B. The Super-Heterodyne Receiver

The "super-het" is by far the most popular receiver architecture in use today.

HO: The Super-Heterodyne Receiver

Q: So how do we tune a super-het? To what frequency should we set the local oscillator?

A: HO: Super-Heterodyne Tuning

Another vital element of a super-het receiver is the preselector filter.

HO: The Preselector Filter

Q: So what should this preselector filter be? How should we determine the required order of this filter?

A: HO: The Image and Third-Order Signal Rejection

Q: I have heard of some receivers being described as up-conversion receivers, what exactly are they?

A: HO: Up-Conversion

There are many variants of the basic super-het receiver that can improve receiver performance. HO: Advanced Receiver Designs
The Super-Heterodyne Receiver

Note that the homodyne receiver would be an excellent design if we always wanted to receive a signal at one particular signal frequency \( f_s \):

No tuning is required!

Moreover, we can optimize the amplifier, filter, and detector performance for one—and only one—signal frequency (i.e., \( f_s \)).

Q: Couldn’t we just build one of these fixed-frequency homodyne receivers for each and every signal frequency of interest?
A: Absolutely! And we sometimes (but not often) do. We call these receivers channelized receivers.
But, there are several important problems involving channelized receivers.

→ They’re big, power hungry, and expensive!

For example, consider a design for a channelized FM radio. The FM band has a bandwidth of 108-88 = 20 MHz, and a channel spacing of 200 kHz. Thus we find that the number of FM channels (i.e., the number of possible FM radio stations) is:

$$\frac{20 \text{ MHz}}{200 \text{ kHz}} = 100 \text{ channels}$$

Thus, a channelized FM radio would require 100 homodyne receivers!

Q: Yikes! Aren’t there any good receiver designs!?!?

A: Yes, there is a good receiver solution, one developed more than 80 years ago by—Edwin Howard Armstrong! In fact, is was such a good solution that it is still the predominant receiver architecture used today.

Armstrong’s approach was both simple and brilliant:

**Instead** of changing (tuning) the receiver hardware to match the desired signal frequency, we should change the signal frequency to match the receiver hardware!
**Q:** Change the signal frequency? How can we possibly do that?

**A:** We know how to do this! We mix the signal with a Local Oscillator!

We call this design the Super-Heterodyne Receiver!

A super-heterodyne receiver can be viewed as simply as a fixed frequency homodyne receiver, proceeded by a frequency translation (i.e., down-conversion) stage.

\[ IF_g(t) = \hat{i}(t) \]

\[ F(f = f_{IF}) \approx 1 \]

\[ F(f \neq f_{IF}) \approx 0 \]

\[ f_{IF} = |f_s - f_{LO}| \]

**A Simple Super-Het Receiver Design**
The fixed homodyne receiver (the one that we match the signal frequency to), is known as the IF stage. The fixed-frequency $f_{IF}$ that this homodyne receiver is designed (and optimized!) for is called the Intermediate Frequency (IF).

Q: So what is the value of this Intermediate Frequency $f_{IF}$?? How does a receiver design engineer choose this value?

A: Selecting the “IF frequency” value is perhaps the most important choice that a “super-het” receiver designer will make. It has many important ramifications, both in terms of performance and cost.

* We will discuss most of these ramifications later, but right now let’s simply point out that the IF should be selected such that the cost and performance of the (IF) amplifier, (IF) filter, and detector/demodulator is good.

* Generally speaking, as we go lower in frequency, the cost of components go down, and their performance increases (these are both good things!). As a result, the IF frequency is typically (but not always!) selected such that it is much less (e.g., an order of magnitude or more) than the RF signal frequencies we are attempting to demodulate.

* Therefore, we typically use the mixer/LO to down-convert the signal frequency from its relatively high RF frequency to a relatively low IF frequency.
We are thus generally interested in the second-order mixer term $|f_{RF} - f_{LO}|$.

As a result, we must tune the LO so that $|f_s - f_{LO}| = f_{IF}$ — that is, if we wish to demodulate the RF signal at frequency $f_s$!

For example, say there exits radio signals (i.e., radio stations) at 95 MHz, 100 MHz, and 103 MHz. Likewise, say that the IF frequency selected by the receiver design engineer is $f_{IF} = 20$ MHz. We can tune to the station at 95 MHz by setting the Local Oscillator to $95 - 20 = 75$ MHz:

\[ f_{LO} = 75 \text{ MHz} \]

\[ T(f) \]

\[ f(t) \]

\[ G(f = 20) \gg 1 \]

\[ T(f = 20) \approx 1 \]

\[ T(f \neq 20) \approx 0 \]
Or, we could tune to the station at 103 MHz by tuning the Local Oscillator to 103-20=83 MHz:

Q: Wait a second! You mean we need to tune an oscillator. How is that any better than having to tune an amplifier and/or filter?

A: Tuning the LO is much easier than tuning a band-pass filter. For an oscillator, we just need to change a single value—its carrier frequency! This can typically be done by changing a single component value (e.g., a varactor diode).
Contrast that to a filter. We must somehow change its center frequency, without altering its bandwidth, roll-off, or phase delay. Typically, this requires that every reactive element in the filter be altered or changed as we modify the center frequency (remember all those control knobs!).

Q: What about the IF filter? I understand that its center frequency is equal to the receiver Intermediate Frequency ($f_{IF}$), but what should its bandwidth $\Delta f_{IF}$ be?

A: Remember, we want only one signal (the desired signal we tuned to) to appear at the demodulator, so the IF filter bandwidth should be just wide enough to allow for the desired signal bandwidth $\Delta f_s$. I.E.,

$$\Delta f_{IF} = \Delta f_s$$

Q: What about the filter "roll-off"? How much stop-band attenuation is required by the IF filter?

A: The most problematic signals for the IF filter are the RF signals (e.g., radio stations) on either side of the desired RF signal frequency $f_s$.

These signals in adjacent channels are by definition very close in frequency to $f_s$, and thus are the most difficult to attenuate.
The attenuation of adjacent channels by the IF filter (in dB) defines selectivity of the receiver. Typically this value is between 30 dB and 60 dB.

A 1934 advertisement enticing "men" to enter the glamorous and lucrative field of radio engineering.
Super-Het Tuning

Say we wish to recover the information encoded on a radio signal operating at a RF frequency that we shall call $f_s$.

