IF/LO Systems for Single Dish Radio Astronomy Centimeter Wave Receivers

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Abstract. Radio astronomy receivers designed to detect electromagnetic waves from faint celestial sources used on single dish centimeter wave telescopes represent a specialized class of microwave receivers. In this paper the principal features and main stages of these receivers are explained with attention to the second stage: the IF/LO (intermediate frequency / local oscillator) system. Description, functionality and basic analysis of mixers and local oscillators are then detailed and the IF/LO systems of NRAO's GBT and Arecibo's Gregorian dome are analyzed.

1.1.1 Introduction to Receivers

Receivers function to amplify, filter and shift in frequency if needed, electromagnetic waves from extremely low-level noise powers produced by faint celestial sources. Radio astronomy receivers' characteristics make them unique as they are usually, but not always: coherent, low-noise, dual channel, have high dynamic range and use specialized back end instruments.

1.1.1 **Coherency**: the phase is preserved as the signal travels through the receiver, up to the backend. The output of such coherent receivers allows full reconstruction of the wave field.

2.1.1 **Low noise** systems are necessary to attain high sensitivity. The parameter T is proportional to the minimum detectable signal. In order to improve this parameter, the system temperature, T_{sys} can be reduced by means of utilizing cryogenically cooled low-noise amplifiers and front end components. Increasing the pre-detection bandwidth, B as much as practical and the integration time all contribute to improving the sensitivity of the receiver. $T = \frac{T_{sys}}{\sqrt{B}}$

3.1.1 **Dual channels** display orthogonal polarizations, and if combined, can double the signal strength and reduce the noise by a factor of $\sqrt{2}$. This provides the ability to do polarization measurements.

4.1.1 **Dynamic range** defines the range between extreme inputs: minimum signal when the telescope is pointed at cold sky and the maximum signal possible without saturating the receiver. The greater this range the more likely the receiver will be able to accurately reproduce small signals faithfully in the presence of strong interfering signals.

The receiving system must be able to distinguish small changes in signal output power when a source is introduced in the antenna beam. Fluctuations in signal level at the output of the receiver are a combination of source noise, antenna spillover, receiver noise and spurious gain fluctuations within the active components.

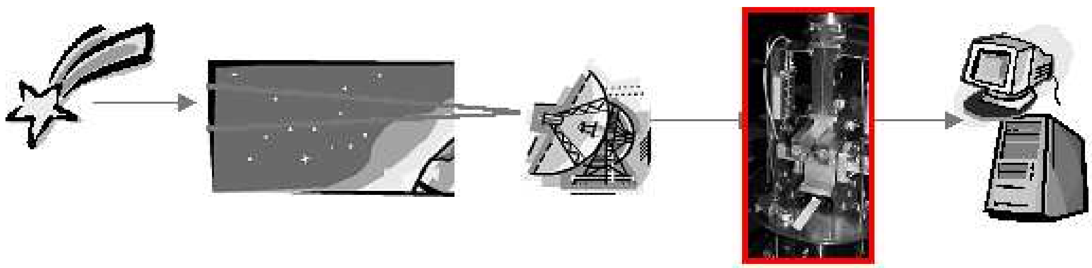

Figure 1 Starting with the celestial object, the radiated electromagnetic signal is seen through vast interstellar regions before finally raining down into the antenna. After focusing and amplifying, the signal is passed through a receiver which further amplifies, frequency selects and shifts so that it can be processed in an application specific back and and recorded.

1.1 Front End Stage

Generally the front end refers to the receiver components up to and including the first frequency shifting (mixing) stage, including the feed horn, orthomode transducer (polarizer), noise calibration coupler, low noise amplifier, band defining filter and often the first mixer. The front end components are highly frequency specific and thus are unique to each band. By using a mixer, the various RF (radio frequency) front ends can be brought together to a common IF/LO frequency chain, thus allowing the components and costs to be shared.

Due to the low power signals typically encountered, the receiver's noise performance is a critical parameter. Since the overall system noise performance is established by the high gain first stages, it is the front end noise which must be minimized. Much effort has therefore been expended to development of parametric amplifiers, maser amplifiers, cryogenic Schottky mixers, super conducting tunnel junction mixers and cooled FET amplifiers.

