Chapter 7

Radio Hardware Theory

The essence of this book is about learning the concepts of radio design, not just copying a recipe for success. This chapter is all theory about how radios work. Once you have an understanding of the principles, you should be able to begin experiments of your own, not necessarily copying a design but modifying a design to work with different components, or to work on a different frequency, for example. Building a known design to start with and getting it working gives you a boost in confidence to carry on and go further. Modifying a design or designing your own gives you a real sense of achievement.

Before looking at how a radio works, the question you may be asking yourself is, "*Why do I have to construct anything? Aren't there lots of radios I can buy ready built?*" It is true there are lots of radios out there, and many could be used for some radio astronomy experiments. But most have disadvantages for radio astronomy, such as narrow bandwidths, automatic gain controls, etc. These features will be covered in the discussions to follow.

A radio telescope is a simple device; often its only task is to measure signal strength, or more exactly to measure received noise power. Usually this involves reducing a high frequency radio signal to a lower, more manageable, frequency and taking the power measurement there. There is no need for complex demodulators and fancy features found in modern receivers. A basic radio telescope will operate at a single frequency (actually a band of frequencies) and may have very few user controls. Even the simplest devices can still be quite effective. Amplification and noise rejection are its main roles. The "signals" received from natural objects such as Jupiter and the Sun are not talking to us, and there is no encoded data. Note I placed the term signals in quote marks to emphasize a point. The definition of signal implies a message is being communicated. This is clearly untrue of natural space radio sources, but because we can study the physics of natural processes by analyzing radio sources, in a twisted way there is information to be had so I will use the term signal in this context. The alternative is to refer to these "signals" as radio noise, but this would be confusing. As astronomers we want to measure the natural radio noise from space but discard the noise generated within our receivers. Not an easy task at times!

The Superheterodyne

To begin looking at how radios work we will concentrate on the superheterodyne. There are simpler designs, but the superhet, as it is often known, is by far the best

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for our purposes. The word "heterodyne" refers to the way two signals are mixed together to form a new frequency, or beat frequency, which is usually but not always lower in frequency than the radio channel.

It is helpful to break down the design of radios, or any electronic circuits, into blocks or modules. These blocks are self contained and could be built independently of the rest of the system. In fact it is recommended to do it this way. By building a radio as separate modules, possibly even in separate screened boxes, it makes it much easier to modify the system later to, say, change the frequency range it covers, or to improve its rejection of unexpected out of band interference, etc. The block diagram is shown in Fig. 7.1.

The items to the left of and including the mixer are known as the "front end." The filter and the mixer are usually combined together into the same board or housing. The filter is needed to remove unwanted mixer products.

The RF amplifier's job is to boost the signal received by the antenna and is often mounted as close to the antenna as possible. There may or may not be an additional stage of amplification before the mixer within the main receiver. A broad band RF amplifier is known as a preamplifier, but in practice filters may be combined with the RF amp to reject unwanted out of band signals interfering with the system. It is then better described as a preselector.

In more sophisticated radios the RF stage may include tunable filters in the preselector that track the required frequency as the system is tuned. Making tunable front ends is beyond the scope of these projects, but it is relatively straightforward to build fixed filters to preselect a required band. Filter design will be covered later.

The mixer stage involves combining the radio signal with an artificially generated sine wave from the local oscillator (LO). Mixers are non linear devices. They generate output frequencies that are the sum and difference of the RF and LO signals. Mixers that are unbalanced also contain copies of the RF and LO as well as their sum and difference. However, double balanced mixers are recommended because they significantly attenuate the RF and LO signals at the outputs.

As an example, a double balanced mixer fed with a radio frequency of 22 MHz, and mixed with a LO of 21.5 MHz will output signals at 500 kHz and 43.5 MHz. If it