Recall that (typically) we must down-convert this signal to a lower IF frequency $f_{\text{IF}}$ (i.e., $f_{\text{IF}} < f_s$), by tuning the LO frequency $f_{\text{LO}}$ to a frequency such that this second-order equation:

$$|f_s - f_{\text{LO}}| = f_{\text{IF}}$$

is satisfied.

Note for a given $f_s$ and $f_{\text{IF}}$, there are two possible solutions for the value of LO frequency $f_{\text{LO}}$:

$$f_s - f_{\text{LO}} = \pm f_{\text{IF}}$$
$$-f_{\text{LO}} = f_0 \pm f_{\text{IF}}$$
$$f_{\text{LO}} = f_0 \mp f_{\text{IF}}$$

Therefore, the two down-conversion solutions are:

$$f_{\text{LO}} = f_s + f_{\text{IF}} \quad \text{OR} \quad f_{\text{LO}} = f_s - f_{\text{IF}}$$

In other words, the LO frequency $f_{\text{LO}}$ should be set such that it is:
1) a value $f_{IF}$ higher than the desired signal frequency (i.e., $f_{LO} = f_s + f_{IF}$).

2) or, a value $f_{IF}$ lower than the desired signal frequency (i.e., $f_{LO} = f_s - f_{IF}$).

Note in the first case, the LO frequency will be higher than the signal frequency ($f_{LO} > f_s$). We call this solution high-side tuning.

For second case, the LO frequency will be lower than the signal frequency ($f_{LO} < f_s$). We call this solution low-side tuning.
For example, consider again the FM band. Say a radio engineer is designing an FM radio, and has selected an IF frequency of 30 MHz. Since the FM band extends from 88 MHz to 108 MHz (i.e., $88 \, MHz \leq f_s \leq 108 \, MHz$), the radio engineer has two choices for LO bandwidth.

If she chooses high-side tuning, the LO bandwidth must be $f_{IF} = 30 MHz$ higher than the RF bandwidth, i.e.,:

$$88 \, MHz + f_{IF} < f_{LO} < 108 \, MHz + f_{IF}$$
$$118 \, MHz < f_{LO} < 138 \, MHz$$

Alternatively, she can choose low-side tuning, with an LO bandwidth of:

$$88 \, MHz - f_{IF} < f_{LO} < 108 \, MHz - f_{IF}$$
$$58 \, MHz < f_{LO} < 78 \, MHz$$

**Q:** Which of these two solutions should she choose?

**A:** It depends! Sometimes high-side tuning is better, other times low-side is the best choice. We shall see later that this choice affects spurious signal suppression. In addition, this choice affects the performance of our Local Oscillator (LO).

Let’s look at the last consideration now. We’ll be positive and look at the advantages of each solution:
Advantages of low-side tuning:

For low-side tuning, the LO will operate at lower frequencies, which generally results in:

1. Lower cost.
2. Slightly greater output power.
3. Lower phase-noise
4. Most importantly, lower frequency generally means better frequency accuracy.

Advantages of high-side tuning:

For high-side tuning, the LO will require a smaller percentage bandwidth, which generally results in:

1. Lower cost.
2. Lower phase-noise.

Q: Percentage bandwidth? Just what does that mean?

A: Percentage bandwidth is simply the LO bandwidth \( \Delta f_{LO} \), normalized to its center (i.e., average) frequency:

\[
\% bw = \frac{\Delta f_{LO}}{f_{LO} \text{ center frequency}}
\]
For our example, each local oscillator solution (low-side and high-side) has a bandwidth of $\Delta f_{LO} = 20 \text{ MHz}$ (the same width as the FM band!).

However, the center (average) frequency of each solution is of course very different.

For low-side tuning:

$$\frac{58 + 78}{2} = 68 \text{ MHz}$$

And thus the percentage bandwidth is:

$$\% \text{ bandwidth} = \frac{20}{68} = 0.294 = 29.4 \%$$

For high-side tuning:

$$\frac{118 + 138}{2} = 128 \text{ MHz}$$

And thus the percentage bandwidth is a far smaller value of:

$$\% \text{ bandwidth} = \frac{20}{128} = 0.156 = 15.6 \%$$

A really wide LO bandwidth is generally not specified in terms of its % bandwidth, but instead in terms of the ratio of its highest and lowest frequency. For our examples, either:
\[
\frac{78}{58} = 1.34 \quad \text{or} \quad \frac{138}{118} = 1.17
\]

Again, a **smaller** value is generally **better**.

If the LO bandwidth is **exceptionally** wide, this ratio can approach or exceed the value of 2.0. If the ratio is equal to 2.0, we say that the LO has an **octave** bandwidth (→ **do you see why?**).

**Generally speaking, it is difficult** to build a **single** oscillator with a octave or greater bandwidth. If our receiver design requires an octave or greater LO bandwidth, then the LO typically must be implemented using **multiple oscillators**, along with a microwave **switch**.

For example, an LO oscillator with a bandwidth from 2 to 6 GHz might be implemented as:

\[
\begin{align*}
2 \text{ GHz to } 3.5 \text{ GHz} \\
3.5 \text{ GHz to } 6.0 \text{ GHz}
\end{align*}
\]
Q: You said that a lower frequency LO would provide better accuracy. Why is that? I thought that long-term stability (in ppm) would be relatively constant with respect to LO frequency.

A: Expressed in parts-per-million (ppm), it is!

But recall that ppm is essentially a percentage (i.e., geometric) error, whereas the importance value for receiver design is the absolute (i.e., arithmetic) error in Hz!

Again consider the example. Say each LO solution (high-side and low-side) has a stability of ±1.0 ppm (i.e., 1 Hz/MHz).

For the low-side solution, this means an absolute error $\varepsilon_{LO}$ of:

$$\varepsilon_{LO} = 68 \text{ MHz} \left( \frac{\pm 1 \text{ Hz}}{\text{MHz}} \right) = \pm 68 \text{ Hz}$$

Whereas for high-side, the error is:

$$\varepsilon_{LO} = 128 \text{ MHz} \left( \frac{\pm 1 \text{ Hz}}{\text{MHz}} \right) = \pm 128 \text{ Hz}$$

The high-side solution has nearly twice as much error!

Q: How much LO accuracy do we need?
A: Remember, the LO must convert the desired RF signal to precisely the receiver IF frequency. If we are “off a little” then all or part of the desired signal might miss some of the narrowband IF filter!

A designer “rule of thumb” is that the absolute LO error must be less than 10% of the IF filter bandwidth:

\[ \varepsilon_{LO} < 0.1 \Delta f_{IF} \]
The Preselector Filter

Say we wish to tune a super-het receiver to receive a radio station broadcasting at 100 MHz.