1.2 IF/LO Stage

Following the front end stage, the IF/LO (intermediate frequency / local oscillator) section is loosely defined, but may include any of the following preceding the back end stage:

5.1.1the first, second and possibly third mixing stages

6.1.1additional amplification and filtering as needed

7.1.1options for power monitoring and adjusting power levels

8.1.1transmission of the signal for long distances on fiber optic cable

9.1.1distribution system to the many backend systems available

1.3 Back End Stage

Colloquially termed "back end", these instruments take the dual-channel output of the IF/LO stage; usually a lower frequency version of the signal and apply it to various instruments depending on the type of astronomical observation. These instruments function specifically for spectral, polarization, timing or pulse analysis. Simple total power measurements are accomplished using a square law detector followed by an integrator using digital or analog techniques. For spectral line observations the signal is further mixed down to a frequency band near 0 Hz and is passed into an auto-correlation or FFT spectrometer. For pulsar observations the signal is either passed into a spectrometer or to special purpose 'pulsar machines'.

2.1.1IF/LO Systems - Components and Functions

The typical IF/LO system can be modeled as a combination of mixing, amplifying, power monitoring, and transmission stages as shown in Figure 2. The front end components; feed, polarizer, low noise amplifier, have been included, and also the back end stage.

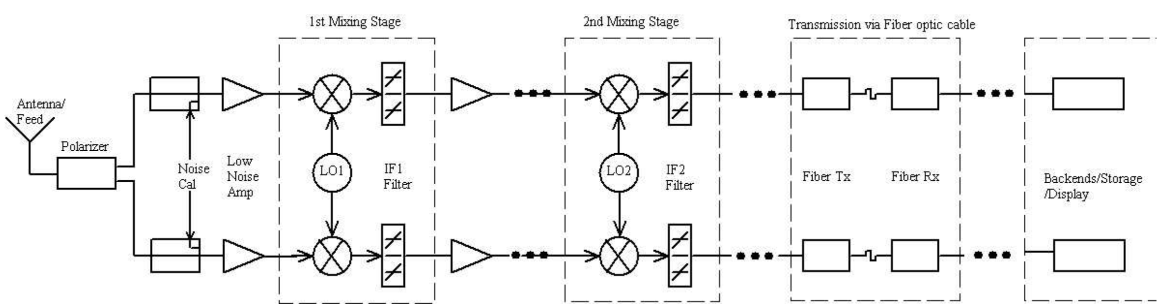

Figure 2 Sample receiver showing front end components, various options for the IF/LO system and backends

2.1 Mixers & Frequency Shifting

Mixers provide the ability to shift the frequency band in a receiver. This frequency translation is often called frequency conversion or mixing, as the radio frequency (RF) signal is combined, or "mixed" with a local oscillator (LO) signal. Mixers are three-port devices, one input RF, one input LO, and one output IF (intermediate frequency) port. There are many spectral components at the output of a mixer, but the products most commonly used are the sum and/or difference frequencies of the input signals. These sum and difference frequencies $\ _{IF\ 1,2} = |\ _{RF} \mp \ _{LO}|$ are shown in Figure 3, and the envelope impressed on the two IF frequency bands carrying the information is unchanged by the mixing operation. The filter on the IF port chooses the desired output band, in this case IF_1.

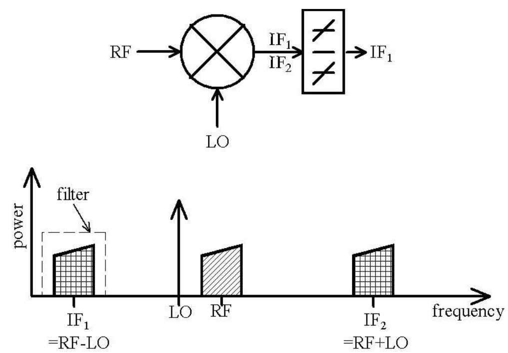

Figure 3 Mixing inputs and outputs showing sum and difference frequencies and effect of output filtering. Top: circuit elements, bottom: frequency spectrum

Why use mixers in a receiver?