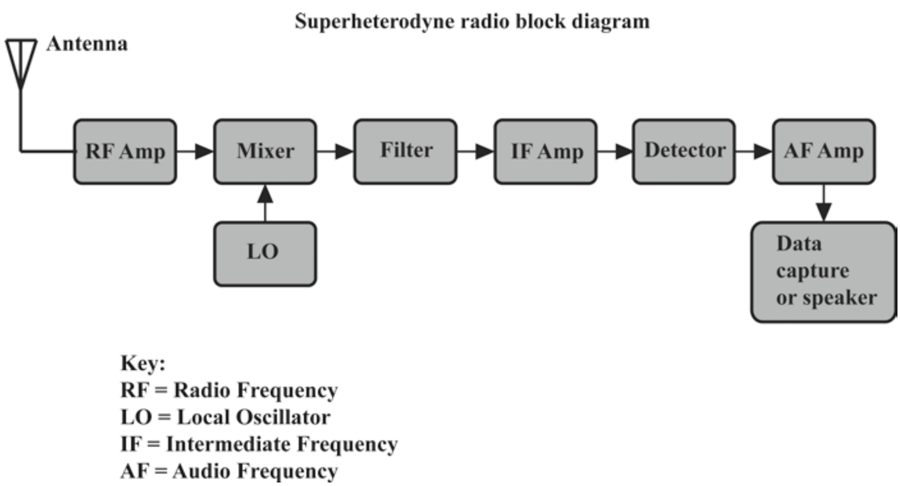

Fig. 7.1. Radio block diagram.

is the lower output that is required the filter following the mixer should be a low pass variety, which blocks the 43.5 MHz product and the original 22 MHz. The actual output of the mixer is more complicated because the local oscillator will produce overtones of its operating frequency at integer multiples of its design frequency. These will also be mixed with the RF signal. So a band pass filter is more often used after the mixer stage to isolate only the output that is required, and attenuate the rest. Even adding a band pass or low-pass filter to the output of the oscillator to select its design frequency may be a good idea to keep the mixer output clean.

At the filter stage it is important to remove unwanted products from the mixer. Practical filter design will be covered later. Refer to Fig. 7.2 to understand the effects of different filters. Filters come in three main types: band pass, low pass, and high pass. Band pass filters allow a selected range of frequencies through to the next stage. Low pass allow low frequencies through while blocking higher frequencies. The high pass is the opposite of this. Filters are designed by deciding where the cutoff must be, and which frequencies need to be blocked. The cutoff points are usually defined as the -3 dB points. This is where the power falls to half of its maximum value. The degree of attenuation at a given frequency is also designed into the filter. In the diagram examples this was set at -40 dB. The difference between this and the −3 dB is known as the stop band. The frequency at which the −3 dB points and stop band points occur define the slope of the filter. If the side slopes are steep the filter is more complex and challenging to build. If the slopes are shallow the filter is simpler and much easier to fabricate.

The IF, or intermediate frequency, amplifier usually does most of the amplification. The mixer is used to reduce the radio channel to the fixed IF. This method makes it easier to design stable high-gain amplifiers that only have to deal with a narrow range of frequencies that don't have to be tuned. It is also much easier to build filters of high quality if the frequency is fixed. Another role of the IF amplifier is to define the band width of the receiver, and to actively reject all those frequencies outside the desired range. In some cases it is desirable to use several different filters in the IF stage, providing a range of receiver band widths. A multi-position switch is used to select the desired one.

The output of the IF unit is a copy of the radio channel, which is translated into frequency. In communications receivers this signal contains a carrier frequency and/or modulated sidebands containing audio information. The detector separates the two, removing the unwanted carrier, leaving an audio signal that can be amplified and heard. In radio astronomy, of course, there is no modulated signal, although the detector can still provide an audio output that will vary with the change in amplitude of the received signal in the same way. It is this variation in amplitude we need to measure, record, and analyze. When dealing with natural radio sources we are in effect measuring the changes in the noise background, which for many objects sounds like the classic hiss. As we shall see later, an alternative to the traditional detector is a logarithmic amplifier. The output of a log amp is a DC voltage whose magnitude is directly proportional to the power of the signal, measured on a decibel scale.

The audio amplifier would follow a traditional detector. In a basic radio telescope the detector would usually be a simple diode, making it effectively an AM or amplitude-modulated receiver. The role of the audio amplifier is to boost the power to the point at which it can drive a speaker. In practice the speaker is not necessary and would be replaced with an integrator or square law detector, which provides a DC output voltage proportional to the received signal amplitude.

