Modern DSP Tools for Amateur Operations

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AE5JI

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Presentation Philosophy

- The world of software defined radio (SDR) and digital signal processing (DSP) is vast and exciting.
- I can't fully address DSP in a 50 min talk – there is *way* too much information to cover.
- Instead, I want you to leave with an understanding of what is possible and the resources to learn more
- Disclaimer: All opinions expressed in this presentation are solely the author's and do not represent those of my employer

Ettus USRP E310 Software Defined Radio
Source: https://www.ettus.com/product/details/E310-KIT

Modern DSP Tools for Amateur Operations: Outline

- Scientific applications of high-performance DSP
- Why software defined radio / digital signal processing?
- ADC Basics
- Traditional & Software Defined Radios
- Signal Processing
- Practical DSP: Theory and Implementation
  - Prototyping Languages (SciPy, MATLAB, Lua, GNU Radio)
  - High performance Languages (C++)
  - Computational Accelerators (GPUs, FPGAs)
- Ham Applications

Key takeaways

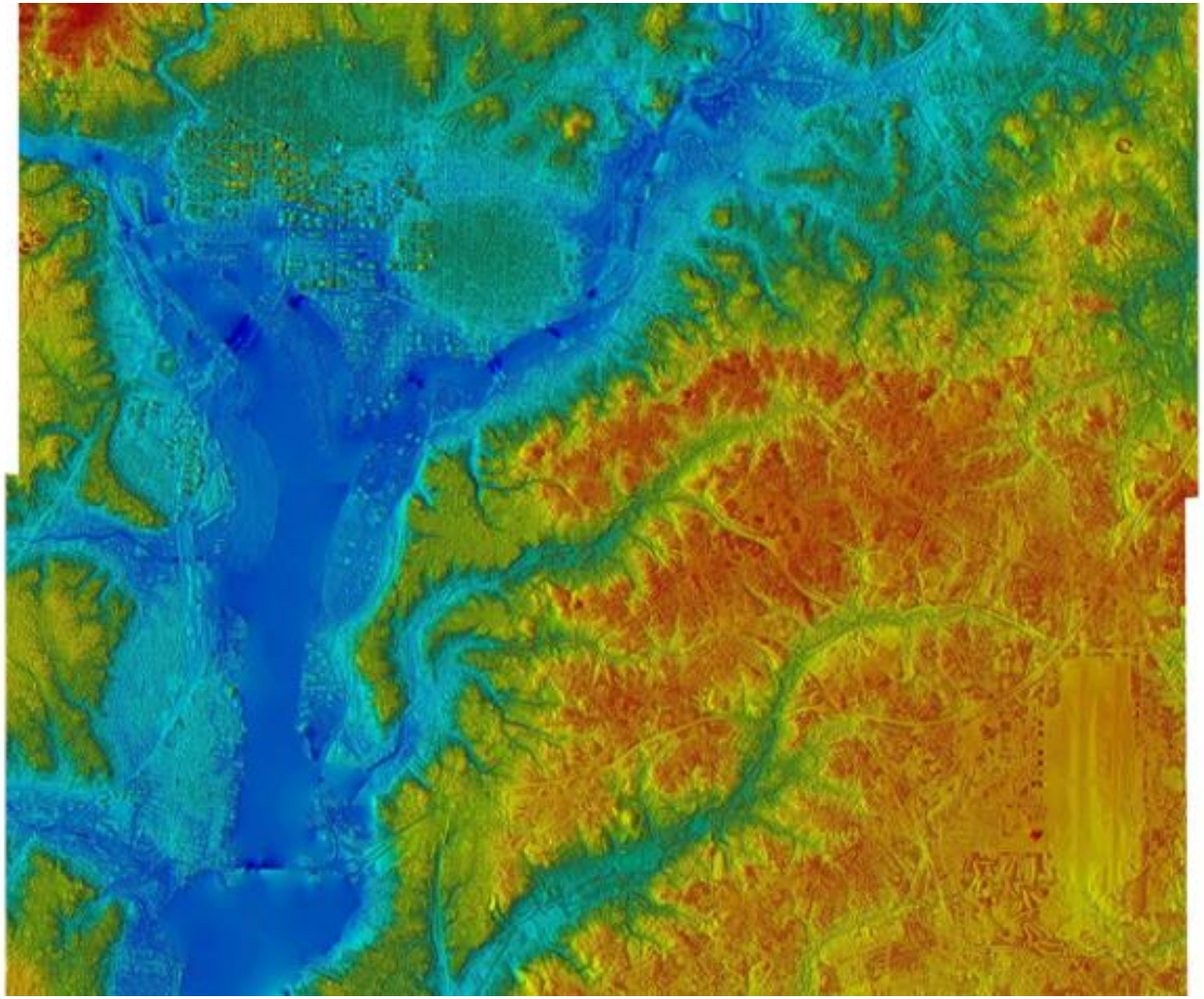
- The move from analog to digital is going to increase
  - This is a good thing for HAMs!
- Analog design / performance is still very important
- Latency is an issue with general purpose computers
  - FPGAs are needed for low latency applications
- Design tools, development environments, and compilers are increasingly available as free & open source

Scientific applications of high-performance DSP

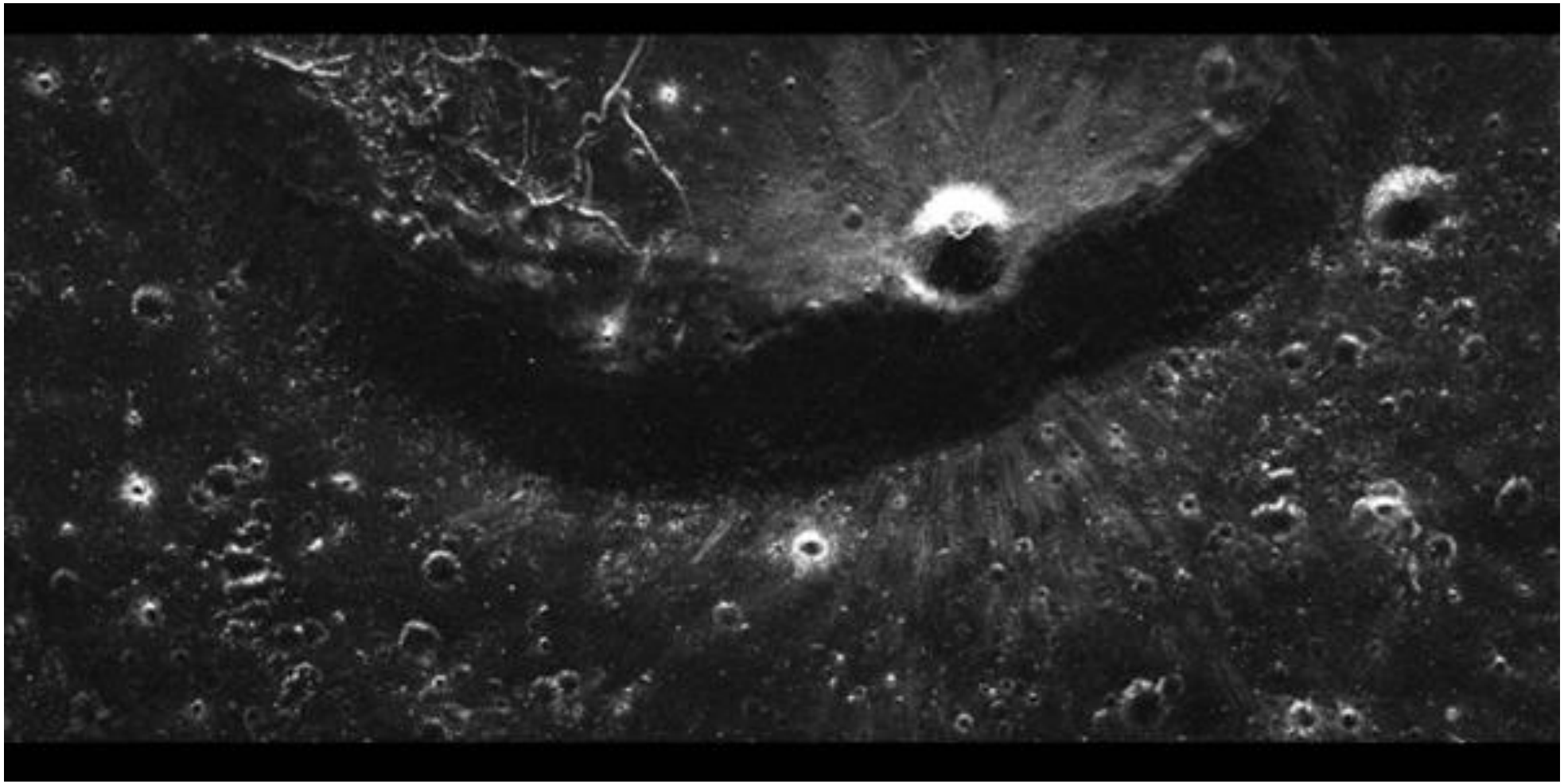
Terrain Mapping

Interferometric Synthetic Aperture Radar (IFSAR) mosaic of greater Washington, DC area from Sandia's Rapid Terrain Visualization (RTV) program.

Source: http://www.sandia.gov/radar/imagery/index.html



Bistatic (SAR) image from Lunar Reconnaissance Orbiter



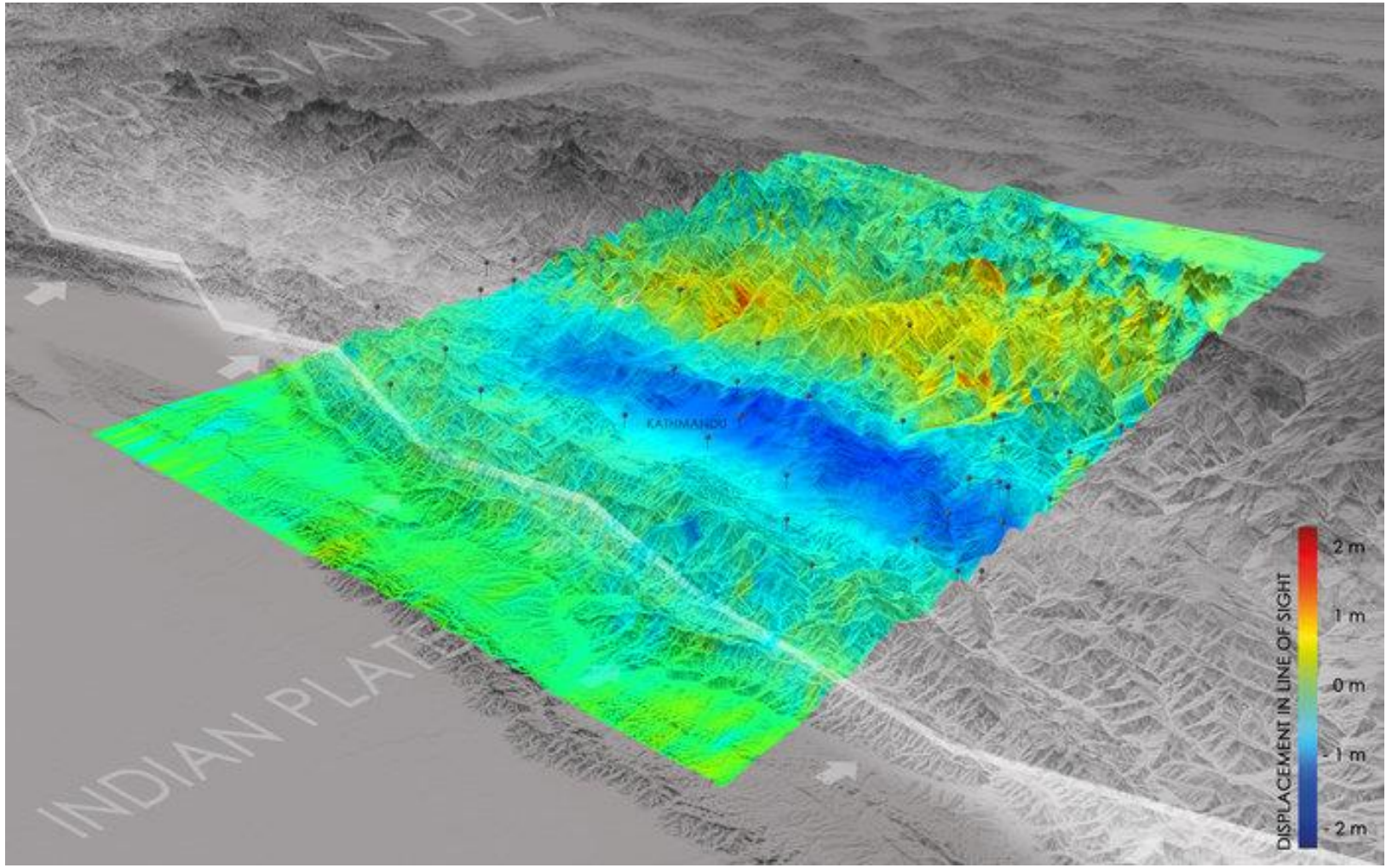
Bistatic Synthetic Aperture Radar (SAR) image from Sandia's Mini-RF on board the Lunar Reconnaissance Orbiter (LRO).
Source: http://www.sandia.gov/radar/imagery/index.html

Copernicus Sentinel-1

- European civil space mission
- Pair of SAR satellites
- Near complete coverage of earth land surfaces with 12-day repeat cycle
- Data is freely available online
  - https://sentinel.esa.int/web/sentinel/sentinel-data-access/access-to-sentinel-data

Source:
http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Sentinel-1/Facts_and_figures

Copernicus Sentinel-1: Nepal earthquake displacement



Source: http://www.esa.int/spaceinimages/Images/2015/04/Nepal_earthquake_displacement

Why software defined radios / digital signal processing?