If the receiver uses and IF frequency of $f_{IF} = 30$ MHz, and uses high-side tuning, we must adjust the local oscillator to a frequency of $f_{LO} = 130$ MHz.

Thus, the desired RF signal will be down-converted to the IF frequency of 30 MHz.

But beware, the desired radio station is not the only signal that will appear at the output of the mixer at 30 MHz!
Q: Oh yes, we remember. The mixer will create all sorts of nasty, non-ideal spurious signals at the mixer IF port. Among these are signals at frequencies:

1\textsuperscript{st} order: \( f_{RF} = 100\,MHz, f_{LO} = 130\,MHz \)

2\textsuperscript{nd} order: \( 2f_{RF} = 200\,MHz, 2f_{LO} = 260\,MHz, \quad f_{RF} + f_{LO} = 230\,MHz \)

\[ |2f_{RF} - f_{LO}| = 70\,MHz, \]
\[ |2f_{LO} - f_{RF}| = 160\,MHz, \]

3\textsuperscript{rd} order: \( 3f_{RF} = 300\,MHz, 3f_{LO} = 390\,MHz, \quad 2f_{RF} + f_{LO} = 330\,MHz, \quad f_{RF} + 2f_{LO} = 360\,MHz \)

Right?

A: Not exactly. Although it is true that all of these products will exist at the IF mixer port—they will not pose any particular problem to us as radio engineers. The reason for this is that there is a narrow-band IF filter between the mixer IF port and the demodulator!

Look at the frequencies of the spurious signals created. They are all quite a bit larger than the filter center frequency of 30MHz. All of the spurious signals are thus rejected by the filter—none (effectively) reach the detector/demodulator!
Now, look again at the statement I just made:

"But beware the desired radio station is not the only signal that will appear at the output of the mixer AT 30 MHz!"

In other words, there can be spurious signals that appear precisely at our IF frequency of 30 MHz.
The IF filter will not of course filter these out (after all—they’re at 30 MHz!), but instead let them pass through unimpeded to the demodulator.

The result \( \Rightarrow \) demodulated signal \( \hat{i}(t) \) is an inaccurate, distorted mess!

**Q:** I’m just totally baffled! Where do these unfilterable signals come from? How are they produced?

**A:** The answer is a profound one—an incredibly important fact that every radio engineer worth his or her salt must keep in mind at all times:

![Warning Symbol]

The electromagnetic spectrum is full of radio signals. We must assume that the antenna delivers signals operating at any and all RF frequencies!

In other words, we are only interested in a RF signal at 100 MHz; but that does not mean that other signals don’t exist. You must always consider this fact!
Q: But I'm still confused. How do all these RF signals cause multiple signals precisely at our IF frequency?

A: Remember, each of the RF signals will mix with the LO drive signal, and thus each RF signal will produce its very own set of mixer products (1st order, 2nd order, 3rd order, etc.)

Here's the problem: some of these mixer products might lie at our IF frequency of 30 MHz!

To see which RF input signal frequencies will cause this problem, we must reverse the process of determining our mixer output products.

* Recall earlier we started with known values of desired signal frequency (e.g., \( f_s = 100 \text{ MHz} \)) and LO tuning frequency (e.g., \( f_{LO} = 130 \text{ MHz} \)), and then determined all of the spurious signal frequencies created at the mixer IF port.

* But now, we start with a known LO tuning frequency (e.g., \( f_{LO} = 130 \text{ MHz} \)), and a known value of the receiver IF (e.g., \( f_{IF} = 30 \text{ MHz} \)), and then we try to determine the frequency of the RF signal that would produce a spurious signal at precisely our receiver IF.
For example, let's start with the 3\textsuperscript{rd} order product $|2f_{RF} - f_{LO}|$. In order for this product to be equal to the receiver IF frequency of 30 MHz, we find that:

\begin{align*}
|2f_{RF} - 130| &= 30 \\
2f_{RF} - 130 &= \pm 30 \\
2f_{RF} &= 130 \pm 30 \\
f_{RF} &= \frac{130 \pm 30}{2} \\
f_{RF} &= 50, 80
\end{align*}

Thus, when attempting to "listen to" a radio station at $f_s=100$ MHz—by tuning the LO to $f_{LO}=130$ MHz—we find that radio stations at both 50 MHz and 80 MHz could create a 3\textsuperscript{rd} order product at 30 MHz—precisely at our IF filter center frequency!

But the bad news continues—there are many other mixer products to consider:

\begin{align*}
|2f_{LO} - f_{RF}| \\
|2(130) - f_{RF}| &= 30 \\
260 - f_{RF} &= \pm 30 \\
f_{RF} &= 260 \pm 30 \\
&= 290, 230
\end{align*}
\[ 2f_{LO} + f_{RF} \]

\[ 2(130) + f_{RF} = 30 \]
\[ 260 + f_{RF} = 30 \]
\[ f_{RF} = 30 - 260 = -230 \]

Q: What?! A radio station operating at a **negative** frequency of -230 MHz? Does this have any meaning?

A: Not in any **physical** sense! We **ignore** any negative frequency solutions—they are **not** a concern to us.

\[ 2f_{RF} + f_{LO} \]

\[ 2f_{RF} + f_{LO} = 30 \]
\[ 2f_{RF} + 130 = 30 \]
\[ f_{RF} = \frac{30 - 130}{2} \]
\[ f_{RF} = -50 \]

Again, a **negative** solution that we can **ignore**.

\[ 3f_{RF} \]

\[ 3f_{RF} = 30 \]
\[ f_{RF} = \frac{30}{3} \]
\[ f_{RF} = 10 \]
OK, that's all the 3\textsuperscript{rd} order products, now let's consider the second-order terms:

\[ f_{LO} - f_{RF} \]

\[ |130 - f_{RF}| = 30 \]
\[ 130 - f_{RF} = \pm 30 \]
\[ f_{RF} = 130 \pm 30 \]
\[ = 100, 160 \]

* Note that this term is the term created by an ideal mixer. As a result, we find that one of the RF signals that will create a mixer product at 30 MHz is \( f_{RF} = 100 \text{ MHz} \) - the frequency of the desired radio station!

* However, we find that even this ideal mixer term causes problems, as there is a second solution. An RF signal at 160 MHz would likewise result in a mixer product at 30 MHz— even in an ideal mixer!

We will find this second solution to this ideal mixer (i.e., down-conversion) term can be particularly problematic in receiver design. As such, this solution is given a specific name—the image frequency.