This completes the description of a basic receiver suitable for radio astronomy projects. It should be noted at this point that most commercially built receivers include an automatic gain control, or AGC. This provides a voltage derived from

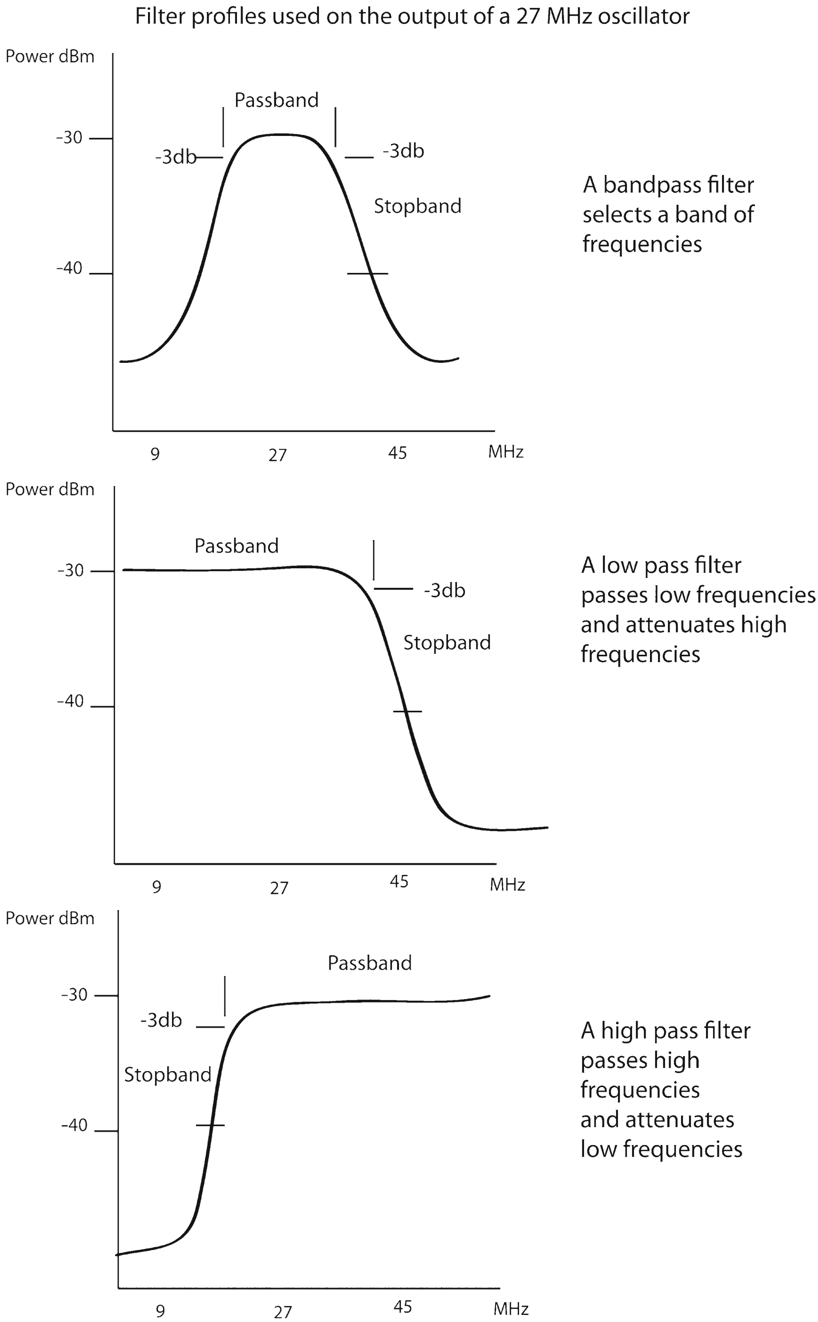

Fig. 7.2. Filter profiles.

the IF stage that controls the gain, or amplification of the RF stage. This is an undesirable feature in a radio telescope. AGC is provided to help smooth out the effects of fading of long-distance communications signals, and to provide constant output level when working between strong and weak channels. Clearly in radio astronomy we are most interested in the difference between strong and weak sources, and in any changes that occur in their strength. Therefore the AGC system should be omitted from the design, and only manual gain control used. Commercial receivers chosen for use in radio astronomy should have the ability to disable the AGC in favor of manual adjustment. A feature of variable bandwidth would be good, too, from narrow – a few kHz – to at least a few tens of kHz.

In the discussion so far we have not mentioned anything about the difference between an AM and FM radio. You will be familiar with these terms from the range of broadcast band receivers on the market. The superheterodyne principle works for all modulation types. Amplitude modulation is where the amplitude of the radio wave is varied and carries the audio information. An FM signal has constant amplitude, but the variation of radio frequency carries the desired audio. It is only the detector stage which differs. FM receivers will not be discussed here, as they are unsuitable for radio astronomy use (except for basic meteor scatter work, which we saw earlier). Other modulation types include single side band (SSB), used by amateur radio enthusiasts. See the Chap. 3 for one use of SSB receivers.