10.1.1Power loss in lengths of coaxial cable is less at lower frequencies. Fiber optic cable is now commonly used for long distances, as it has extremely low loss.

11.1.1The possibility of feedback is minimized if the IF amplifiers, which provide most of the gain in the receiver, are at a different frequency than the RF frequency. This prevents small amounts of power leaking into the low noise amplifier and producing unwanted oscillations.

12.1.1Standard IF/LO paths and backends can be used if the front ends are mixed to a common IF frequency.

13.1.1High gain low noise amplifiers and filters are simpler to construct at lower frequencies.

Mixers form products of the input RF signal and LO signal. The non-linear combination of multiplication produces new signals at the shifted frequencies. The combination of RF and LO signals produce: $\sin(\ _{RF}\, t)\sin(\ _{LO}\, t) = \frac{1}{2}\left[\cos(\ _{RF} - \ _{LO})\, t - \cos(\ _{RF} + \ _{LO})\, t\right]$, components at frequencies of $n\,{}_{RF} + m\,{}_{LO}$ where $n\,,m$ are integers and a DC component. A filter placed after the mixer selects the desired band and attenuates the undesired band.

The same IF band can be produced by setting the LO frequency either above or below the RF band. Figure 4 shows the situation where the LO is below the RF frequency, creating an "image" band below the LO so that ${}_{RF\,,\,image} = {}_{LO} \pm {}_{IF}$. In this example, the image band is the lower sideband (LSB) and the desired band is the upper sideband (USB). If no filtering is applied, both the USB and LSB will be superimposed to form the output IF band. This is called double sideband operation. If this is not desired, the image frequency must be removed prior to the mixing stage, resulting in single sideband operation.

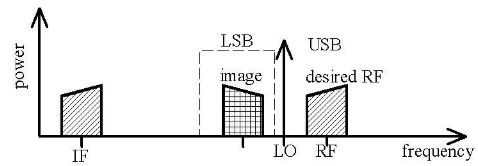

Figure 4 The image frequency problem

2.2 *Local Oscillators (LO)*

Local oscillators produce continuous wave signals used as inputs to mixers to shift the frequency of the RF signal. Oscillators used for radio astronomy are usually locked to a site frequency/time standard such as a hydrogen maser to ensure high accuracy and long term stability.

2.2.1 Local Oscillator Types

Local oscillator signals may be generated by, but not limited to, the following techniques:

14.1.1**Gunn oscillators** take advantage of the solid state phenomenon called the Gunn effect. A detailed description can be found in Streetman (1990[1], and in summary, it is a form of a negative-resistance oscillator. The two-port semiconductor device acts as a source of negative resistance, which when coupled to a resonant circuit forms a useful microwave oscillator. The frequency can be tuned to some degree by varying the input DC voltage and have a long operating life.

15.1.1**Crystal oscillators** use the mechanical oscillation of a quartz crystal. They are used in circuits that have more stringent requirements than a usual LC oscillator for frequency stability. These are usually used in phase-lock loops to lock a house atomic standards.

16.1.1**Frequency multiplication** is often used when high LO frequencies are desired, a Gunn or crystal oscillator can be used to drive a nonlinear circuit element such as a diode. The waveform that results has many harmonics of the input fundamental frequency. A bandpass filter can filter out the desired harmonic.

Frequency synthesizers are signal generators that can be tuned to a discrete set of frequencies and their stability is set from a precise frequency standard as outlined in the next section. Generally, synthesizers have high frequency resolution, better than 1 Hz nominally. Direct synthesis involves frequency multipliers, dividers and mixers. Indirect synthesis uses phase locked loops.

2.2.2 LO Requirements

High Spectral Purity: Ideally local oscillator signals are a pure sine wave, but realistically they will have noisy "wings" on either side of the tone in the frequency spectrum. These wings are due to phase noise and can be reduced to a certain point.