For this example, 160 MHz is the image frequency when we tune to a station at 100 MHz.
\[
f_{LO} + f_{RF} = 130 + f_{RF} = 30
\]
\[
130f_{RF} = 30 - 130 \quad \text{No problem here!}
\]
\[
f_{RF} = -100
\]

\[
2f_{RF} = 30
\]
\[
f_{RF} = \frac{30}{2} = 15
\]

Finally, we must consider one 1\textsuperscript{st} order term:

\[
f_{RF} = 30
\]

In other words, an RF signal at 30 MHz can “leak” through the mixer (recall mixer RF isolation) and appear at the IF port—after that there’s no stopping it until it reaches the demodulator!

In summary, we have found that that:

1. An RF signal (e.g., radio station) at 30 MHz can cause a 1\textsuperscript{st}-order product at our IF filter frequency of 30 MHz.

2. RF signals (e.g., radio stations) at either 15 MHz or 160 MHz can cause a 2\textsuperscript{nd} -order product at our IF filter frequency of 30 MHz.
3. RF signals (e.g., radio stations) at 10 MHz, 50 MHz, 80 MHz, 230 MHz, or 290 MHz can cause a 3rd-order product at our IF filter frequency of 30 MHz.

Many other spurious signals at other freq. are likewise created, but not shown!

Q: Arrrg! I now see the problem! There is no way to separate the spurious signals at the IF frequency of 30 MHz from the desired station at 30 MHz. Clearly, your hero E.H. Armstrong was wrong about this Super-Heterodyne receiver design!
There is an **additional** element of Armstrong's super-het design that we have **not** yet discussed.

⇒ **The preselector filter.**

The **ONLY** way to keep the mixer from **creating** spurious signals at the receiver IF is to **keep** the signals that produce them **from** the mixer RF port!

Of course, we must **simultaneously** let the desired station reach the mixer.

Q: *Hmmm... A device that lets signals pass at *some* frequencies, while rejecting signals at *other* frequencies—sounds like a microwave filter!*

A: That’s correct! By inserting a **preselector filter** between the antenna and the mixer, we can **reject** the signals that create spurious signals at our IF center frequency, while **allowing** the desired station to pass through to the mixer unimpeded.
A: The pass-band of the preselector filter must be just wide enough to allow any and all potential desired signals to pass through.
* Consider our example of $f_s = 100 \text{ MHz}$. This signal is smack-dab in the middle of the FM radio band, and so let’s assume it is an FM radio station (if it were, it would actually be at frequency 100.1 or 99.9 MHz).

* If we are interested in tuning to one FM station, we might be interested in tuning into any of the others, and thus the preselector filter pass-band must extend from 88 MHz to 108 MHz (i.e., the FM band).

* Note we would not want to extend the pass-band of the preselector filter any wider than the FM band, as we are (presumably) not interested in signals outside of this band, and those signals could potentially create spurious signals at our IF center frequency!

As a result, we find that the preselector filter effectively defines the RF bandwidth of a superheterodyne receiver.

Q: OK, one last question. When calculating the products that could create a spurious signal at the IF center frequency, you neglected the terms $f_{LO}$, $2f_{LO}$ and $3f_{LO}$. Are these terms not important?
A: They are actually very important! However, the value of $f_{LO}$ is not an unknown to be solved for, but in fact was (for our example) a fixed value of $f_{LO} = 130\text{MHz}$.

Thus, $2f_{LO} = 260\text{MHz}$, and $3f_{LO} = 390\text{MHz}$—none of these are anywhere near the IF center frequency of $30\text{ MHz}$, and so these products are easily rejected by the IF filter. However, this need not always be true!

* Consider, for example, the case were we again have designed a receiver with an IF center frequency of $30\text{ MHz}$. This time, however, we desire to tune to radio signal operating at $60\text{ MHz}$.

* Say we use low-side tuning in our design. In that case, the LO signal frequency must be $f_{LO} = 60 - 30 = 30\text{MHz}$.

* Yikes! You must see the problem! The Local Oscillator frequency is equal to our IF center frequency ($f_{LO} = f_{IF}$). The LO signal will "leak" through mixer (recall mixer LO isolation) and into the IF, where it will pass unimpeded by the IF filter to the demodulator (this is a very bad thing).

Thus, when designing a receiver, it is unfathomably important that the LO frequency, along with any of its harmonics, lie nowhere near the IF center frequency!
Image and Third-Order Signal Rejection

Recall in a previous handout the example where a receiver had an IF frequency of $f_{IF} = 30 \text{ MHz}$. We desired to demodulate a radio station operating at $f_s = 100 \text{ MHz}$, so we set the LO to a frequency of $f_{LO} = 130 \text{ MHz}$ (i.e., high-side tuning).

We discovered that RF signals at many other frequencies would likewise produce signals at precisely the receiver IF frequency of 30 MHz—a very serious problem that can only be solved by the addition of a preselector filter.

Recall that this preselector filter must allow the desired signal (or band of signals) to pass through unattenuated, but likewise must sufficiently reject (i.e., attenuate) all the RF signals that could create spurious signals at the IF frequency.

We found for this example that these annoying RF signals reside at frequencies:

- $10 \text{ MHz}, 15 \text{ MHz}, 30 \text{ MHz}, 80 \text{ MHz}$
- $160 \text{ MHz}, 230 \text{ MHz},$ and $290 \text{ MHz}$

Note that the most problematic of these RF signals are the two at $80 \text{ MHz}$ and $160 \text{ MHz}$.
Q: Why do these two signals pose the greatest problems?

A: Because the frequencies 80 MHz and 160 MHz are the closest to the desired signal frequency of 100 MHz. Thus, they must be the closest to the pass-band of the preselector filter, and so will be attenuated the least of all the RF signals in the list above.

As a result, the 30 MHz mixer products produced by the RF signals at 80 MHz and 160 MHz will be likely be larger than those produced by the other problem frequencies—they are the ones most need to worry about!

Let's look closer at each of these two signals.

**Image Frequency Rejection**

We determined in an earlier handout that the radio frequency signal at 160 MHz was the RF image frequency for this particular example.