Measurement Scales

When designing or buying a radio for astronomy use there are a number of things to consider in their specifications. Next we will look at the requirements in detail. Before that it is important you understand some of the units of measure used in radio specifications.

Radios need to be very sensitive, in order to handle the tiny input voltages obtained from an antenna. These voltages are measured in nano volts (nV) or micro volts (μV), and the concept of scientific notation of small values is covered in the Chap. 8. However the values of voltage or power are often expressed on a decibel scale.

Consider the input side of a radio (see Fig. 7.3).

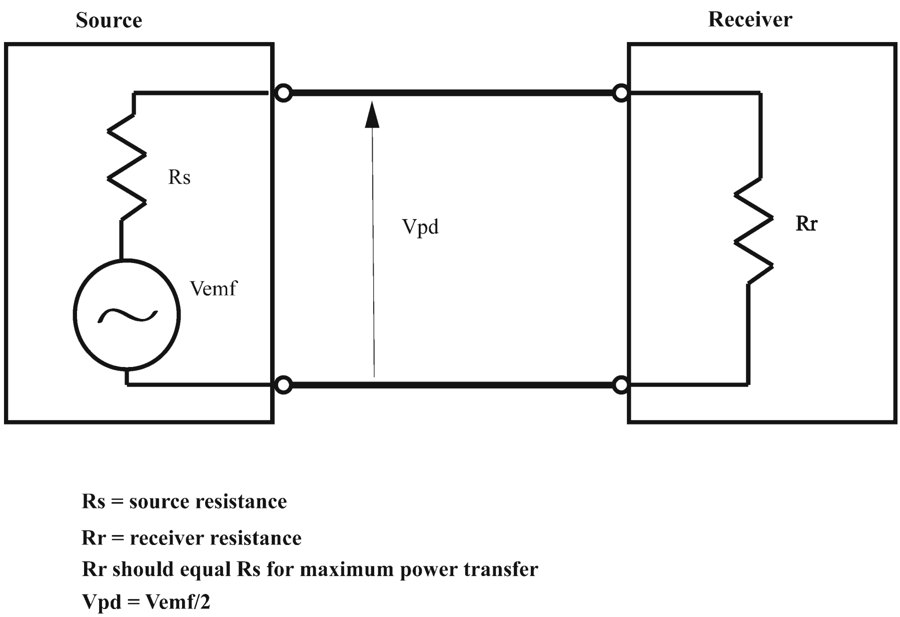

Fig. 7.3. The input side of a radio.

The voltage a source can supply if measured in open-circuit mode will give a value of V_{emf}. However, when connected to the receiver, the resistive impedance of the source and radio should match perfectly (for best performance), in which case the voltage appearing across the input terminals V_{pd} is half of V_{emf} because R_s and R_{in} act as a potential divider.

The dBm Unit

The decibel scale is logarithmic and based on the ratio of two values. Since it is dimensionless (it has no units) it needs to be qualified with a small letter appended to the right. Here dBm is decibels relative to one milliwatt (1 mW) as dissipated across a 50 Ω load. Radio circuits are usually designed to have 50 Ω input impedance. The value of dBm is calculated from the following formula. (Note the power ratio is P mW/1 mW, so the 1 mW is omitted from the formula.)

$$dBm = 10LOG(PmW)$$

where LOG is the base 10 logarithm of the power measured in milliwatts so that the power of 0.5 mW is −3.0 dBm and a power of 2 mW is +3.0 dBm.

Note that if the dBm value is less than 0, the power level is simply less than 1 mW, and if positive it is more than 1 mW. Also note that +3 dB on any decibel scale is double the value, and −3 dB is half. This is useful to remember as bandwidth of circuits is defined by their half power points, the difference between the upper and lower frequency where the power has dropped by 3 dB.

The dBmV

As the name suggests the dBmV is the decibel referred to as 1 mV, but this time it is based on a 75 Ω impedance rather than 50 Ω. It is a unit used in defining specifications of television and video equipment, whose characteristic impedance is usually 75 Ω.

The dBμV

The dBμV is the decibel referred to as 1 μV, across a 50 Ω load. The voltage usually refers to the V_{emf}. In order to convert dBμV to dBm simply subtract 113. Therefore 60 dBμV is −53 dBm.