Frequency Agility: The oscillator must be frequency agile in order to allow for the RF band center and subsequent IF band centers to be specified. The switching speed of the oscillator may be critical in systems utilizing frequency switching.

Small Increments in Frequency: Many commercial local oscillators today have the ability to move in small frequency increments, to finely adjust the position of the RF and IF bandpasses.

Ideally the LO spectrum should be a narrow carrier in the frequency domain; a pure sinusoid in the time domain, but realistically there will be extra noise power that broadens the carrier. It is desired to reduce these noisy sidebands, as they could mix with the incoming signal to produce false output signals. At times it can be useful to use a switching LO waveform.

2.2.3 LO Phase Stability

Changes in the local oscillator frequency can be attributed to such systematic parameters as changes in temperature, humidity, vibration, component aging, power supply variations and load variations. These are primarily responsible for the long-term stability of the oscillator and most of these can be controlled to a degree. The short-term stability is directly proportional to the circuit Q^2. This is one reason for using high-Q circuits in oscillators, another is the ability of the tuned circuit to filter out undesired harmonics and noise.

2.2.4 Precise Frequency Standards

Oscillators have been improving over time, from the invention of the quartz crystal oscillator in the 1920s to atomic frequency standards in the 1950s with the introduction of cesium-beam clocks and later hydrogen maser clocks. Atomic frequency standards --

rubidium, cesium and hydrogen maser clocks are based on the detection of an atomic or molecular resonance. These atomic standards use crystal oscillators that are phase locked to the atomic process, to improve the short term stability performance. The crystal oscillator's spectral purity affects the performance of the phase-locked loops involved in generating the local oscillator signal.

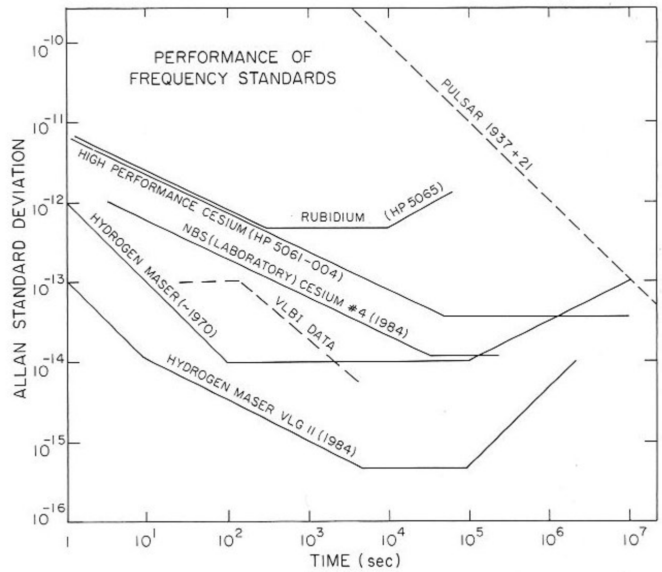

Figure 5 Idealized performance of various frequency standards and other systems. From Thompson et al 1986[3]

The Allan variance, a measure of the stability of the oscillator, of the standards shown in Figure 5 are somewhat idealized, but the clear superior performance of the hydrogen maser as a frequency standards vs cesium and rubidium can be seen.

3.1.1IF/LO Systems in Practice - GBT and Arecibo

Two systems that you'll likely need to use as observers, and will benefit from understanding are the IF/LO systems of the GBT and Arecibo.

3.1 GBT IF/LO System

The GBT receiver and IF/LO system is shown in Figure 6. The receiver front ends are located at the receiver room (and prime focus location) and are mixed down to a first IF. From there the IFs feed into the IF Router located on the turret's center post and then onto optical fiber to be sent down off the telescope and into the Equipment Room in the Jansky Building. At the Equipment Room, the optical receiver modules transfer the signal back onto coaxial cable and then into the Converter Rack which mixes the signals up to about 9.5 GHz and then back down to a third IF with output ports for various backends.

