection / Analysis

- **Gather** the radiation
- **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
- **Transmit** the signal to the “backend”
- **Analyze** the signal in the backend

Antenna

Frontend Receiver

I.F. (Intermediate Frequency) System

Backend

Spectrometer
Parts of the system

- Feed
- Cold Electronics
- Warm Electronics
- I.F. Electronics
- I.F. Electronics
- Spectrometer
- Receiver
- Frontend
- IF
- Backend
- Rx cabin
- 2km fiber
- Jansky Lab

Green Bank Observatory

NSF

Associated Universities Inc.
Instrumentation Chain

Receiver

IF system

Backend

Local Oscillator
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
<table>
<thead>
<tr>
<th>Receiver</th>
<th>Band</th>
<th>Frequency Range (GHz)</th>
<th>Focus</th>
<th>Polarization</th>
<th>Beams</th>
<th>Polarizations per Beam</th>
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<tbody>
<tr>
<td>PF1</td>
<td>342 MHz</td>
<td>0.290-0.395</td>
<td>Prime</td>
<td>Lin/Circ</td>
<td>1</td>
<td>2</td>
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<tr>
<td></td>
<td>450 MHz*</td>
<td>0.385-0.520</td>
<td>Prime</td>
<td>Lin/Circ</td>
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<td>2</td>
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<td></td>
<td>600 MHz*</td>
<td>0.510-0.690</td>
<td>Prime</td>
<td>Lin/Circ</td>
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<td></td>
<td>800 MHz</td>
<td>0.680-0.920</td>
<td>Prime</td>
<td>Lin/Circ</td>
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<td>2</td>
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<td>PF2*</td>
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<td>0.910-1.23</td>
<td>Prime</td>
<td>Lin/Circ</td>
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<td>1.15-1.73</td>
<td>Greg.</td>
<td>Lin/Circ</td>
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<td>2</td>
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<td>Lin/Circ</td>
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<td>Ka-Band</td>
<td>MM-F1</td>
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<td>Circ</td>
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<td>Q-Band</td>
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<td>Circ</td>
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<td>2</td>
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<td>W-Band 4mm</td>
<td>MM-F1</td>
<td>67-74</td>
<td>Greg.</td>
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<td>85-93.3</td>
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<td>Mustang2</td>
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<td>80-100</td>
<td>Greg.</td>
<td>—</td>
<td>200</td>
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<td>ARGUS</td>
<td></td>
<td>80-115.3</td>
<td>Greg.</td>
<td>Circ</td>
<td>16</td>
<td>1</td>
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</table>
Typical Components in System Block Diagrams:

- Amplifiers
- Mixers
- Attenuators
- Power Detectors
- Synthesizers
- Multipliers
- Splitters
- Couplers
- Filters
- Switches
Types of Filters

- Band Pass Filter
- Low Pass Filter
- High Pass Filter
- Notch Filter

Edges are smoother than illustrated
Types of Mixers

- $n$ 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: $f_{LO} < f$

$f_{IF} = n*f_{LO} + m*f$
Example "Down Conversion" Mixing

Example "Down Conversion" Mixing

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

USB = LO + IF
LSB = LO - IF

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

IF1 = 1.525 GHz
LO2 = 11.275 GHz

IF2 = 9.75 GHz

IF3 = 0.75 GHz

LO2 is tuneable
Up convert

Output to VEGAS;
usable bandwidth 0.15-1.4 GHz
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?

**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

**Options**
- 3000 MHz
- 6000 MHz
Answers (BPF 1)

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

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

**LO1 options:**
- 1000 - 10,000 MHz

**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

**Options**
- 3000 MHz
- 6000 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.

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

Options
• 3000 MHz
• 6000 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.

**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

**BPF 1 options:**
- 1150 - 1750 MHz
- 2600 - 3400 MHz

**BPF 2 options:**
- IF1 = ?
- Options
  - 3000 MHz
  - 6000 MHz

**LO1 options:**
- 1000 - 10,000 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.

**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

**Options**
- 3000 MHz
- 6000 MHz
Answers Summary

Questions?

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

Options
• 3000 MHz
• 6000 MHz

RF=1420 MHz

IF Rack

BPF 1

1150 - 1750 MHz

2600 - 3400 MHz

LO1

1000 - 10,000 MHz

4420 MHz

LO1=?

BPF 2

IF1=?
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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

RF = 1420 MHz

LO1 = ?

LO2 = ?

LO3 = ?

RF = 1420 MHz

BPF 1: 1150 - 1750 MHz

BPF 2: 2600 - 3400 MHz

IF1 = ?

IF2 = ?

BPF 3: 50 - 100 MHz

Spectrometer

BPF 1: 8500 - 10350 MHz

BPF 2: 10500 MHz

BPF 3: 500 MHz
**Answers** (Note: most folks regardless of experience will mess this up which is why the configuration choices are done in software for our users....):

RF = 1420 MHz

Receiver

1300-1450 MHz

BPF 1

IF1 = 3000 MHz

IF Rack

2960-3040 MHz

LO1 = 4420 MHz

1000 - 10,000 MHz

Converter Module

IF2 = 10075 MHz

LO2 = 13075 MHz

10500 - 18500 MHz

10500 MHz

Analog Filter Module

IF3 = 425 MHz

50-100 MHz

LPF 485 MHz

BPF 3

500 MHz

Spectrometer
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  \( \Rightarrow \)  \( LO = 1420 + 3000 = 4420 \text{ MHz} \)

USB mix does not work: RF(USB) = 1420 MHz = LO + IF  \( \Rightarrow \)  \( LO = -1580 \text{ MHz} \) 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.

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

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

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

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