Noise

It is important to consider the noise performance in any radio, but especially important in radio astronomy. Obviously, if the noise generated within the receiver is higher than that of a radio source, the source will not be visible, right? Wrong! The output of a radio receiver is the sum of all the sources of noise. Even if the system noise is high compared to a weak source, the source still adds a little bit to the output. If the receiver is then switched to detect a known calibrated noise source and the difference is taken between the two, then the system noise cancels out, leaving the value of the weak source relative to your calibration source. In this way weak sources can still be detected. This is not a reason to ignore system noise; it should still be minimized as much as possible.

Noise is generated by all electronic components. Careful design of a radio can minimize the effects. It is the temperature of the components that generates thermal noise, and this is most significant in the first stage of a radio, the RF amplifier. Careful selection of low noise components helps a lot in practical designs. Active devices based on gallium arsenide rather than silicon offer good low noise performance, and it is this material that enabled the easy and cheap direct reception of satellite television for home users. The noise performance is good enough to avoid the need for cooling the front end.

The more the front end amplifier can be kept cool the better it will work. It would not be out of the question to thermally insulate the front end and use a Peltier cooler inside to stabilize the temperature. (Peltier cooling is used in many CCD cameras designed for astronomy.) Although a simple Peltier-based system may not reduce the overall noise performance by much, if temperature regulation was used at least the noise performance should be consistent from one season to the next. Cooling systems will not be discussed in these projects, but it would be an interesting exercise to explore the possibilities later, when you gain some experience.

When mounting an RF amplifier consider its placement. If you are observing the Sun with a dish-based antenna, the worst place for the amp is at the focus of a dish. The heat of the Sun will also be focused there and could even damage the amplifier.

Radio receiver noise performance can be specified using one of three possible methods: the noise factor (Fn), a simple ratio value; the noise figure (NF) on a decibel scale; or the noise temperature (Te) in kelvin:

Noise Factor, Fn

The equation for this is:

$$Fn = \left(\frac{P_{no}}{P_{ni}}\right)$$

where F_n is the noise factor, P_{no} is the output noise power, and P_{ni} is the input noise power.

For comparison purposes the F_n value is given for room temperature, often 21°C. In the brackets the ratio is noise power output of the radio, divided by the noise power input.

Noise Figure, NF

The noise figure is simply the noise factor converted to decibels:

$$NF = 10LOG(Fn)$$

The lower the NF the better the receiver is.

Noise Temperature, Te

Noise temperature is a theoretical concept, and it refers to the noise that would be generated by a resistor raised to the temperature Te. The noise temperature is related to the noise factor by:

$$T_e = (F_n - 1)T_o$$

where F_n is the noise factor, and T_0 is the reference temperature in kelvin (standard room temperature is 290 K).

T_e is related to the noise figure by:

$$T_e = KT_0 LOG^{-1}\left(\frac{NF}{10} - 1\right)$$

where K is the Boltzmann constant, T_0 the reference temperature, and NF is the noise factor.

When cascading modules together in a radio system, the significance of the noise performance of each stage down the chain drops very quickly, so the dominating noise is that of the first stage. The combination of noise performance for all the modules in a radio receiver is given by:

$$F_n = F_1 + \left(\frac{F_2 - 1}{G_1}\right) + \left(\frac{F_3 - 1}{G_1 G_2}\right) + \cdots + \left(\frac{F_n - 1}{G_1 G_2 \ldots G_{N+1}}\right)$$

where F_n is the overall noise factor, and the F_1, F_2, etc., are the noise factors of stage 1 and 2, etc., G_1 and G_2 are the gains of stage 1 and 2, etc.

It is clear from this equation that the dominant noise source is the first stage. The contribution of noise presented by subsequent stages quickly drops to a small value.

Radio Hardware Theory

Sensitivity and Selectivity

Sensitivity refers to how well a radio will respond to weak signals, while selectivity refers to its ability to distinguish between two frequencies close together.

Sensitivity is quoted for radios in micro volts, but it should be referenced by signal to noise ratio in a specified bandwidth. For example an ICOM IC-707 quotes a sensitivity of less than 2.0 μV for a 10 dB signal to noise ratio over the range of 1.8–30 MHz in AM mode. The AM bandwidth for a single channel will be around 6 kHz. If the bandwidth of a channel is reduced, the sensitivity will increase by the square root of the ratio, although wide bandwidths do allow the collection of more power. So there is a tradeoff between received power and sensitivity. If the celestial objects emit radio in a very broad range of frequencies, then increasing the bandwidth will collect more power, and it will be easier to observe the object. However, if the telescope is used to study radio emission lines, broad bandwidth is then undesirable, and a narrow bandwidth will greatly improve the sensitivity.