Recall the RF image frequency is the other $f_{RF}$ solution to the (ideal) second-order mixer term $|f_{RF} - f_{LO}| = f_{IF}$. I.E.:

\[
|f_{RF} - f_{LO}| = f_{IF} \\
\Rightarrow \quad f_{RF} - f_{LO} = \pm f_{IF} \\
\Rightarrow \quad f_{RF} = f_{LO} \pm f_{IF}
\]
For low-side tuning, the desired RF signal is (by definition) the solution that is greater than $f_{LO}$:

$$f_{LO} = f_s - f_{IF} \Rightarrow f_s = f_{LO} + f_{IF} \quad \text{(low-side tuning)}$$

And thus—for low-side tuning—the RF image signal is the solution that is less than $f_{LO}$:

$$f_{image} = f_{LO} - f_{IF}$$

Using the fact that for low-side tuning $f_{LO} = f_s - f_{IF}$, we can likewise express the RF image frequency as:

$$f_{image} = f_{LO} - f_{IF}$$
$$= (f_s - f_{IF}) - f_{IF}$$
$$= f_s - 2f_{IF}$$
And thus in summary:

\[
\begin{align*}
\text{image LO IF} &= f_{\text{image}} = f_{\text{LO}} - f_{\text{IF}} \\
&= f_s - 2f_{\text{IF}} & \text{(low-side tuning)}
\end{align*}
\]

Similarly, for high-side tuning, the desired RF signal is (by definition) the solution that is less than \(f_{\text{LO}}\):

\[
\begin{align*}
f_{\text{LO}} &= f_s + f_{\text{IF}} \\
\Rightarrow f_s &= f_{\text{LO}} - f_{\text{IF}} & \text{(high-side tuning)}
\end{align*}
\]

And thus—for high-side tuning—the RF image signal is the solution that is greater than \(f_{\text{LO}}\):

\[
f_{\text{image}} = f_{\text{LO}} + f_{\text{IF}}
\]

Using the fact that for high-side tuning \(f_{\text{LO}} = f_s + f_{\text{IF}}\), we can likewise express the RF image frequency as:

\[
\begin{align*}
f_{\text{image}} &= f_{\text{LO}} + f_{\text{IF}} \\
&= (f_s + f_{\text{IF}}) + f_{\text{IF}} \\
&= f_s + 2f_{\text{IF}}
\end{align*}
\]
And thus in summary:

\[ f_{image} = f_{LO} + f_{IF} \]
\[ = f_s + 2f_{IF} \]  
(high-side tuning)

Note for both high-side and low-side tuning, the difference between the desired RF signal and its RF image frequency is 2\( f_{IF} \):

\[ |f_{RF} - f_{image}| = 2f_{IF} \]

This is a very important result, as it says that we can increase the “distance” between a desired RF signal and its image frequency by simply increasing the IF frequency of our receiver design!
For example, again consider the FM band (88 MHz to 108 MHz). Say we decide to design an FM radio with an IF of 20 MHz, using high-side tuning.

Thus, the LO bandwidth must extend from:

\[
88 + f_{IF} < f_{LO} < 108 + f_{IF} \\
88 + 20 < f_{LO} < 108 + 20 \\
108 < f_{LO} < 128
\]

The RF image bandwidth is therefore:

\[
108 + f_{IF} < f_{image} < 128 + f_{IF} \\
108 + 20 < f_{image} < 128 + 20 \\
128 < f_{image} < 148
\]

Thus, the preselector filter for this FM radio must have pass-band that extends from 88 to 108 MHz, but must also sufficiently attenuate the image signal band extending from 128 to 148 MHz.

Note that 128 MHz is very close to 108 MHz, so that attenuating the signal may be very difficult.

Q: By how much do we need to attenuate these image signals?
A: A very good question; one that leads to a very important point. Since the image frequency creates the same second-order product as the desired signal, the conversion loss associated with each signal is precisely the same (e.g. 6 dB)!

As a result, the IF signal created by image signals will typically be just as large as those created by the desired FM station.

This means that we must greatly attenuate the image band, typically by 40 dB or more!

Q: Yikes! It sounds like we might require a filter of very high order!?!?

A: That's certainly a possibility. However, we can always reduce this required preselector filter order if we simply increase our IF design frequency!

To see how this works, consider what happens if we increase the receiver IF frequency to $f_{IF} = 40\, MHz$. For this new IF, the LO bandwidth must increase to:

$$88 + f_{IF} < f_{LO} < 108 + f_{IF}$$
$$88 + 40 < f_{LO} < 108 + 40$$
$$128 < f_{LO} < 148$$

The new RF image bandwidth has therefore increased to:
The amount by which the preselector attenuates the image signals is known as the **image rejection** of the receiver.

For example, if the preselector filter attenuates the image band by at least **50 dB**, we say that the receiver has **50 dB of image rejection**.

\[
108 + f_{IF} < f_{image} < 128 + f_{IF} \\
128 + 40 < f_{image} < 148 + 40 \\
168 < f_{image} < 188
\]

Note this image band is now much higher in frequency than the FM band—and thus much more easily filtered!
So by increasing the receiver IF frequency, we can either get greater image rejection from the same preselector filter order, or we can reduce the preselector filter order while maintaining sufficient image rejection.

But be careful! Increasing the IF frequency will also tend to increase cost and reduce detector performance.

3rd-Order Signal Rejection

In addition to the image frequency (the other solution to the second order term \(|f_{RF} - f_{LO}| = f_{IF}\)), the other radio signals that are particularly difficult to reject are the \(f_{RF}\) solutions to the 3rd-order product terms \(2f_{RF} - f_{LO} = f_{IF}\) and \(2f_{LO} - f_{RF} = f_{IF}\).

There are four possible RF solutions (two for each term):

\[
\begin{align*}
  f_1 &= \frac{f_{LO} + f_{IF}}{2} \\
  f_2 &= \frac{f_{LO} - f_{IF}}{2} \\
  f_3 &= 2f_{LO} + f_{IF} \\
  f_4 &= 2f_{LO} - f_{IF}
\end{align*}
\]

Each of these four solutions represents the frequency of a radio signal that will create a 3rd-order product precisely at the receiver IF frequency, and thus all four must be adequately rejected by the preselector filter!
However, solutions $f_1$ and $f_4$ will typically* be the most problematic (i.e., closest to the desired RF frequency band). For instance, in our original example, the “problem” signal at 80 MHz is the term $f_1$ (i.e., $f_1 = 80$ MHz).