Why digital?

- Digital cost / function rapidly dropping vs. constant analog cost
- They allow component reuse and design standardization
  - Economy of scale is a HUGE price influence in electronics design
- SDRs *may* be reprogrammable to allow future improvements in design
- Newer ICs have lower supply voltages – an issue for analog designs

World class performance in a commodity product

- >2.5 GHz analog bandwidth now available as a commodity product
- Available from many vendors, an example is the XU-TX by Innovative Integration
  - Two, 5 GSPS, 16-bit DACs, 4.8GHz PLL, Xilinx UltraScale FPGA with 4 GB DDR4 Memory

RoHS 2002/95/EC compliant

XU TX

Source: https://www.innovative-dsp.com/products.php?product=XU-TX

SDR: Low barrier to entry

- RTL-SDR
  - SDR Receiver for $8
  - Active development community at http://www.rtl-sdr.com/
  - Originally marketed as a tuner for European DVB digital TV
  - R820T2+RTL2832U
  - 3MHz bandwidth with a center frequency from 24 – 1766 MHz

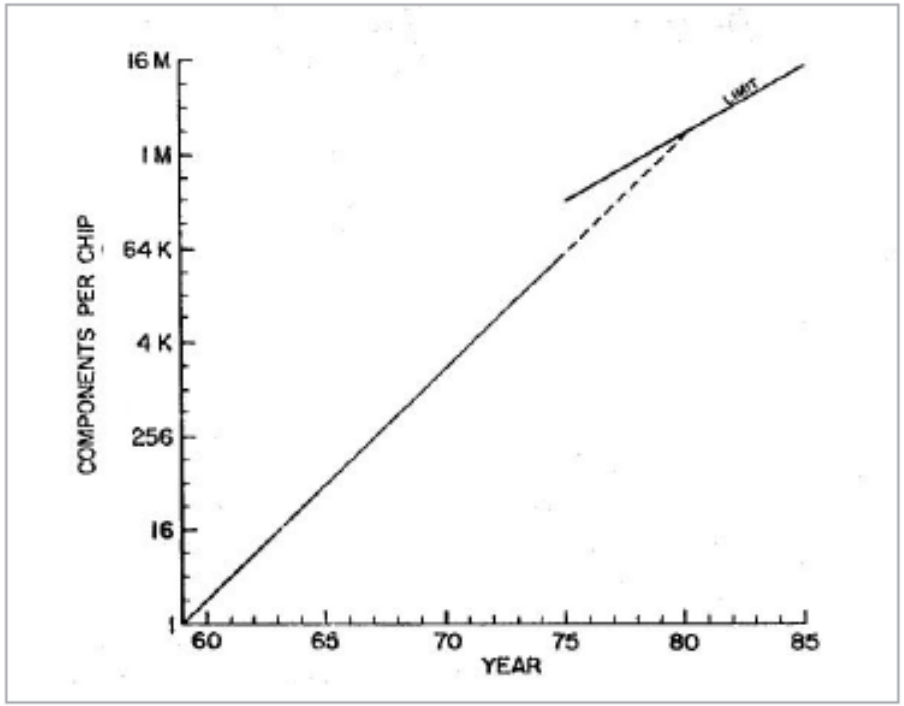
Source: http://www.amazon.com

Moore's Law

IC transistor density will on average double every 2 years

"With this factor disappearing as an important contributor, the rate of increase of complexity can be expected to change slope in the next few years as shown in Figure 5. The new slope might approximate a doubling every two years, rather than every year, by the end of the decade."

Figure 5 Projection of the complexity curve reflecting the limit on increased density through invention.



Source: [3] http://ieeexplore.ieee.org/iel5/9941/31745/01478174.pdf

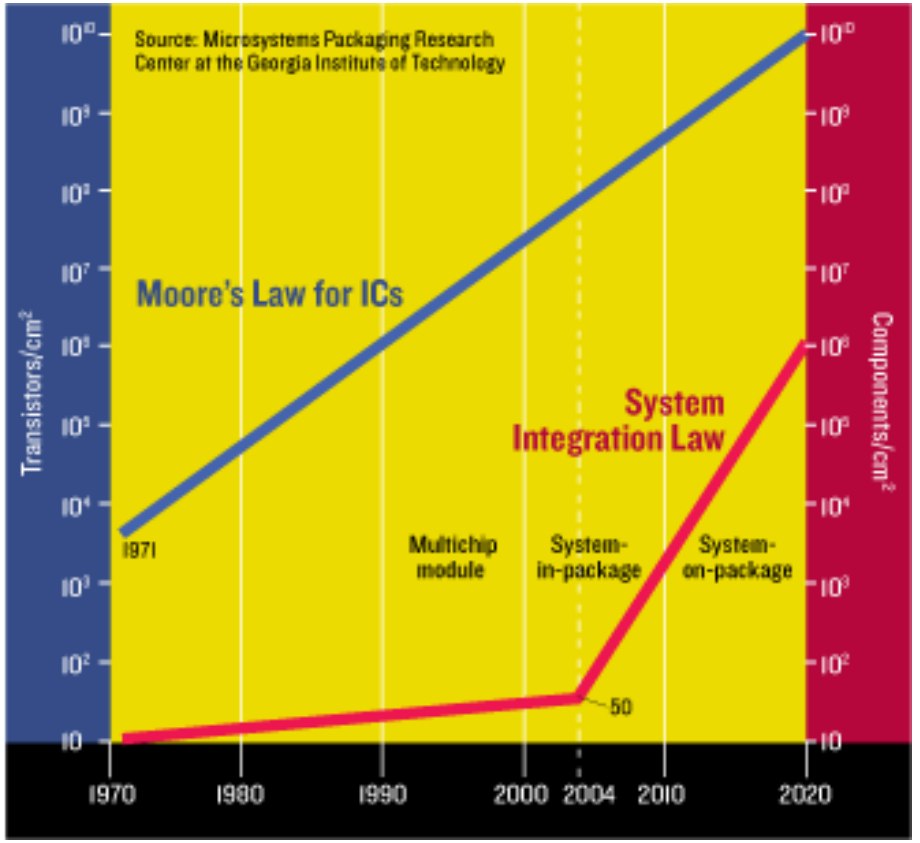
[1] Moore, Gordon E. "Cramming More Components Onto Integrated Circuits, Electronics,(38) 8." (1965).

[2] Moore, Gordon E. "Cramming more components onto integrated circuits, Reprinted from Electronics, volume 38, number 8, April 19, 1965, pp. 114 ff." *IEEE Solid-State Circuits Society Newsletter* 20.3 (2006): 33-35.

[3] Moore, Gordon E. "Progress in digital integrated electronics." *Electron Devices Meeting*. Vol. 21. 1975.

Other “Moore’s Law” like factors

- Improvements in oscillators
  - Driven largely by the world wide cell phone market (>5 billion active GSM subscribers)
- Improvements in analog-to-digital converters (ADC)
- Increase in complexity of systems on a chip (SoC) [1]

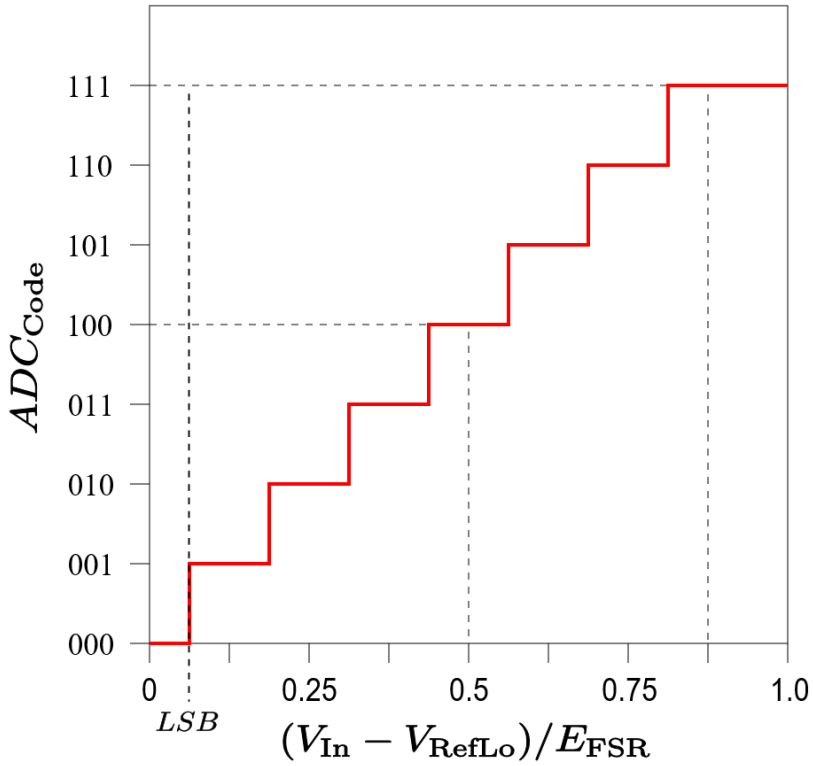


Source: [1]

[1] http://spectrum.ieee.org/computing/hardware/moores-law-meets-its-match

Analog to Digital Converters (ADC) Basics

- The most conceptually simple ADC is the N-bit ADC. It maps a set voltage level to a specific output.
- Another very common form of ADC is the ∑Δ ADC. It is beyond the scope of this talk, however, lots of great resources online [2]

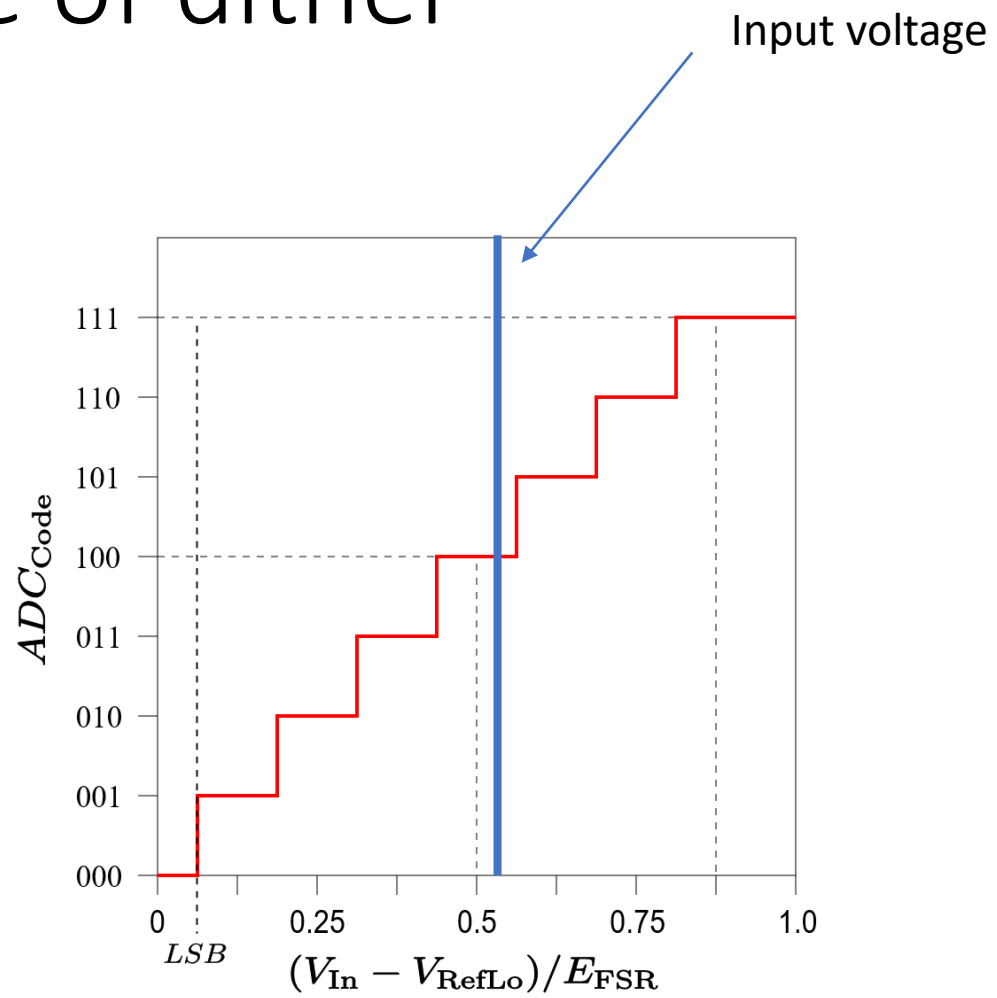


[1] Source: https://en.wikipedia.org/wiki/File:ADC_voltage_resolution.svg
[2] https://www.maximintegrated.com/en/app-notes/index.mvp/id/1870

ADCs and the importance of dither

- What if I feed an ideal 3-bit ADC a constance 0.51*Vref input?
  - The output will *always* be 100, and this will be mapped to 0.5*Vref

- But what if I feed in: 0.51*Vref + guassian noise with a variance of $\Delta/2$?