Selectivity specifications define how great the attenuation is at a given frequency difference. Again the IC-707 states that for AM mode, there is a 6 dB attenuation more than 6 kHz from center frequency, and this increases to 40 dB attenuation at

20 kHz away from center frequency. Note that the specifications will probably show the figures as −6 and −40 dB without mentioning attenuation. The negative sign means loss or attenuation in this case.

Although having a sensitive receiver is important, it is more important to have a good selective receiver. Strong out of band interference is thus reduced or eliminated rather than having a sensitive unit subject to bad noise performance.

Image Rejection

Image frequency is frequency that occurs twice as far away from the radio frequency of interest than the intermediate frequency. Whether that is above or below the channel frequency depends on the local oscillator. In the earlier discussion on mixers it was assumed that the local oscillator had a frequency lower than the radio frequency. It could equally be higher and still provide the same sum and difference outputs. These are referred to as low and high side injection, respectively.

For example, a radio receiver is designed to observe solar flares and Jupiter storms at 22 MHz. The intermediate frequency chosen is 455 kHz because filters are easily obtained for 455 kHz. This means the LO frequency for low side injection is 22–0.455 MHz, or 21.545 MHz.

If there was a strong noise source at a frequency of 2 × 0.455 MHz below the RF frequency, at 21.09 MHz, when mixed with 21.545 MHz, you get an output of 455 kHz and 42.635 MHz. The noise source will pass unimpeded through the system! Note you can't have a negative frequency, so if frequency minus local oscillator is negative then the difference is local oscillator minus frequency

There are a few options open to solve this problem. If you switched to high side injection with an LO of 22.455 MHz the image frequency would now be above the RF channel at 22.91 MHz, which may be clear. Otherwise a different local oscillator frequency must be chosen. Some receivers avoid the problem by using double conversion, first by increasing the RF to a higher first IF, then filtering the required output, and then reducing again to a lower IF.

It is important to understand this concept of image frequency when designing equipment, so go through the numbers above a few times until they are clear.

Third Order Intercept Point, IP3

This refers to intermodulation products (IPs). It's an important parameter, but a bit tricky to explain.

Third order IP products are normally very small when a receiver is operated with normal parameters and will be smaller than the receiver noise floor until the front end is overloaded with a strong signal that saturates the RF amplifier. At this point the amplifier is driven into non-linear operation, generating significant frequency products in a similar way to a mixer. These products then get mixed and enter the signal path as noise.

A given receiver will have a quoted IP3 figure. Refer to Fig. 7.4 for clarification.

Problems occurring where third order intermodulation products are produced are less likely to occur in a radio telescope dealing with weak signals. However to

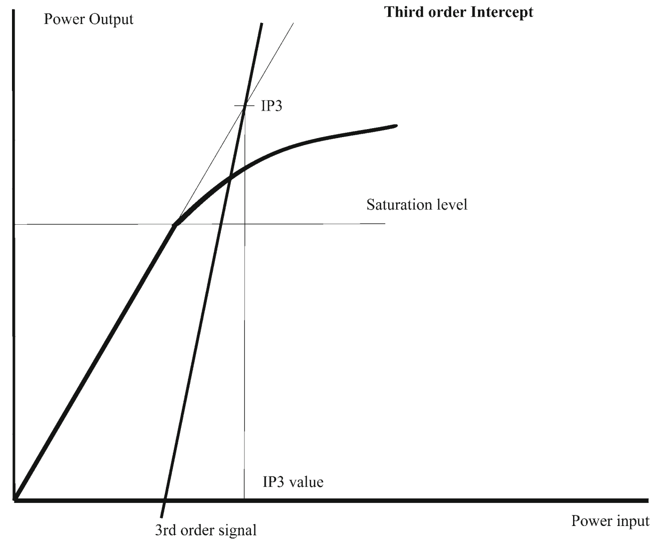

Fig. 7.4. Third order intercept.

stop the problem, an attenuator should be added to the front end, thereby bringing the operation of the front end back into linear operation once again.

For a more in depth description of radio performance the books *Radio Science Observing*, Volumes 1 and 2, by Joseph J. Carr are highly recommended reading.