For low-side tuning, where $f_{LO} = f_s - f_{IF}$, these 3\textsuperscript{rd}-order RF solutions can likewise be expressed as:

\begin{align*}
  f_1 &= \frac{f_s}{2} \\
  f_3 &= 2f_s - f_{IF} \\
  f_2 &= \frac{f_s - 2f_{IF}}{2} \\
  f_4 &= 2f_s - 3f_{IF}
\end{align*}

(low-side tuning)

And for high-side tuning, where $f_{LO} = f_s + f_{IF}$, these 3\textsuperscript{rd}-order RF solutions can likewise be expressed as:

\begin{align*}
  f_1 &= \frac{f_s + 2f_{IF}}{2} \\
  f_3 &= 2f_s + 3f_{IF} \\
  f_2 &= \frac{f_s}{2} \\
  f_4 &= 2f_s + f_{IF}
\end{align*}

(high-side tuning)

* Note that “typically” does not mean “always”.

*
Of course, in a good receiver design the preselector filter will attenuate these problematic RF signals before they reach the mixer RF port.

The amount by which the preselector attenuates these 3rd-order solutions is known as the 3rd-order signal rejection of the receiver.

Q: By how much do we need to attenuate these signals?

A: Since these signals produce 3rd-order mixer products, the IF signal power produced is generally much less than that of the (2nd order) image signal product. As a result, we can at times get by with as little as 20 dB of 3rd-order signal rejection—but this depends on the mixer used.

Q: Just 20 dB of rejection? It sounds like achieving this will be a "piece of cake"—at least compared with satisfying the image rejection requirement!

A: Not so fast! Often we will find that these 3rd-order signals will be very close to the desired RF band. In fact (if we're not careful when designing the receiver) these 3rd-order signals can lie inside the desired RF band—then they cannot be attenuated at all!
Thus, rejecting these 3rd order radio signals can be as difficult (or even more difficult) than rejecting the image signal.

Q: We found earlier that by increasing the IF frequency, we could make the image rejection problem much easier. Is there a similar solution to improving 3rd order signal rejection?

A: Yes there is—but you won't like this answer!

Look at these RF solutions for the 3rd-order mixer terms:

\[ f_4 = 2f_s - 3f_{IF} \] (low-side tuning)

and:

\[ f_1 = \frac{f_s + 2f_{IF}}{2} \] (high-side tuning)

From these solutions, it is evident that some 3rd-order RF solutions can be moved away from the desired RF band (thus making them easier to filter) by decreasing the IF frequency.

This solution of course is exactly opposite of the method used to improve image rejection. Thus, there is a conflict between the two design goals. It is your job as a receiver designer to arrive at the best possible design compromise, providing both sufficient image and 3rd-order signal rejection.

→ Radio Engineering is not easy! ↔
**Up-Conversion**

Typically, we **down-convert** a desired RF signal at frequency $f_s$ to a **lower** Intermediate Frequency (IF), such that:

$$f_{IF} < f_s$$

This down-conversion is a result of the ideal $2^{nd}$-order mixer term:

$$|f_s - f_{LO}| = f_{IF} \quad \therefore f_{IF} < f_s$$

Recall, however, that there is a **second** ideal $2^{nd}$-order mixer term:

$$f_s + f_{LO} = f_{IF} \quad \therefore f_{IF} > f_s$$

Note that the resulting frequency $f_{IF}$ is **greater** than the original RF signal frequency $f_s$. This term produces an *up-conversion* $f_s$ to a **higher** frequency $f_{IF}$.

The **tuning solution** for this up-conversion term is (given $f_s$ and $f_{IF}$):

$$f_{LO} = f_{IF} - f_s \quad \therefore f_{IF} > f_{LO}$$

Note that unlike its down-conversion counterpart, the up-conversion term only has **one solution**!
Q: So, there is no such thing as high-side tuning or low-side tuning for up-conversion?

A: Yes and no. There is only one tuning solution, so we do not choose whether to implement a high-side solution ($f_{LO} > f_s$) or a low-side solution ($f_{LO} < f_s$).

Instead, the single solution $f_{LO} = f_{IF} - f_s$ will “choose” for us!

This solution for $f_{LO}$ will either be greater than $f_s$ (i.e., high-side), or less than $f_s$ (i.e., low-side). Hopefully is apparent to you that a low-side solution will result if $f_{IF} > 2f_s$, whereas a high-side solution must occur if $0 < f_s < f_{IF}/2$.

Occasionally receivers are designed that indeed use up-conversion instead of down conversion!

Q: But wouldn’t the IF frequency for these receivers be very high??

A: That’s correct! The IF of an up-conversion receiver might be in the range of 1-6 GHz—or even higher!

Q: But that would seemingly increase cost and reduce performance. Why would a receiver designer do that?

A: Let’s examine the frequencies ($f_{RF}$) of any RF signals that would create spurious responses precisely at an up-conversion
receiver IF, given this receiver IF \( f_{IF} \), and given that the LO is tuned to frequency \( f_{LO} \).

They are:

**1\(^{st}\)-order**

\[
f_{RF} = f_{IF}
\]

**2\(^{nd}\)-order**

\[
\begin{align*}
    f_{RF} &= f_{LO} \pm f_{IF} \\
    f_{RF} &= \frac{f_{IF}}{2}
\end{align*}
\]

**3\(^{rd}\)-order**

\[
\begin{align*}
    f_{RF} &= \frac{f_{IF}}{3} \\
    f_{RF} &= \frac{f_{IF} - f_{LO}}{2} \\
    f_{RF} &= f_{IF} - 2f_{LO}
\end{align*}
\]

\[
\begin{align*}
    f_{RF} &= \frac{f_{LO} + f_{IF}}{2} \\
    f_{RF} &= 2f_{LO} + f_{IF}
\end{align*}
\]

\[
\begin{align*}
    f_{RF} &= \frac{f_{LO} - f_{IF}}{2} \\
    f_{RF} &= 2f_{LO} - f_{IF}
\end{align*}
\]

Since we know that \( f_{IF} > f_s \) and \( f_{IF} > f_{LO} \) we can conclude that the terms above which are most problematic (i.e., they might be close to desired signal frequency \( f_s \)) are:
Inserting the up-conversion tuning solution \( f_{LO} = f_{IF} - f_s \) into these results, we can determine the problematic RF frequencies in terms of IF frequency \( f_{IF} \) and desired RF signal frequency \( f_s \):

\[
\begin{align*}
    f_{RF} &= \frac{f_{IF}}{3} \\
    f_{RF} &= \frac{f_{IF} - f_{LO}}{2} \\
    f_{RF} &= f_{IF} - 2f_{LO} \\
    f_{RF} &= \frac{f_{IF}}{2} \\
    f_{RF} &= 2f_{LO} - f_{IF} \\
    f_{RF} &= \frac{f_{LO} + f_{IF}}{2} \\
    f_{RF} &= \frac{f_{IF}}{2} \\
    f_{RF} &= f_{IF} - 2f_s \\
    f_{RF} &= \frac{2f_{IF} - f_s}{2}
\end{align*}
\]

There are some important things to note about these frequencies:

1) The only 2\textsuperscript{nd}-order term is \( f_{RF} = f_{IF}/2 \). In other words, there is no image frequency! This of course is a result of the fact that the up-conversion term \( f_s + f_{LO} = f_{IF} \) has only one solution.