Mapping ADC bits to SNR

DR (dB) = 6.021N + 1.761 (ideal N-bit ADC)

=> direct result from examining quantization noise

DR (dB) = 6.021N – 4.260 (optimally-dithered N-bit ADC)

Source: Course Notes, UT Austin EE382M-19: Mixed Signal System Design and Modeling, Eric Swanson

Analog to Digital Converters (ADC)

- ADCs have been improving at a rate that is analogous to Moore's Law
- Several Figures of Merit (FOM) have been defined that are useful in examining this performance growth
- (Very) Roughly: 2dB/year improvement in dynamic range (>1MHz)
  - Rate highly depends on sampling frequency

- Several Excellent Survey's exist:
  - Walden, Robert H. "Analog-to-digital converter survey and analysis." *IEEE Journal on selected areas in communications* 17.4 (1999): 539-550.
  - A/D-converter performance evolution (2012) [Online]. Available: https://converterpassion.files.wordpress.com/2013/01/adc-performance-evolution-1v1.pdf
  - B. Murmann, "ADC Performance Survey 1997-2016," [Online]. Available: http://web.stanford.edu/~murmann/adcsurvey.html.

ADC Performance Versus Time

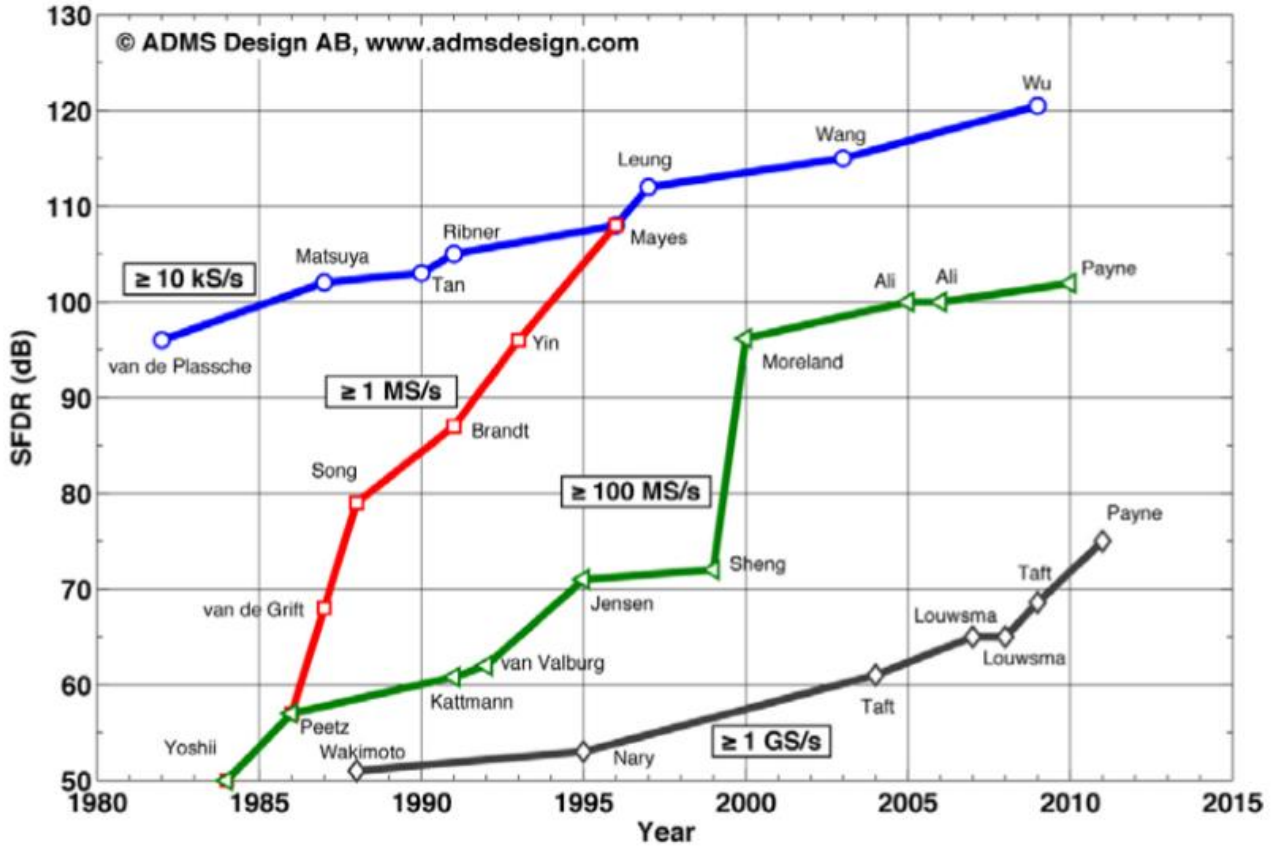


Figure 8.3. Scientifically reported ADC implementations: Peak SFDR evolution over time for minimum sampling rates of 10k (○), 1M (□), 100M (◁), and 1GS/s (◇).

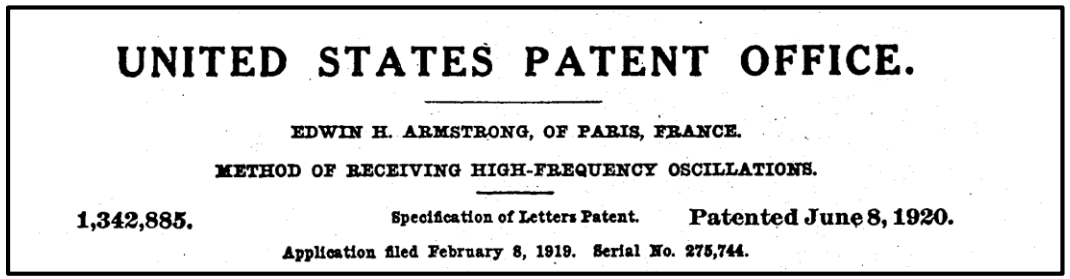
Source: https://converterpassion.files.wordpress.com/2013/01/adc-performance-evolution-1v1.pdf

Traditional & Software Defined Radios

Superheterodyne receiver

- Armstrong's invention is one of the most important of the 20th century:

  "Method of receiving high-frequency oscillations." U.S. Patent 1,342,885, issued June 8, 1920.



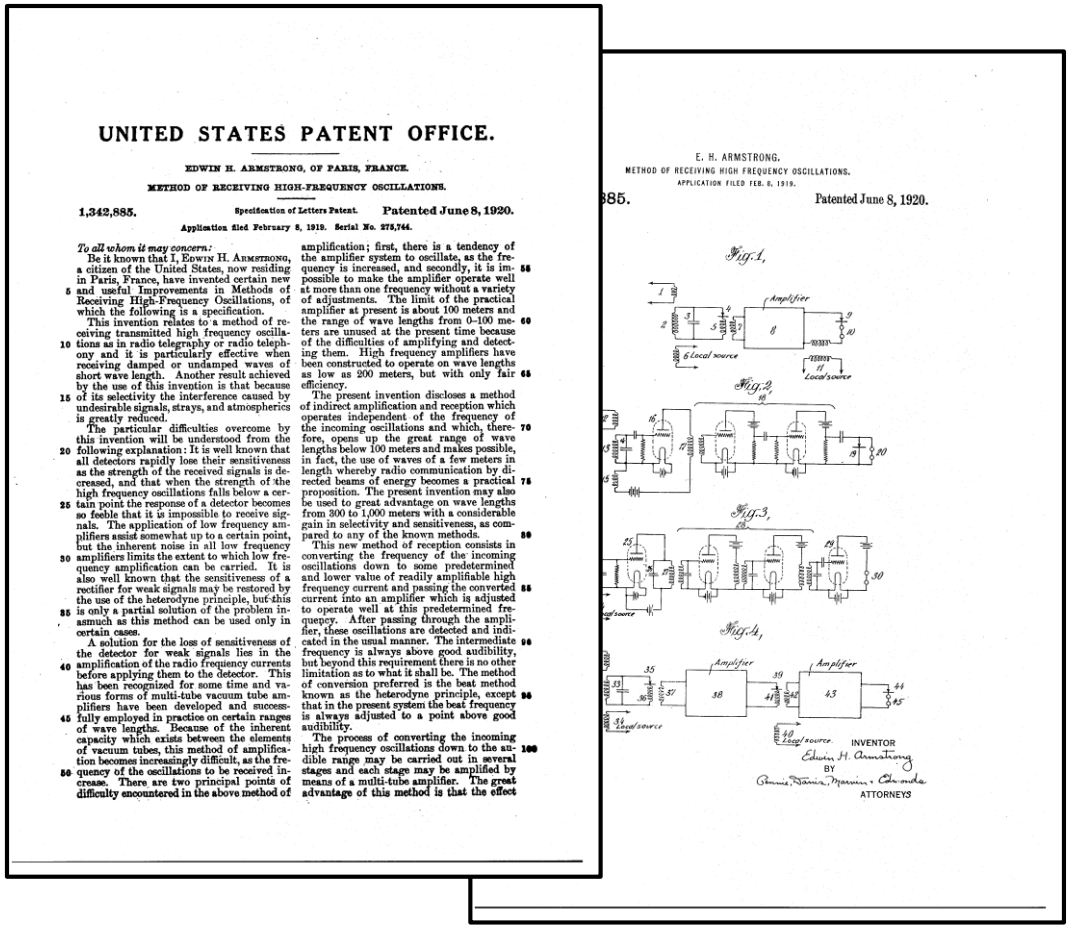
UNITED STATES PATENT OFFICE.

EDWIN H. ARMSTRONG, OF PARIS, FRANCE.

METHOD OF RECEIVING HIGH-FREQUENCY OSCILLATIONS.

1,342,885. Specification of Letters Patent. Patented June 8, 1920.

Application filed February 8, 1919. Serial No. 275,744.



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To all whom it may concern:

Be it known that I, EDWIN H. ARMSTRONG, a citizen of the United States, now residing in Paris, France, have invented certain new and useful Improvements in Methods of Receiving High-Frequency Oscillations, of which the following is a specification.

This invention relates to a method of receiving transmitted high frequency oscillations as in radio telegraphy or radio telephony and it is particularly effective when receiving damped or undamped waves of short wave length. Another result achieved by the use of this invention is that because of its selectivity the interference caused by undesirable signals, strays, and atmospherics is greatly reduced.

The particular difficulties overcome by this invention will be understood from the following explanation: It is well known that all detectors rapidly lose their sensitiveness as the strength of the received signals is decreased, and that when the strength of the high frequency oscillations falls below a certain point the response of a detector becomes so feeble that it is impossible to receive signals. The application of low frequency amplifiers assist somewhat up to a certain point, but the inherent noise in all low frequency amplifiers limits the extent to which low frequency amplification can be carried. It is also well known that the sensitiveness of a rectifier for weak signals may be restored by the use of the heterodyne principle, but this is only a partial solution of the problem inasmuch as this method can be used only in certain cases.

A solution for the loss of sensitiveness of the detector for weak signals lies in the amplification of the radio frequency currents before applying them to the detector. This has been recognized for some time and various forms of multi-tube vacuum tube amplifiers have been developed and successfully employed in practice on certain ranges of wave lengths. Because of the inherent capacity which exists between the elements of vacuum tubes, this method of amplification becomes increasingly difficult, as the frequency of the oscillations to be received increase. There are two principal points of difficulty encountered in the above method of amplification; first, there is a tendency of the amplifier system to oscillate, as the frequency is increased, and secondly, it is impossible to make the amplifier operate well at more than one frequency without a variety of adjustments. The limit of the practical amplifier at present is about 100 meters and the range of wave lengths from 0–100 meters are unused at the present time because of the difficulties of amplifying and detecting them. High frequency amplifiers have been constructed to operate on wave lengths as low as 200 meters, but with only fair efficiency.

The present invention discloses a method of indirect amplification and reception which operates independent of the frequency of the incoming oscillations and which, therefore, opens up the great range of wave lengths below 100 meters and makes possible, in fact, the use of waves of a few meters in length whereby radio communication by directed beams of energy becomes a practical proposition. The present invention may also be used to great advantage on wave lengths from 300 to 1,000 meters with a considerable gain in selectivity and sensitiveness, as compared to any of the known methods.

This new method of reception consists in converting the frequency of the incoming oscillations down to some predetermined and lower value of readily amplifiable high frequency current and passing the converted current into an amplifier which is adjusted to operate well at this predetermined frequency. After passing through the amplifier, these oscillations are detected and indicated in the usual manner. The intermediate frequency is always above good audibility, but beyond this requirement there is no other limitation as to what it shall be. The method of conversion preferred is the beat method known as the heterodyne principle, except that in the present system the beat frequency is always adjusted to a point above good audibility.

The process of converting the incoming high frequency oscillations down to the audible range may be carried out in several stages and each stage may be amplified by means of a multi-tube amplifier. The great advantage of this method is that the effect

E. H. ARMSTRONG.

METHOD OF RECEIVING HIGH FREQUENCY OSCILLATIONS.

APPLICATION FILED FEB. 8, 1919.

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Fig. 1.

Fig. 2.