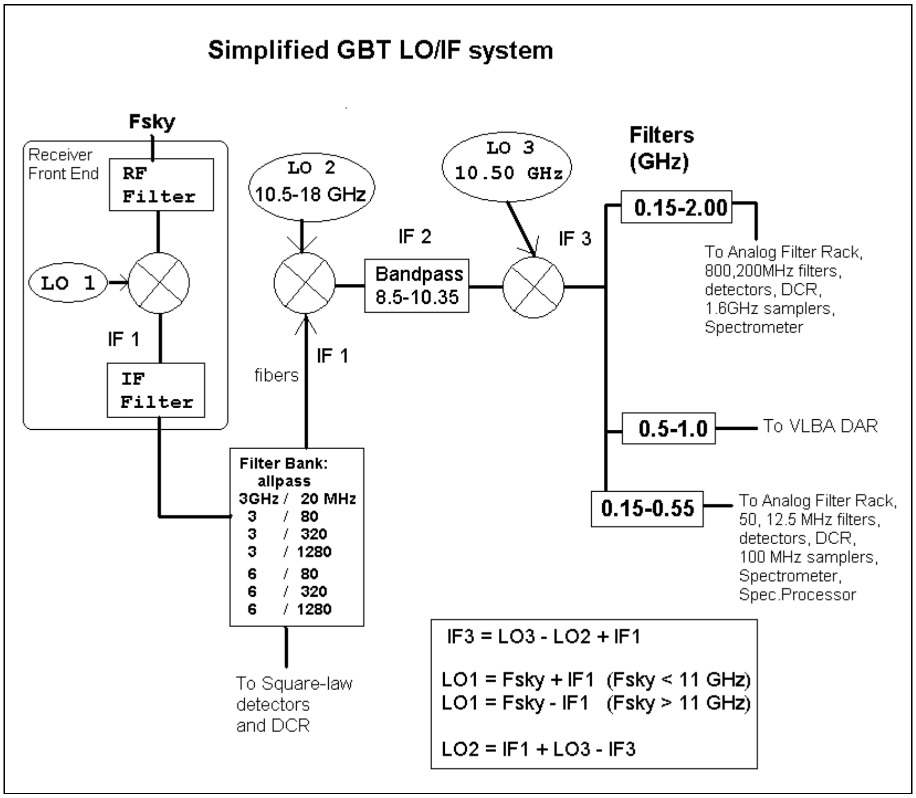

Figure 6 Functional block diagram of NRAO Green Bank's GBT IFLO system, found at http://www.gb.nrao.edu/~fghigo/gbtdoc/loif.html

The GBT visual observing software CLEO is an intellectual treat for nerdy engineers and astronomers. The display of the Converter Rack shown in Figure 7 shows very clearly the setup for the second and third mixing stages. Easy monitoring and control is available for the converter rack inputs, the second LO level and frequency, variable power level control, desired backend and much more.

Initial CLEO Converter Rack Screen:

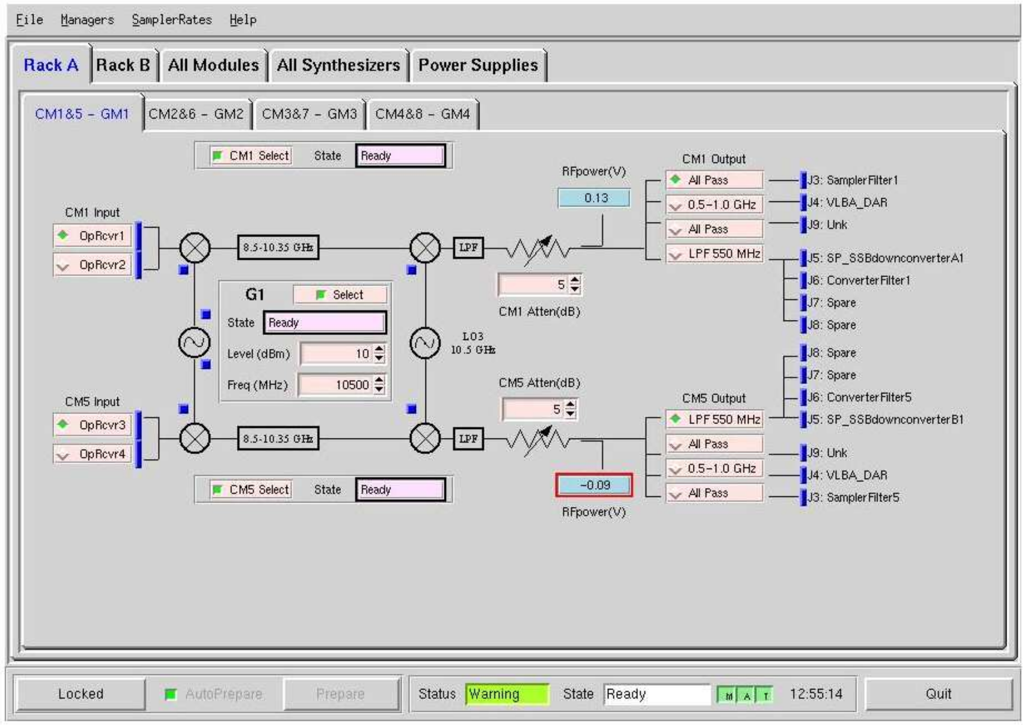

Figure 7 Screen capture of the CLEO converter rack screen of NRAO's GBT receiver control software, obtained from <u>http://www.gb.nrao.edu/~rmaddale/CLEOManual/applications/converterrack.html</u>

3.2 Arecibo's Gregorian Dome IFLO System

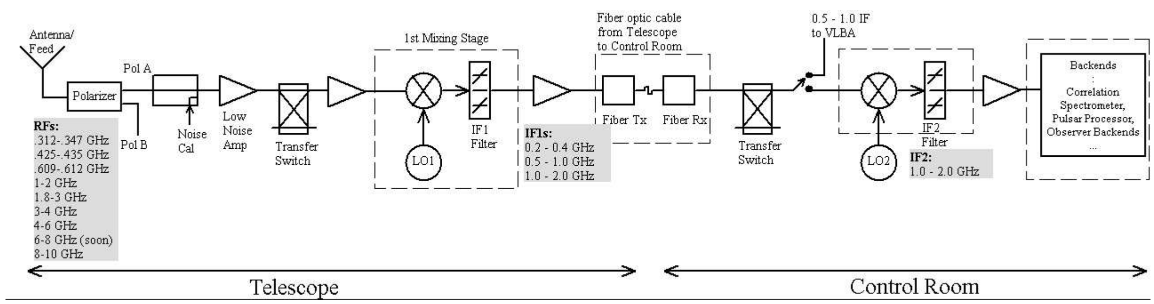

Figure 8 Functional block diagram of Arecibo Observatory's Gregorian dome receiver system and downstairs IFLO

Receivers in the Arecibo Observatory's Gregorian dome are selectable on the fly because of a rotating turret floor housed inside the dome. The front ends cover most of the band from 0.3 to 10 GHz, the exact RF bands are noted on Figure 8. After the front end all the signals are switched into a common path including the first mixing stage with a tunable local oscillator. A fiber optic transmitter sends the signal down off the telescope to the control room. An instantaneous bandwidth of up to 1 GHz per polarization is possible. A second mixing stage is available depending on the backend that is chosen. Up to four IF sub-bands can be selected for transmission to the correlation spectrometer or other signal processing equipment. Doppler offsets can be applied at the first and/or second LO.

The current detailed drawing of the Gregorian IFLO system can be obtained at: http://www.naic.edu/~astro/techinfo/iflo/ Included at that webpage is a link to *Setting up the IF/LO*; information for setting up the IFLO system parameters including choosing the LO frequencies and filter choices.

[1] Streetman, B.G. (1990) *Solid State Electronic Devices*, 3rd edn. Englewood Cliffs, NJ: Prentice Hall.

[2] Rohde, U.L. and Bucher, T.T.N. (1988) *Communications Receivers: principles and design*, McGraw-Hill, Inc.

[3] Thompson, A.R., Moran, J.M., Swenson Jr, G.W. (1986) *Interferometry and Synthesis in Radio Astronomy,* John Wiley & Sons, Incl.