2) These terms are much different than those deemed important for the down-conversion receiver.
3) As the value of the receiver IF frequency $f_{IF}$ becomes large (i.e., $f_{IF} > 2f_s$) we find that the frequency of all these problematic RF signals likewise become large ($2f_s - f_{IF}$ becomes negative).

As a result, these spurious-signal causing RF signals can be (if they exist) at much higher frequencies than the desired signal $f_s$—they can be easily filtered out by a preselector filter, and thus the spurious signal (i.e., image and 3$^{rd}$-order) suppression can be very good for up-conversion receivers.

For example, consider a desired RF signal bandwidth of:

$$0.5 \, \text{GHz} \leq f_s \leq 0.6 \, \text{GHz}$$

Say we design an up-conversion receiver with an IF of 3.0 GHz. The problematic RF signals are thus:

$$\frac{f_{IF}}{3} \Rightarrow f_{RF} = 1 \, \text{GHz} \quad \frac{f_{IF}}{2} \Rightarrow f_{RF} = 1.5 \, \text{GHz}$$

$$\frac{2f_{IF} + f_s}{2} \Rightarrow 3.25 \, \text{GHz} \leq f_{RF} \leq 3.3 \, \text{GHz}$$

$$f_{IF} - 2f_s \Rightarrow 1.8 \, \text{GHz} \leq f_{RF} \leq 2.0 \, \text{GHz}$$

$$\frac{2f_{IF} - f_s}{2} \Rightarrow 2.7 \, \text{GHz} \leq f_{RF} \leq 2.75 \, \text{GHz}$$
Note that the frequencies of all these potentially spur-
creating RF signals are a significant “distance” from the
desired RF signal band of \(0.5 \text{ GHz} \leq f_s \leq 0.6 \text{ GHz}\).

Thus, a receiver designer can easily attenuate these
problematic signals with a preselector filter whose passband
extends from 0.5 GHz to 0.6 GHz.

**Q:** Wow! Why don’t we just design receivers with very high
IF frequencies?

**A:** Remember, increasing the receiver IF will in general
increase cost and reduce performance (this is bad!).

In addition, note that increasing the center frequency of the
IF filter \((f_{IF})\)—while the IF bandwidth \(\Delta f_{IF}\) remains
constant—decreases the percentage bandwidth of this IF
filter. Recall there is a practical lower limit on the
percentage bandwidth of a bandpass filter, thus there is a
practical upper limit on receiver IF frequency, given an IF
bandwidth \(\Delta f_{IF}\)!

For example, consider a desired signal with a bandwidth \(\Delta f_s\)
of:

\[
\Delta f_s = 10 \text{ MHz}
\]

The receiver IF filter, therefore would likewise require a
bandwidth of \(\Delta f_{IF} = 10 \text{ MHz}\). If it is impractical for the IF
bandpass filter to have a **percentage** bandwidth less than 0.2%, then:

\[
0.002 > \frac{\Delta f_{IF}}{f_{IF}}
\]

And so:

\[
f_{IF} > \frac{\Delta f_{IF}}{0.002} = \frac{10 \text{ MHz}}{0.002} = 5.0 \text{ GHz}
\]

In other words, for **this** example, the receiver IF must be less than 5.0 GHz in order for the IF filter to be **practical**.
Advanced Receiver Designs

So, we know that as our IF frequency increases, the rejection of image and (some) other spurious signals will improve.

But, as our IF frequency decreases, the cost and performance of our receiver and demodulator will improve.

Q: Isn't there some way to have it both ways? Can't we have our cake and eat it too?

A: Yes, there is (sort of)!

To achieve exceptional image and 3rd-order product rejection, and enjoy the cost and performance benefits of a low IF frequency, receiver designers often employ these two advanced receiver architectures.
1. Selectable Preselection

Instead of implementing a single preselector filter, we can use a bank of selectable preselector filters:

In other words, we use multiple preselector filters to span the desired receiver RF bandwidth. This is particularly useful for wideband receiver design.

Q: Why? How is this useful? What good is this design?

A: Consider an example. Say we have been tasked to design a receiver with an RF bandwidth extending from 8 GHz to 12 GHz. A standard receiver design might implement a single preselector filter, extending from 8 GHz to 12 GHz.
Instead, we could implement a bank of preselector filters that span the RF bandwidth. We could implement 2, 3, 4, or even more filters to accomplish this.

Let’s say we use four filters, each covering the bandwidths shown in the table below:

<table>
<thead>
<tr>
<th>Filter</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter #1</td>
<td>8 - 9 GHz</td>
</tr>
<tr>
<td>Filter #2</td>
<td>9 - 10 GHz</td>
</tr>
<tr>
<td>Filter #3</td>
<td>10 - 11 GHz</td>
</tr>
<tr>
<td>Filter #4</td>
<td>11 - 12 GHz</td>
</tr>
</tbody>
</table>

Say we wish to receive a signal at 10.3 GHz; we would tune the local oscillator to the proper frequency, AND we must select filter #3 in our filter bank.

Thus, all signals from 10-11 GHz would pass through to the RF port of the mixer—a band that includes our desired signal at 10.3 GHz.

However, signals from 8-10 GHz and 11-12 GHz will be attenuated by filter #3—ideally, little signal energy from these bands would reach the RF port of the mixer. If we wish
to receive a signal in these bands, we must select a different filter (as well as retune the LO frequency).

→ As a result, signals over “just” 1GHz of bandwidth reach the RF port of the mixer, as opposed to the single filter design wherein a signal spectrum 4GHz wide reaches the mixer RF port!

Q: Again I ask the question: How is this helpful?