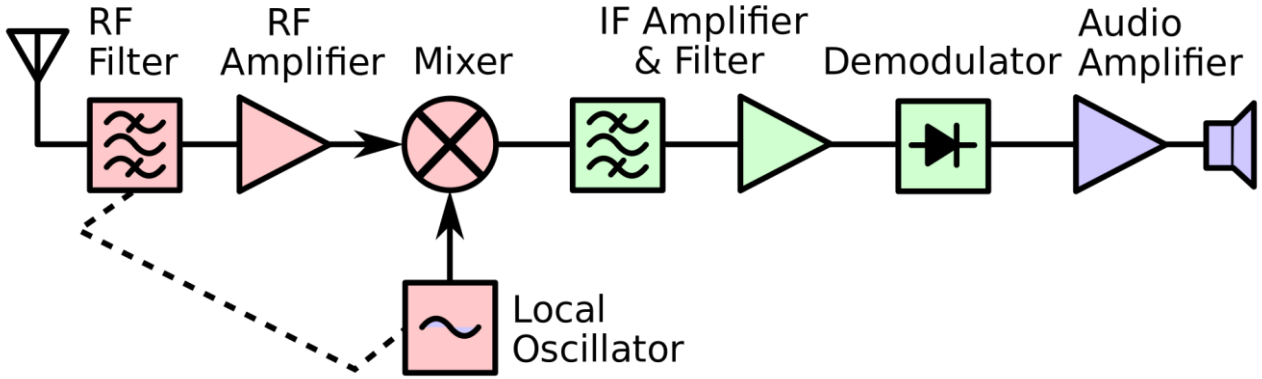
Fig. 3.

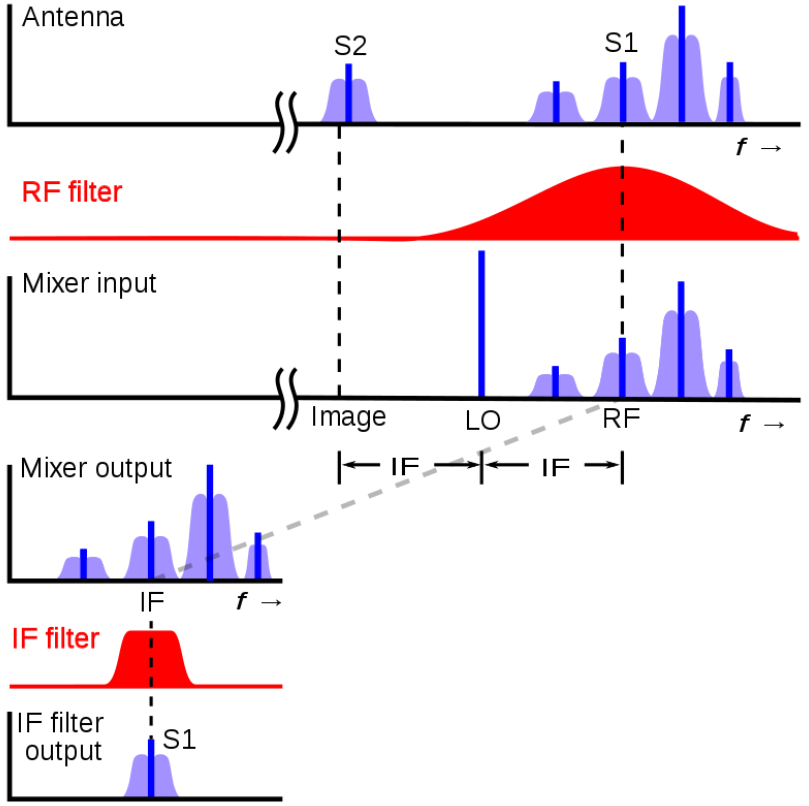
Fig. 4.

INVENTOR
Edwin H. Armstrong
BY
ATTORNEYS

Source: http://www.freepatentsonline.com/1342885.html

Superheterodyne receiver

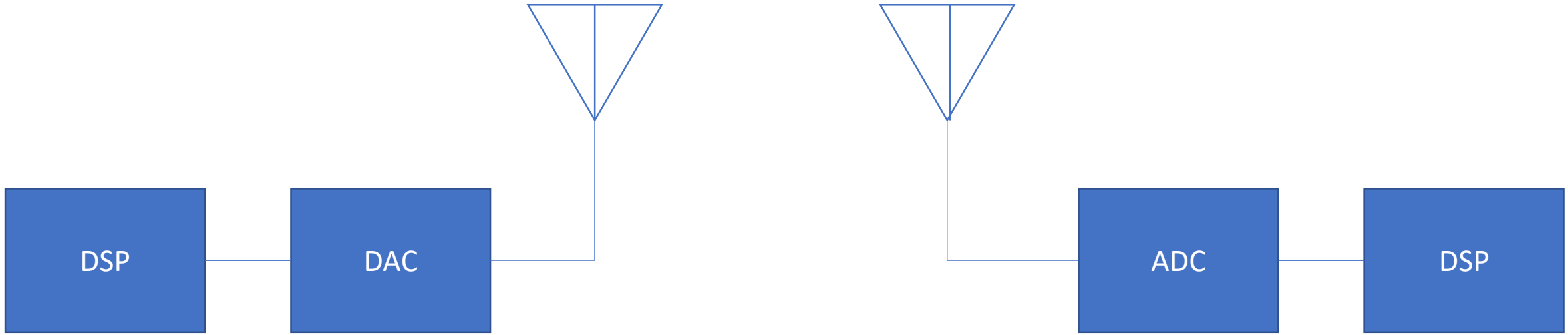




Sources:
https://en.wikipedia.org/wiki/Superheterodyne_receiver#/media/File:Superheterodyne_receiver_block_diagram_2.svg
https://en.wikipedia.org/wiki/Superheterodyne_receiver#/media/File:How_superheterodyne_receiver_works.svg

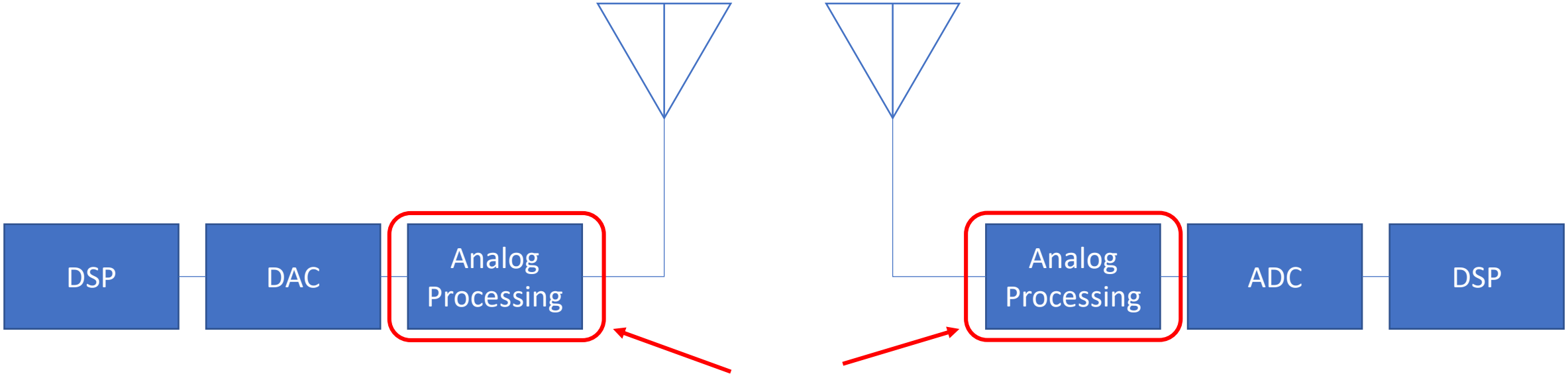
But… we don’t need that anymore, we have SDR!

Conceptual SDR models: perception



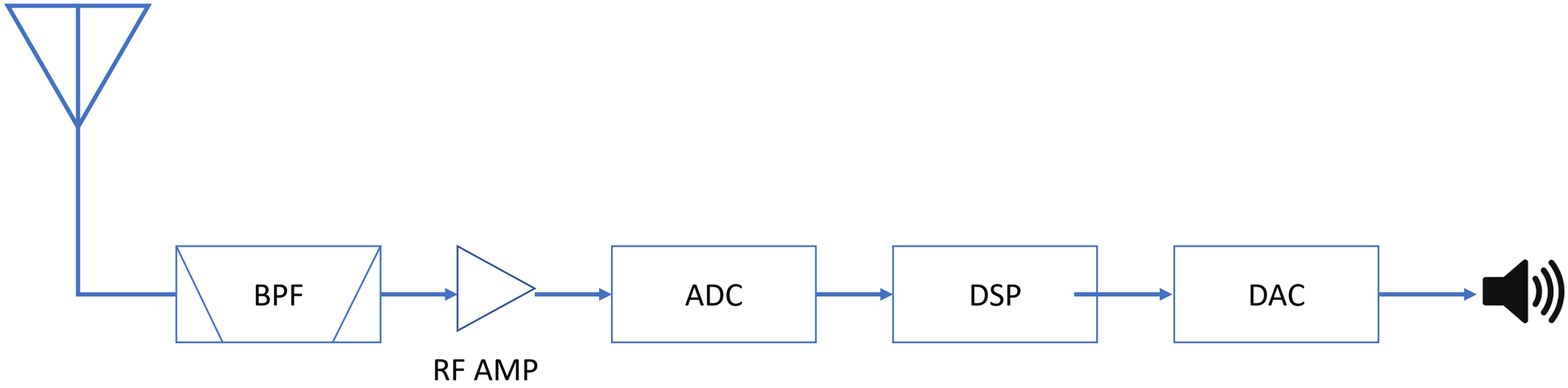
A common (and incorrect) model of software defined radios.
An ADC and an antenna, all we need?

Conceptual SDR models: reality

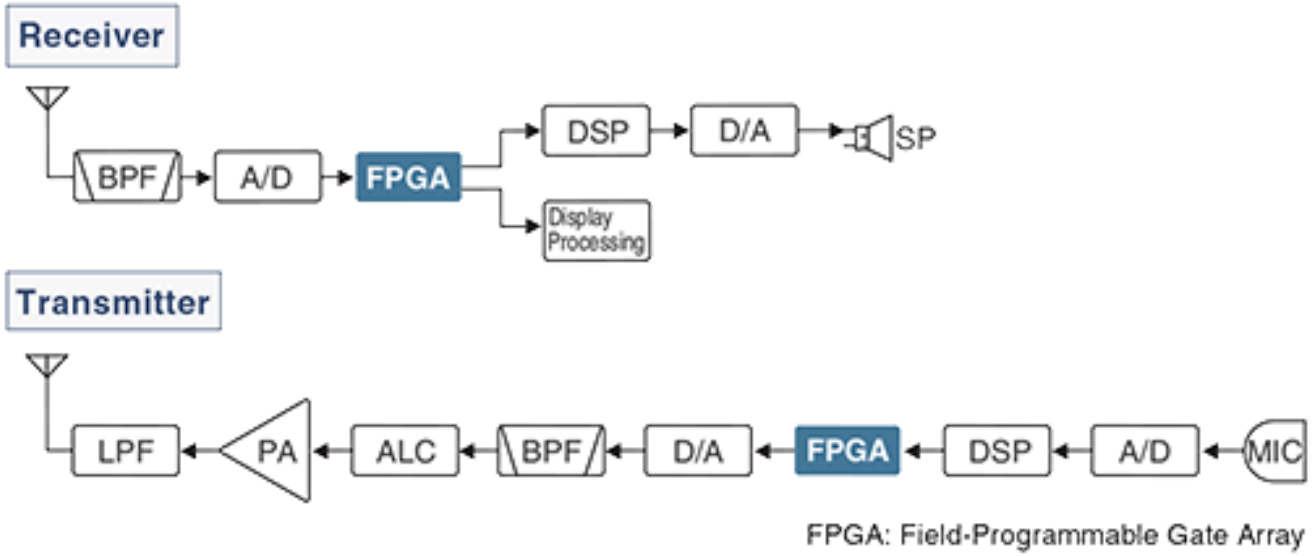


The analog processing can easily be as sophisticated and specialized to a particular frequency / bandwidth as a traditional transceiver design

Conceptual SDR models: Direct Sampling

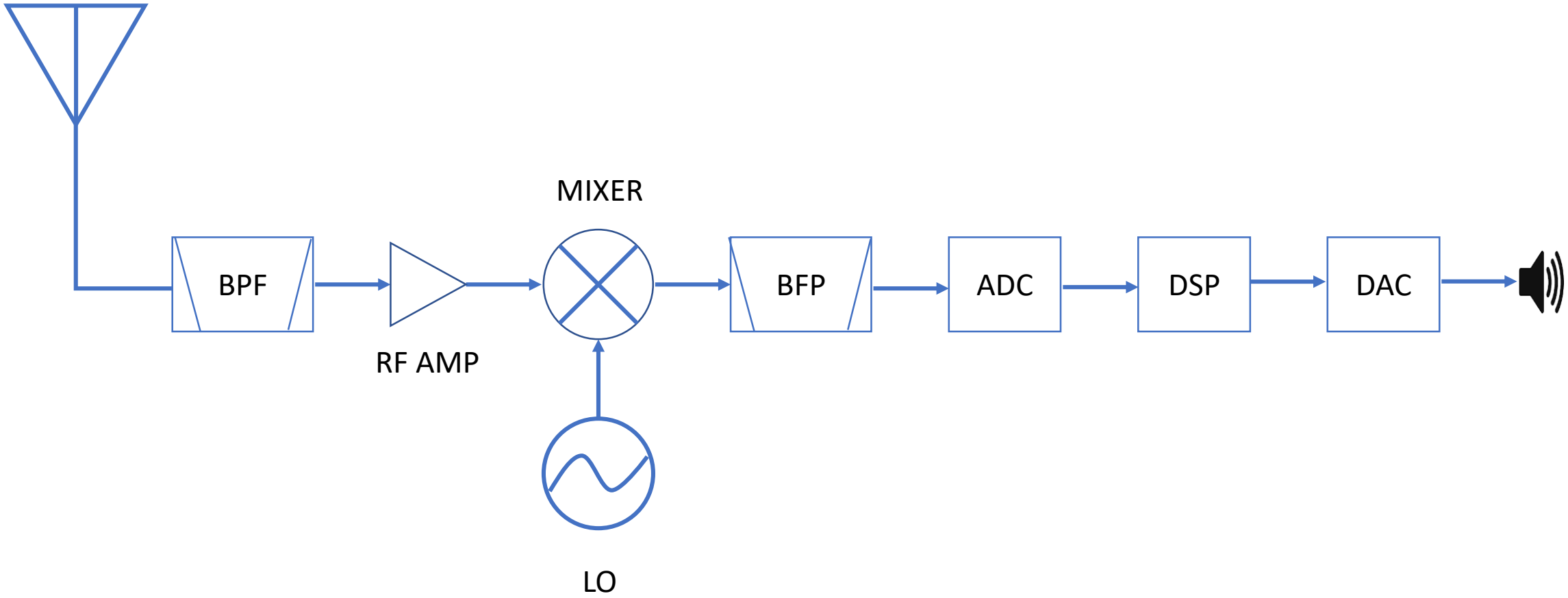


Commercial Example: IC-7300



Source: http://www.icomamerica.com/en/products/amateur/hf/7300/default.aspx

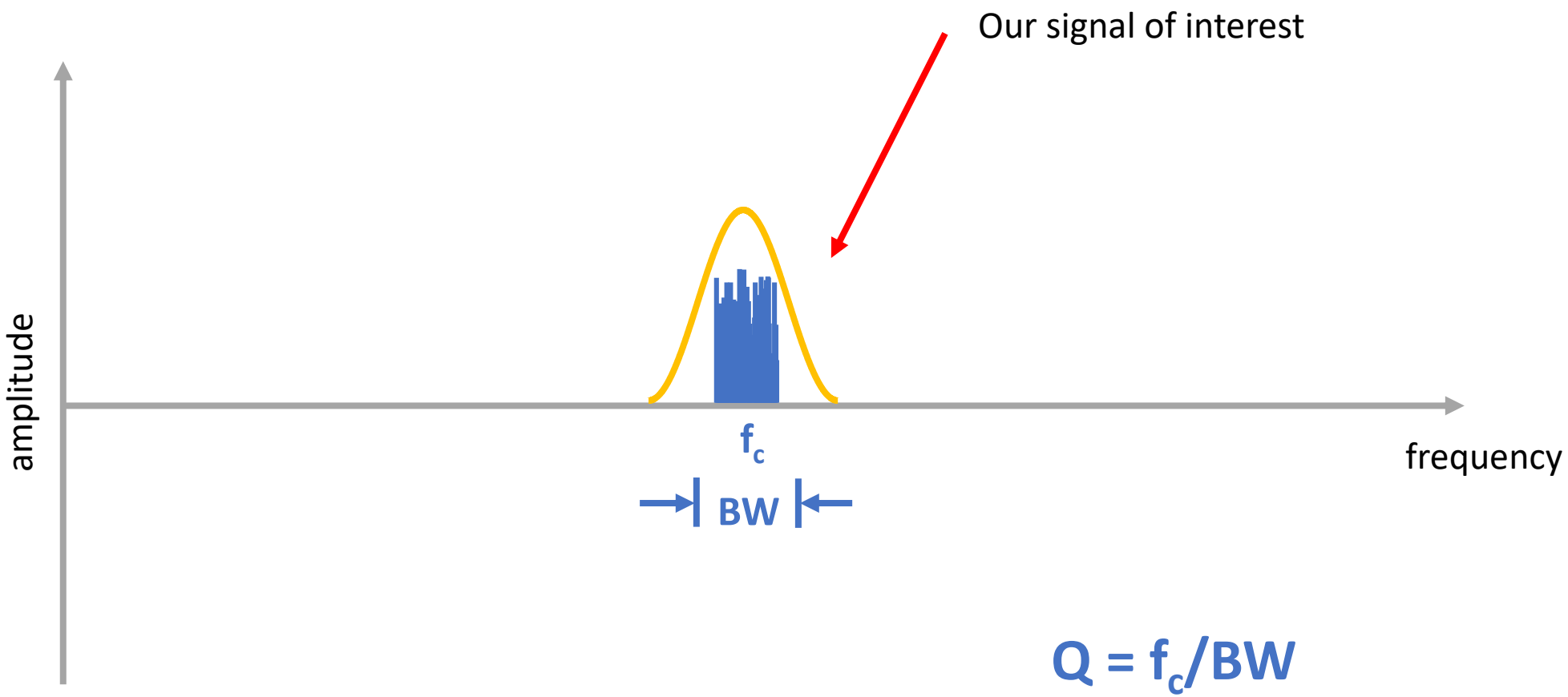
Conceptual SDR models: Superhet



Analog design and SDRs

- Analog components of SDR are as important as the digital
  - Once undesired signals (noise, interference) are aliased into our desired signals there is no way to completely remove them
  - Antenna and front-end design are critically important
  - Proper analog filtering is very important
  - Practical amateur VHF+ designs will most likely *not* be directly sampled – they will use a mixer and an IF frequency
- Your antenna is an important part of the analog front-end
  - Antennas provide spatial and frequency selectivity

Filtering quality (Q) factor



$$Q = f_c/BW$$

What do we need for amateur VHF+ applications?

Band	Frequency (MHz)	Bandwidth (kHz)	Q Factor **
6 Meters	50.1 – 54.0	25	2000
2 Meters	144.1 – 148.0	25	5760
1.25 Meters	220.0 – 225.0	100	2200
70 cm	420.0 – 450.0	6000	70
33 cm	902.0 – 928.0	6000	150
23 cm	1240 – 1300	6000	207
13 cm	2300 – 2310	1000	2300
13 cm	2390 – 2450	1000	2390
9 cm	3300 – 3500	22000	150
5 cm	5650 – 5925	>= 1000	5650
3 cm	10000 – 10500	>= 1000	10000

** best case, e.g., highest bandwidth on ARRL bandplan

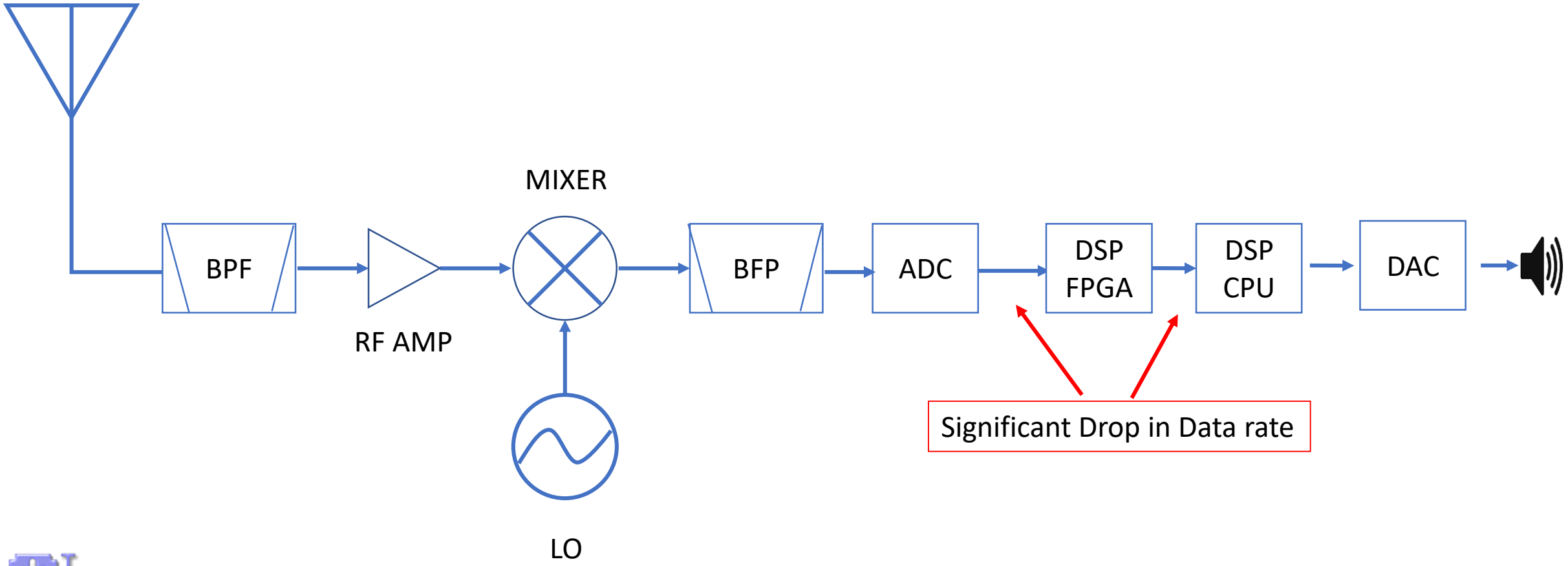
Those Q factors look awfully high…

- In traditional analog designs these might require double or triple conversion…

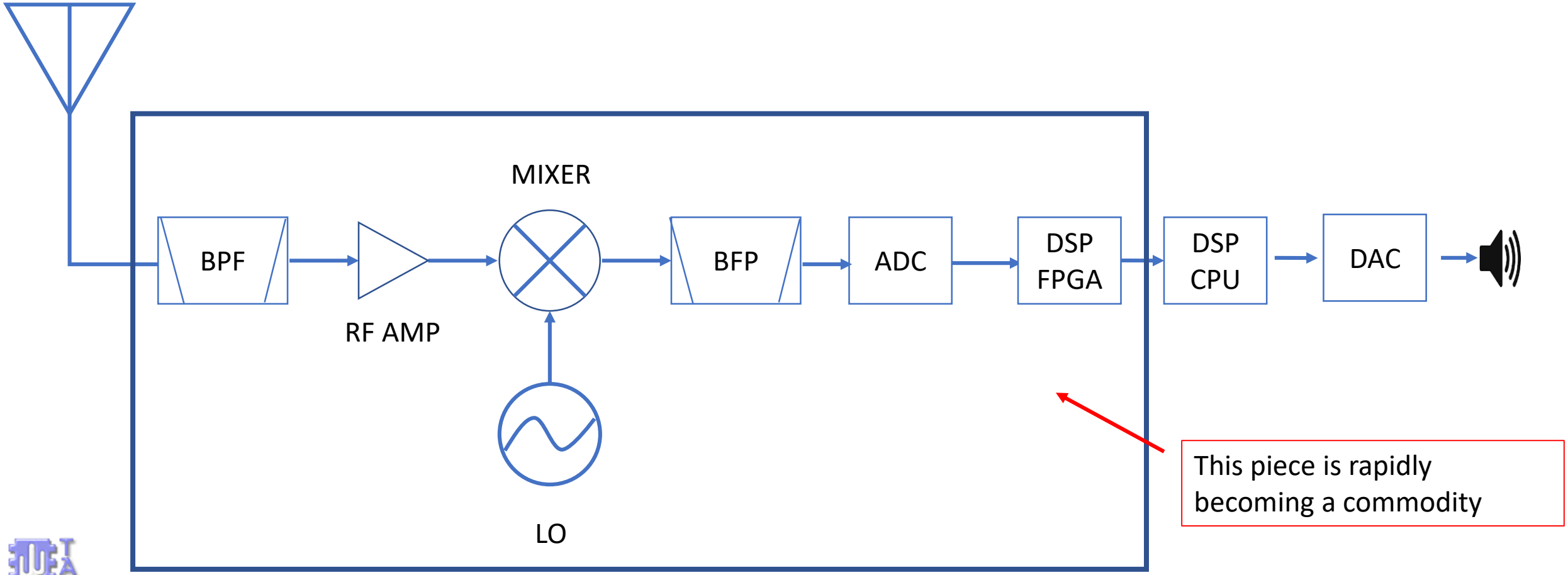
- But no problem, we can get super high rate ADCs!
- Use a lower Q factor analog filter and then a brick wall (or cascading brick wall) FIR filter once the data is digitized.