A: Let’s say this receiver design likewise implements low-side tuning. If we wish the tune to a RF signal at 12 GHz (i.e., $f_s = 12$ GHz), we find that the image frequency lies at:

$$f_{image} = 12\,\text{GHz} - 2f_{IF}$$

Of course, we need the preselector filter to reject this image frequency. If we receiver design used just one preselector filter (from 8 to 12 GHz), then the image signal frequency $f_{image}$ must be much less than 8 GHz (i.e., well outside the filter passband). As a result, the receiver IF frequency must be:

$$8\,\text{GHz} \gg 12\,\text{GHz} - 2f_{IF}$$
$$8\,\text{GHz} + 2f_{IF} \gg 12\,\text{GHz}$$
$$2f_{IF} \gg 4\,\text{GHz}$$
$$f_{IF} \gg 2\,\text{GHz}$$
In other words, the 4.0 GHz RF bandwidth results in a requirement that the receiver Intermediate Frequency (IF) be much greater than 2.0 GHz.

→ This is a pretty darn high IF!

Instead, if we implement the bank of preselector filters, we would select filter #4, with a passband that extends from 12 GHz down to 11 GHz.

As a result, image rejection occurs if:

\[
11\, \text{GHz} \gg 12\, \text{GHz} - 2f_{IF} \\
11\, \text{GHz} + 2f_{IF} \gg 12\, \text{GHz} \\
2f_{IF} \gg 1\, \text{GHz} \\
f_{IF} \gg 0.5\, \text{GHz}
\]

In other words, since the preselector filter has a much narrower (i.e., 1GHz) bandwidth than before (i.e., 4GHz), we can get adequate image rejection with a much lower IF frequency (this is a good thing)!

Moreover, this improvement in spurious signal rejection likewise applies to other order terms, including that annoying 3\textsuperscript{rd}-order term!

Thus, implementing a bank of preselector filters allows us to either:
1. Provide **better** image and spurious signal rejection at a **given** IF frequency.

2. **Lower** the **IF** frequency necessary to provide a **given** level of image and spurious signal rejection.

As we increase the **number** of preselector filters, the image and spurious signal rejection will increase **and/or** the required IF frequency will decrease.

But beware! Adding filters will **increase** the **cost** and size of your receiver!

---

**2. Dual Conversion Receivers**

A **dual conversion** receiver is another great way of achieving exceptional image and spurious rejection, while maintaining the benefits of a low IF frequency.

In this architecture, instead of employing multiple preselector filters, we employ multiple (i.e. two) **IF filters**!

As the name implies, a **dual** conversion receiver converts the signal frequency—**twice**. As a result, this receiver architecture implements **two** Local Oscillators and **two** mixers.
Q: Two frequency conversions! Why would we want to do that?

A: The first mixer/local oscillator converts the RF signal to the first IF frequency $f_{IF1}$. The value of this first IF frequency is selected to optimize the suppression of the image frequency and all other RF signals that would produce spurious signals (e.g., 3$^{rd}$ order products) at the first IF.

Optimizing spurious signal suppression generally results in an IF frequency $f_{IF1}$ that is very high—much higher than a typical IF frequency.

Q: But won’t a high IF frequency result in reduced IF component and demodulator performance, as well as higher cost?

A: That’s why we employ a second conversion!
The second mixer/local oscillator simply down converts the signal to a lower IF \((f_{IF2})\)—a frequency where both component performance and cost is good.

**Q:** What about spurious signals produced by this second conversion; don’t we need to worry about them?

**A:** Nope! The first conversion (if designed properly) has adequately suppressed them. The first IF filter (like all IF filters) is relatively narrow band, thus allowing only the desired signal to reach the RF port of the second mixer. We then simply need to down-convert this one signal to a lower, more practical IF frequency!

Now, some very important points about the dual-conversion receiver.

**Point 1**

The first LO must be tunable—just like a “normal” super-het local oscillator. However, the second LO has a fixed frequency—there is no need for it to be tunable!

**Q:** Why is that?

**A:** Think about it.

The signal at the RF port of the second mixer must be precisely at frequency \(f_{IF1}\) (it wouldn't have made it through the first IF filter otherwise!). We need to down-convert this
signal to a second IF frequency of $f_{IF1}$, thus the second LO frequency must be:

$$f_{LO2} = f_{IF1} + f_{IF2} \quad \text{(high-side tuning)}$$

or:

$$f_{LO2} = f_{IF1} - f_{IF2} \quad \text{(low-side tuning)}$$

Either way, no tuning is required for the second LO!

This of course means that we can use, for example, a crystal or dielectric resonator oscillator for this second LO.

**Point 2**

Recall the criteria for selecting the first IF is solely image and spurious signal suppression. Since the second conversion reduces the frequency to a lower (i.e., lower cost and higher performance) value, the first IF frequency $f_{IF1}$ can be as high as practicalable.

In fact, the first IF frequency can actually be higher than the RF signal!

$\Rightarrow$ In other words, the first conversion can be an up-conversion.

For example, say our receiver has an RF bandwidth that extends from 900 MHz to 1300 MHz. We might choose a first
IF at $f_{IF1}=2500$ MHz, such that the first mixer/LO must perform an up-conversion of as much as 1600 MHz.

**Q:** Say again; why would this be a good idea?

**A:** Remember, we found that an extremely high first IF will make the preselector’s job relatively easy—all RF signals that would produce spurious signals at the first IF are well outside the preselector bandwidth, and thus are easily and/or greatly suppressed.

But be careful! Remember, the RF signals that cause spurious signals when up-converting are not the “usual suspects” we found when down-converting.

You must carefully determine all offending RF signals produced from all mixer terms ($1^{st}$, $2^{nd}$, and $3^{rd}$ order)!

**Point 3**

The bandwidth of the first IF filter ($\Delta f_{IF1}$) should be narrow, but not as narrow as the bandwidth of the second IF filter ($\Delta f_{IF2}$):

$$\Delta f_{IF1} > \Delta f_{IF2}$$

Remember, the second IF filter will have a much lower center frequency, and so it will generally have a much larger percentage bandwidth, and typically better performance (e.g.,
insertion loss) than the higher frequency bandpass filter required for the first IF.

Thus, designers generally rely on the second IF to provide the requisite selectivity.

In fact, cascading two filters with the same 3dB bandwidth is a bad idea, as the 3dB bandwidth effectively becomes a 3+3=6db bandwidth!

A designer “rule-of-thumb” is to make the first IF filter bandwidth about **10 times** that of the second:

$$\Delta f_{IF1} \approx 10 \Delta f_{IF2}$$

One last point. The astute receiver designer will often find that a combination of these two architectures (multiple preselection and dual conversion) will provide an elegant, effective, and cost efficient solution!