- But wait… isn't that an awful lot of data?
  - Yes, more than we can deal with on a commodity PC / standard computer buses

Conceptual SDR models: With Pre-processing FPGA



Conceptual SDR models: With Pre-processing FPGA



Thick Pipe vs. Thin Pipe

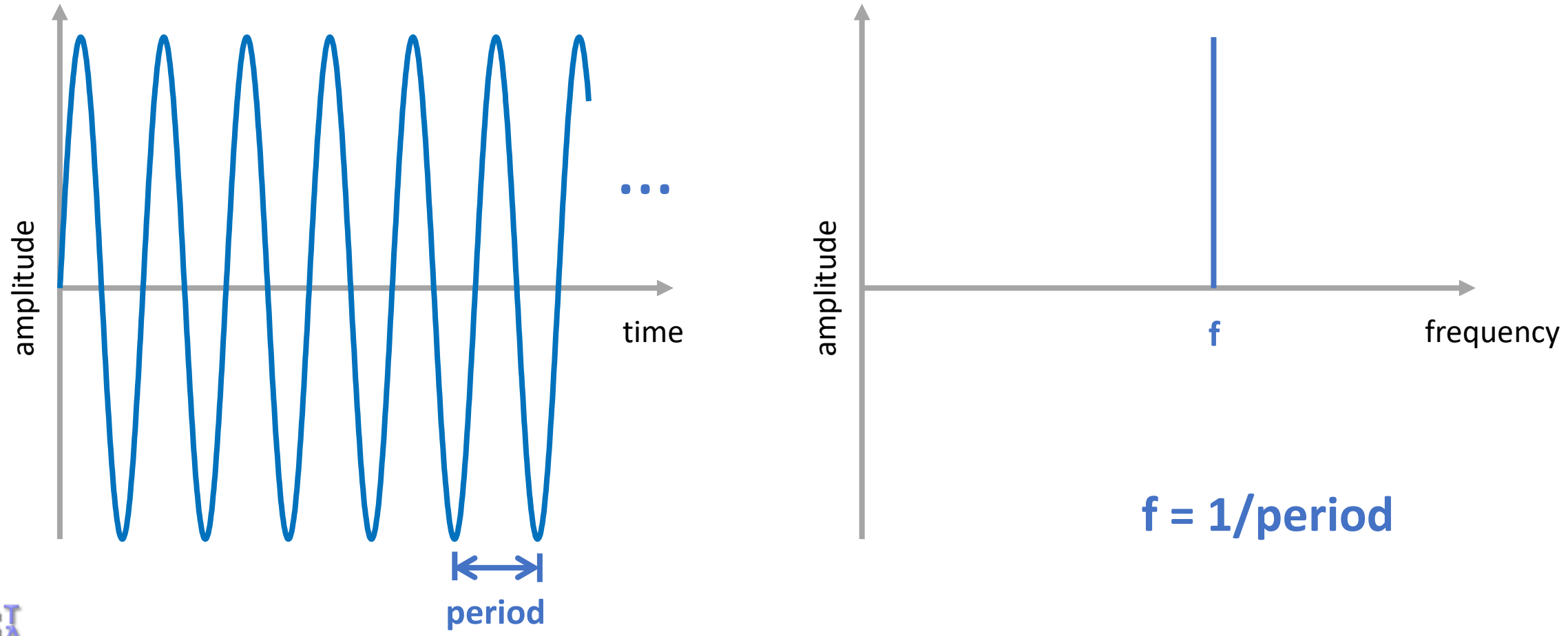
Source: http://flexradio.com

Signal Processing

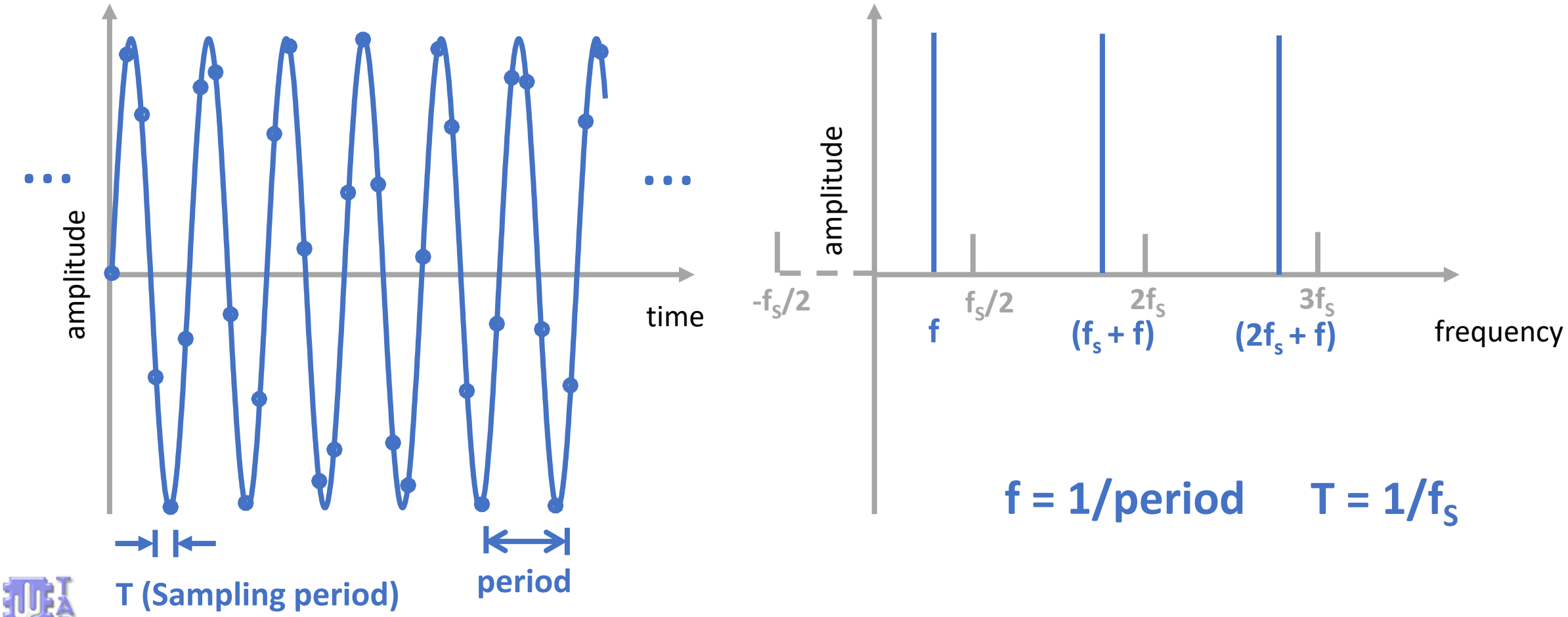
What is Signal Processing?

- Manipulation of signals representing real-world values such as amplitude, phase, temperature, etc.
- This manipulation of signals enhances them in some way:
  - Remove or lessen noise and interference
  - Accentuate a signal or signal attribute of interest
  - Extract information (e.g., demodulate digital information)
- Common signal processing tasks:
  - Filtering (attenuation of signals based on frequency)
- Typically involves working with both a time (continuous or discretely-sampled) and frequency (continuous of discretely-sampled) domain

Time and Frequency Domains: Continuous

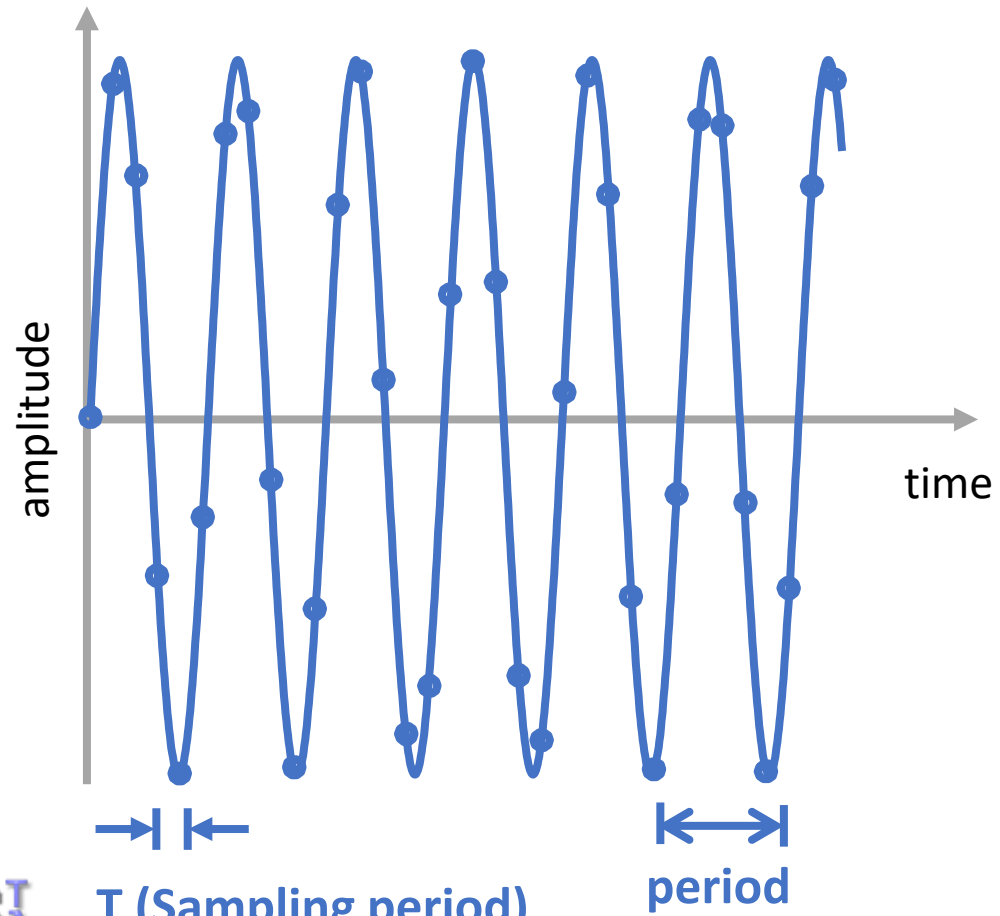


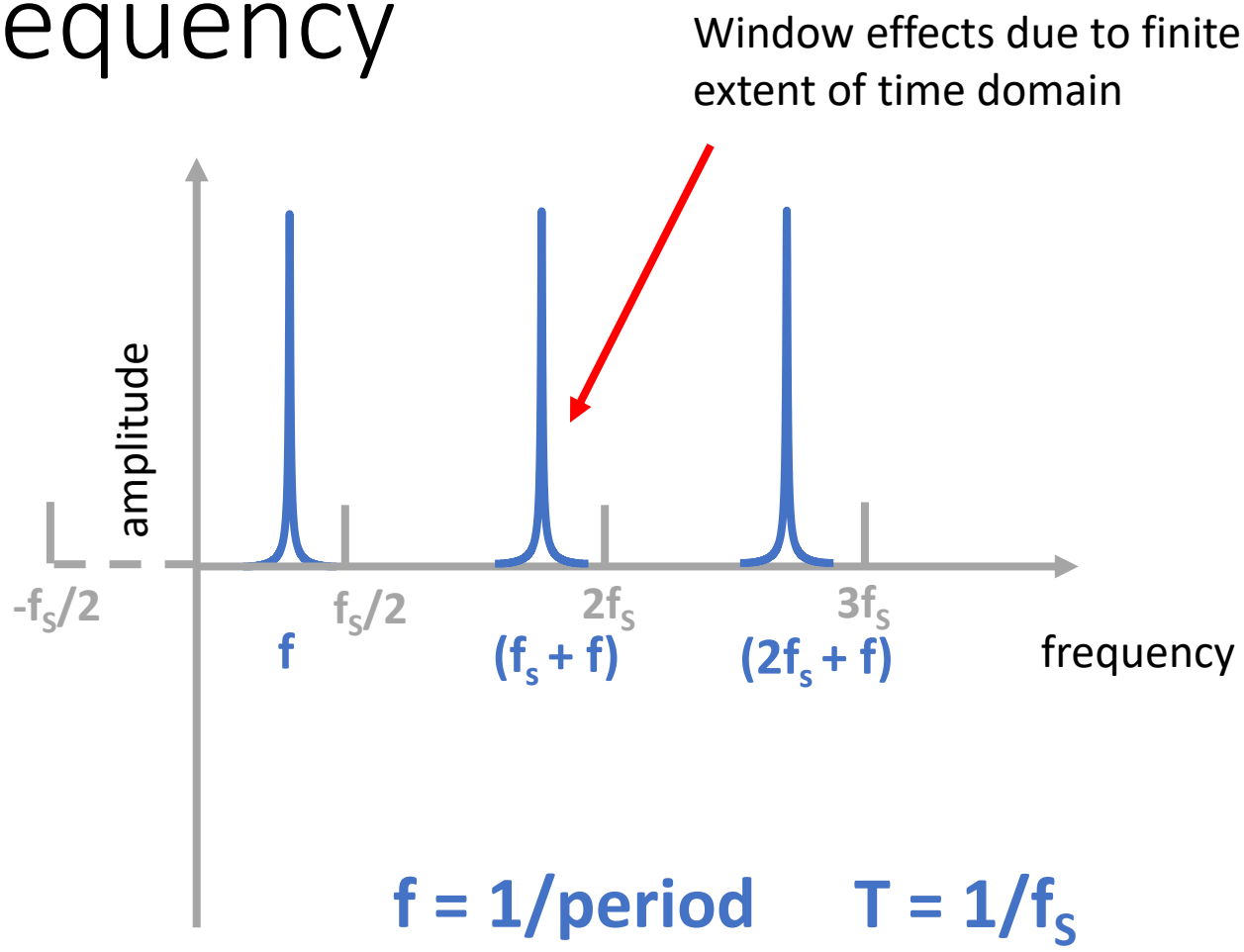
Time and Frequency Domains: Discrete Time



Frequency of Complex Exponential / Complex (IQ) Sampled

Time and Frequency Domains: Discrete Time and Frequency





Frequency of Complex Exponential / Complex (IQ) Sampled

Sampling

- Sampling in one domain leads to periodicity in the other
- **Nyquist–Shannon sampling theorem [1]**
  - “If a function x(t) contains no frequencies higher than *B* hertz, it is completely determined by giving its ordinates at a series of points spaced 1/(2*B*) seconds apart.”
- Anything outside the frequency limits will alias

[1] Shannon, Claude Elwood. "Communication in the presence of noise." *Proceedings of the IRE* 37.1 (1949): 10-21.

Signal Processing Domains for Mixed-signal Systems

Type of Signals	Time	Frequency	Fourier Transform	Filter Design
Continuous time analog processing	Continuous	Continuous	Continuous Fourier Transform	Laplace Transform (s-domain)
Sampled-data analog processing	Discrete	Continuous (Periodic)	Discrete-time Fourier Transform (DTFT)	Z-Transform (z-domain) **
Sampled-data digital Processing	Discrete (Periodic)	Discrete (Periodic)	Discrete Fourier Transform (DFT)	Z-Transform (z-domain) ** / DFT

**For IIR Filter Design we can use the bilinear transform $s = \frac{2(z-1)}{T(z+1)}$

Analog processing

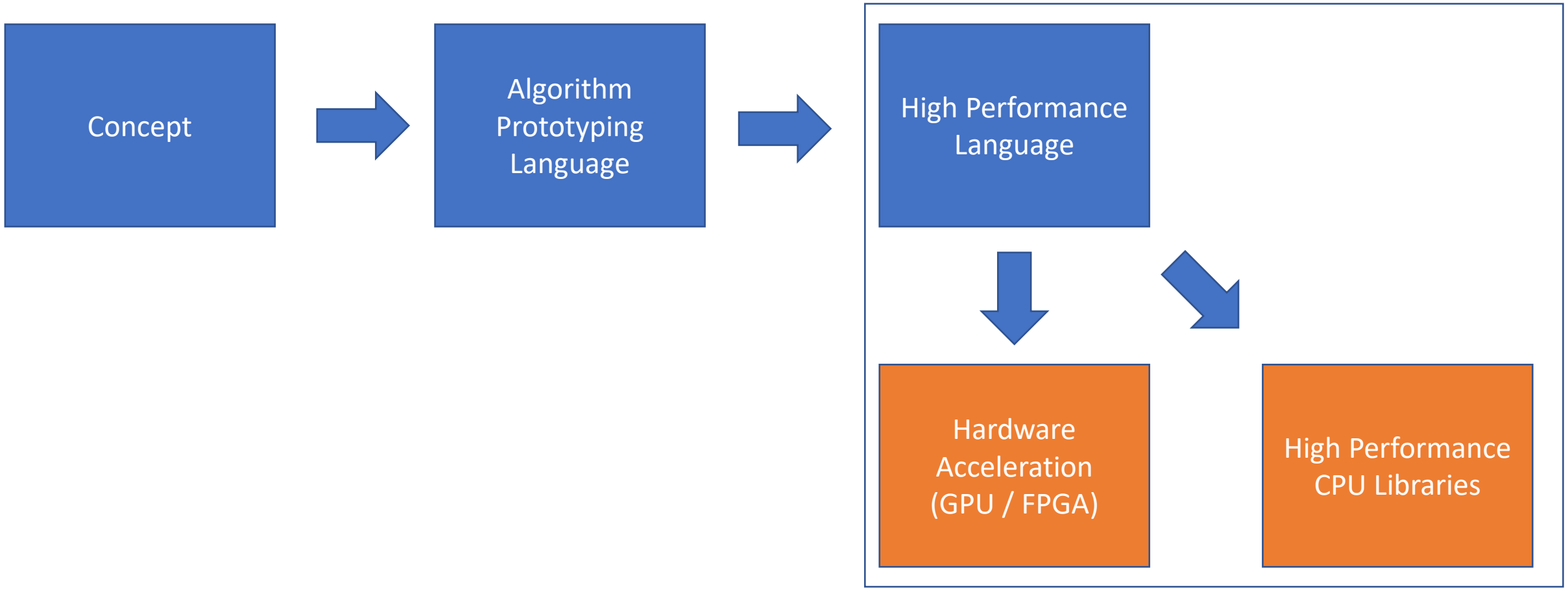
- Mixed-signal design (that is, analog and digital on one chip) is very difficult
  - Only a handful of development group capable of achieving world class performance
- Component variations huge compared to discrete analog
- Component aging also a big concern
- A successful design will likely utilize external analog filtering
- Suggestions for designing analog filters:
  - The theory and math behind filter design is fairly accessible
    - No need to use canned design tools, dig into the design!
    - Analog filter design is typically taught in a EE course titled “Circuit Design” with lots of material available on the open web
  - Learn the basics of the Laplace transform
  - Sanity check and DC and Daylight
  - Use consistent axis when plotting responses to build intuition

Resources for further Learning

- MIT Open Courseware: Digital Signal Processing
  - Prof. Alan V. Oppenheim
  - https://ocw.mit.edu/resources/res-6-008-digital-signal-processing-spring-2011/video-lectures/lecture-14-design-of-iir-digital-filters-part-1/
- Analog Filter Design (e.g., Laplace Transforms)
  - Typically covered in an undergrad course called Electric Circuits
    - https://ocw.mit.edu/courses/electrical-engineering-and-computer-science/6-002-circuits-and-electronics-spring-2007/index.htm
  - Also covered in Digital Signal Processing (DSP) Courses (e.g., Lecture 14 in MIT course)
  - Lots of HAM recourses
    - For example: http://www.arrl.org/rf-and-af-filters
- Digital Filter Design
  - Covered in DSP Courses (e.g., Lecture 17 in MIT Course)

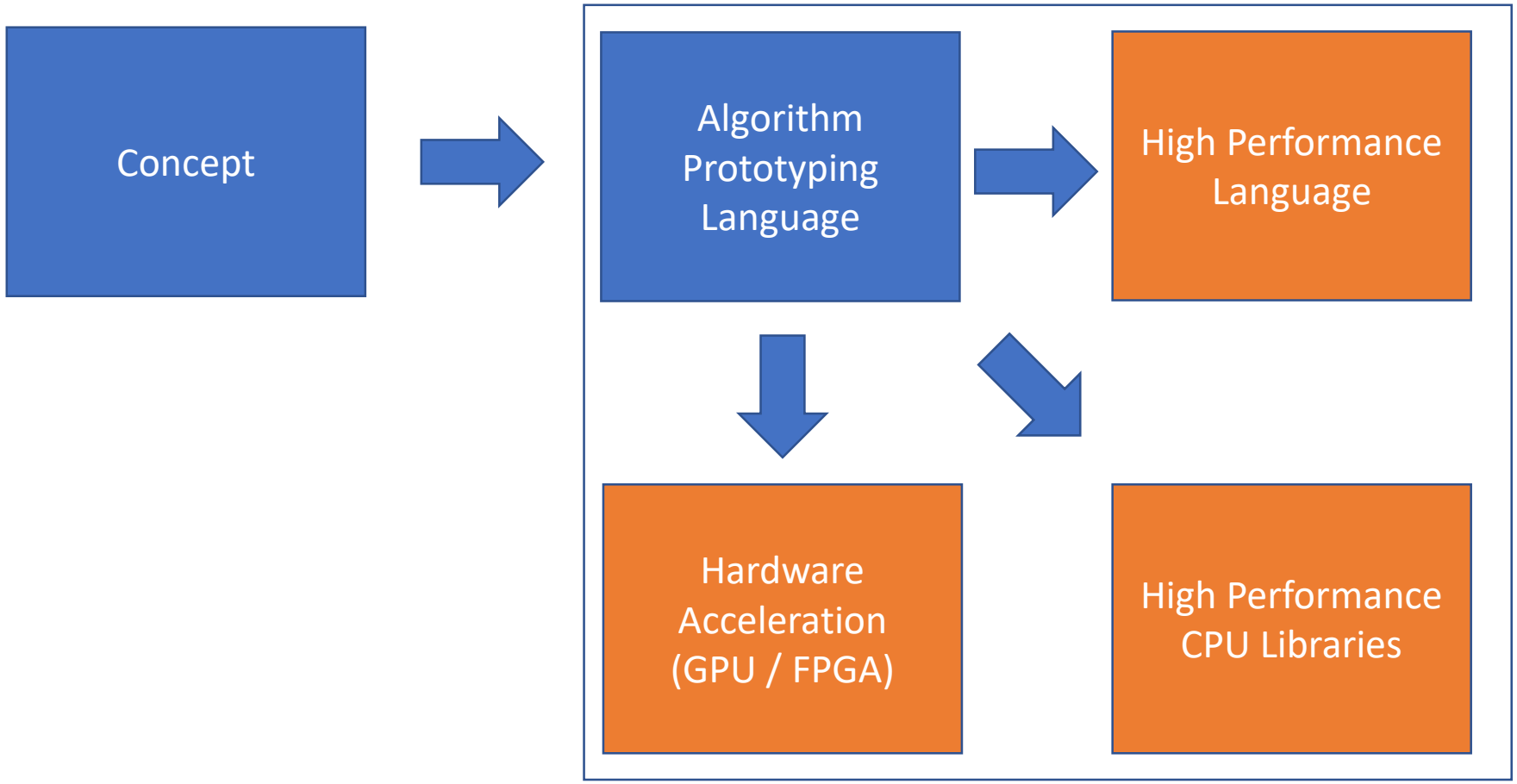
Practical DSP: Theory and Implementation

Signal Processing Development Model (1)

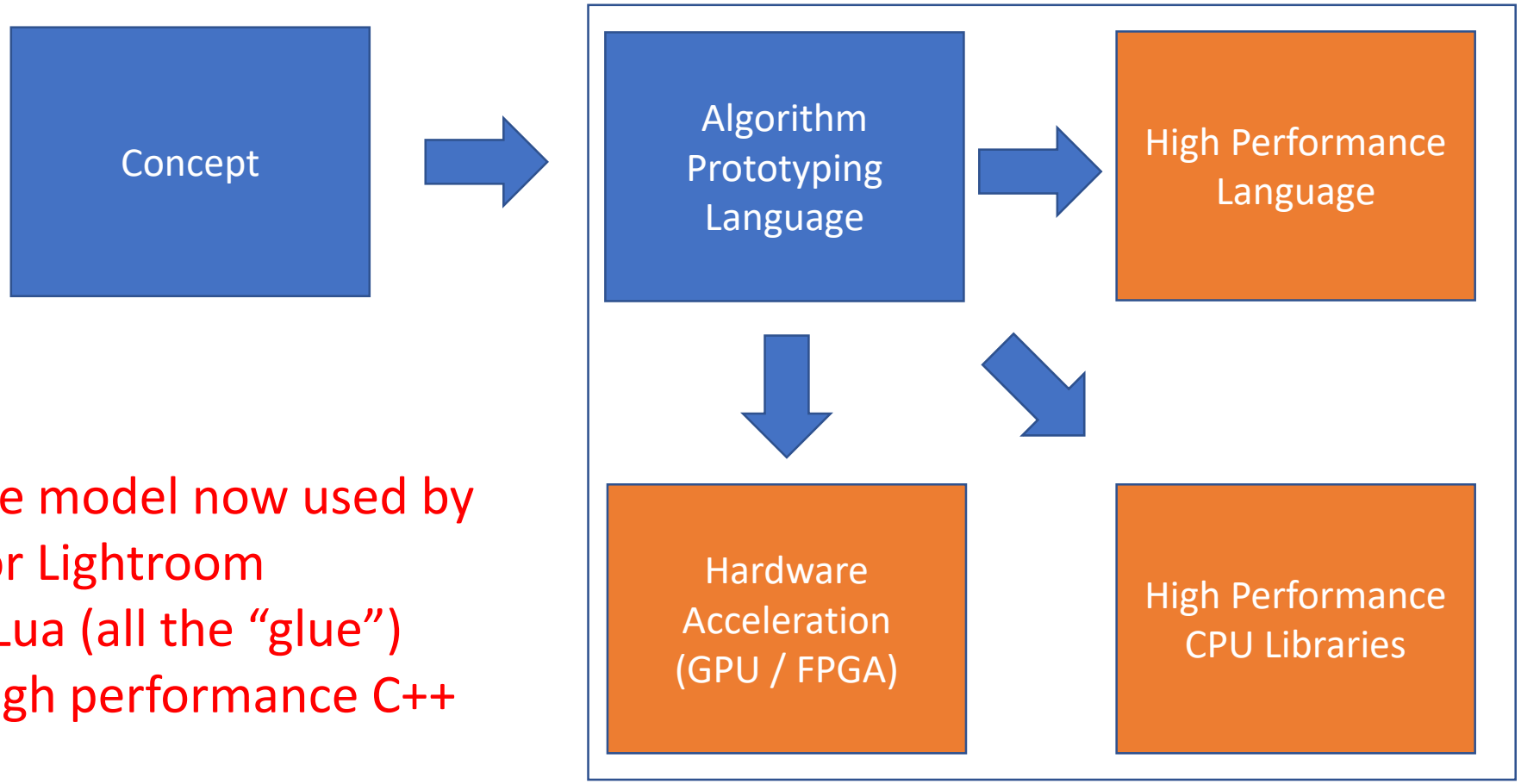


Final Design

Signal Processing Development Model (2)



Signal Processing Development Model (2)



This is the model now used by Adobe for Lightroom

- 60%+ Lua (all the “glue”)
- 30% high performance C++

Development Environments

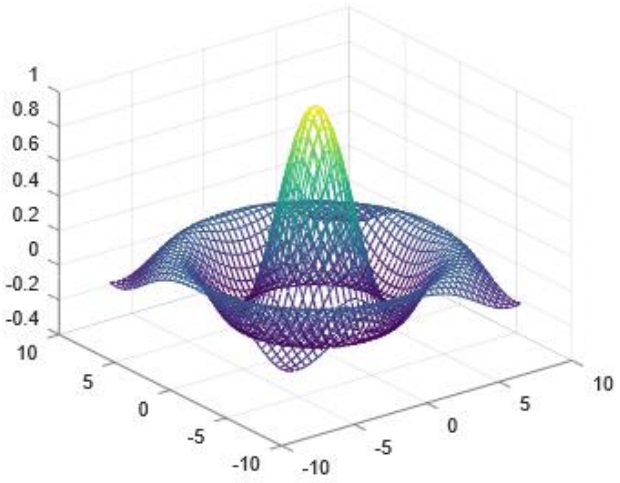
- Algorithm development / prototyping languages
  - MATLAB (Octave / Scilab)
  - Scientific Python
  - Julia
- High performance languages and libraries
  - C/C++
  - Classic Numerical Libraries (BLAS, LAPACK)
  - OpenMP, OpenCL, CUDA
  - C++ Templated Libraries
    - Armadillo, Eigen, FLAME
- Hardware Acceleration
  - VHDL
  - OpenCL (High level language that supports GPU / FPGA acceleration)

MATLAB

- The defacto (and in my opinion, best) algorithm design language for signal processing
- Expensive for commercial use, but relatively inexpensive for personal, hobby, and student licenses
- Home: $149 Base + $49 / add on
- Student: $49 Base + $29 / add on
- Great debugger and visualization support build in
- Used in many classrooms, and so there is a lot of support on the web
- Born in New Mexico! (Clive Moler / UNM)

http://mathworks.com

MATLAB compatible languages



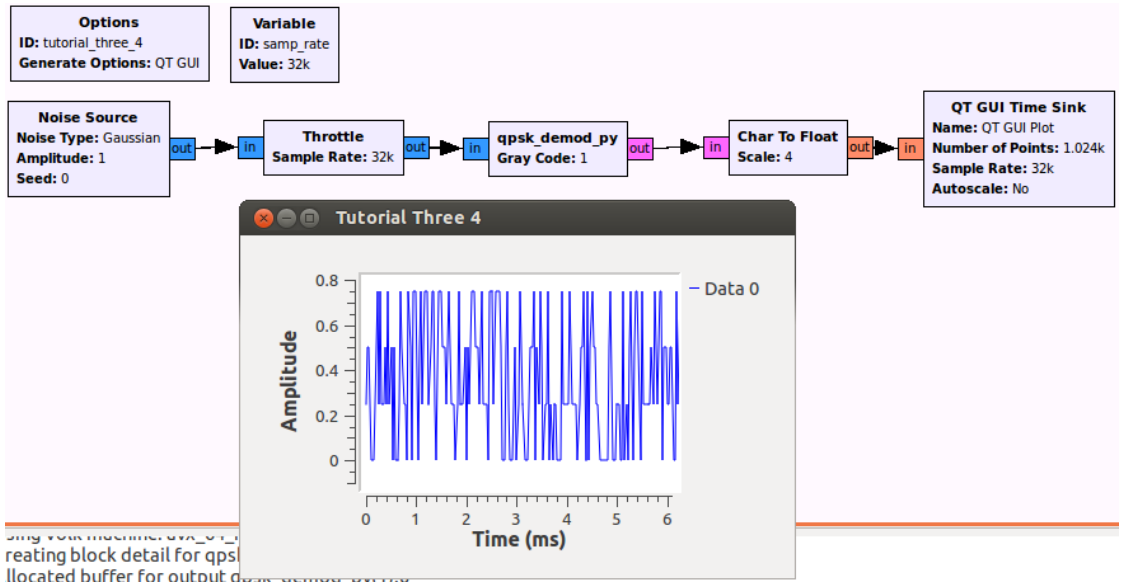
GNU Octave
http://gnu.org/software/octave

Scilab
http://scilab.org

FreeMAT
http://freemat.sourceforge.net/

GNU Radio

- Free, open source
- Actively developed
- Lots of add on packages available
- Provides signal processing blocks that can be tied together to implement software radios

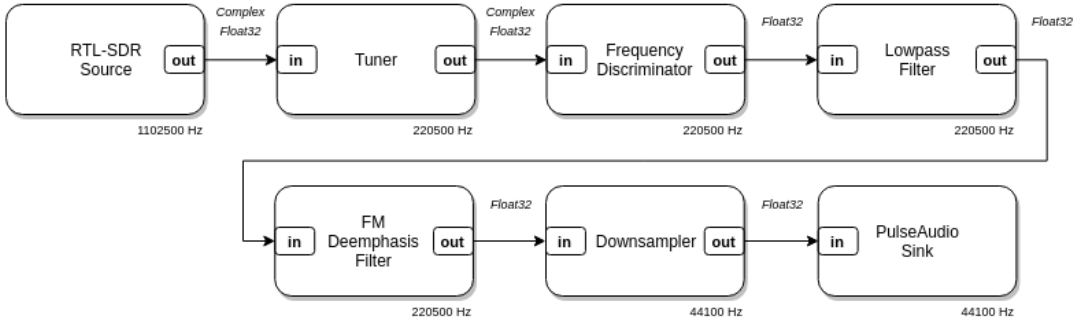


http://gnuradio.org

Image source: https://wiki.gnuradio.org/index.php/Guided_Tutorial_GNU_Radio_in_Python

LuaRadio

- Free, open source
- Actively developed
- Lightweight, embeddable flow graph signal processing framework for software-defined radio.
- Similar to GNU Radio, but smaller and more lightweight: designed to be embedded



http://luaradio.io/

Scientific Python

- Free, open source
- Actively developed
- Lots of add on packages available
- Integrates well with compiled C/C++ code
- Actually refers to a set of base packages:
  - Python
  - NumPy
  - SciPy
  - Matplotlib
  - etc…
- Several different interfaces are available
  - iPython
  - Spyder
  - …

https://www.scipy.org/

SciPy Distributions

- Anaconda (https://www.continuum.io/downloads)
- Enthought Canopy (https://www.enthought.com/products/canopy/)
- Python(x,y) (http://python-xy.github.io/)
- WinPython (http://winpython.github.io/)
- Pyzo (http://www.pyzo.org/)

SciPy.org provides links to all of the above

Julia

- Free, open source
- Actively developed
- Lots of add on packages available
- Integrates well with compiled C/C++ code

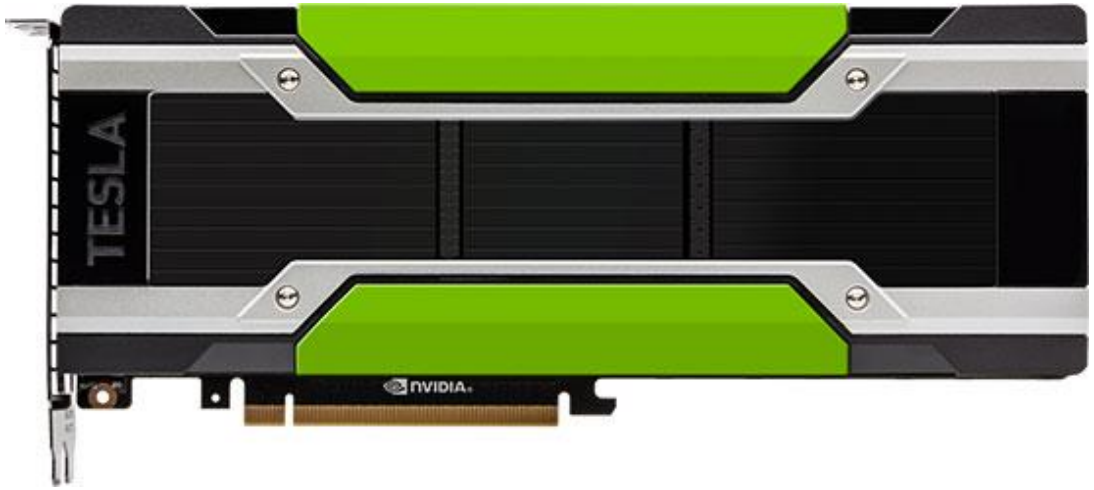
https://julialang.org/

High performance numerical libraries

- First, the classics:
  - Basic Linear Algebra Subprograms (BLAS)
    - http://www.netlib.org/blas/
  - Linear Algebra Package (LAPACK)
    - http://www.netlib.org/lapack/
  - Fastest Fourier Transform in the West (FFTW)
    - http://www.fftw.org
- Templated Metaprogramming:
  - Armadillo: C++ Linear Algebra
    - http://arma.sourceforge.net
  - FLAME
    - http://www.cs.utexas.edu/~flame/web/
- Open Computing Language (OpenCL)
  - https://www.khronos.org/opencl

Hardware Accelerators

GPUs



5.3 TeraFLOPS double / 10.6 TeraFLOPS single

NVIDIA Tesla P100
Source: http://www.nvidia.com

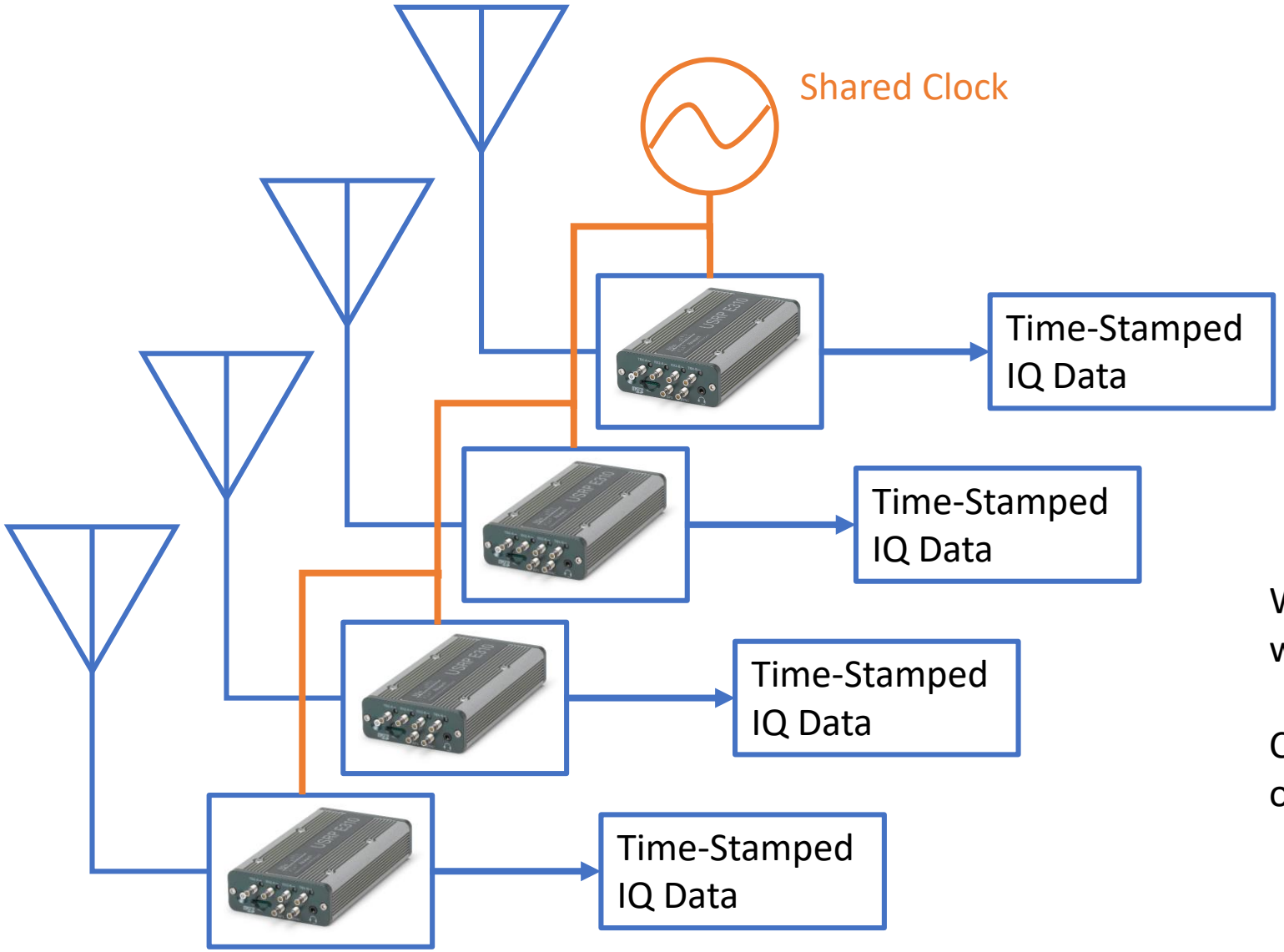
FPGAs

Two Arria 10 FPGAs / 3+ TeraFLOPS

Nallatech 510T
Source: http://www.nallatech.com

Ham Applications

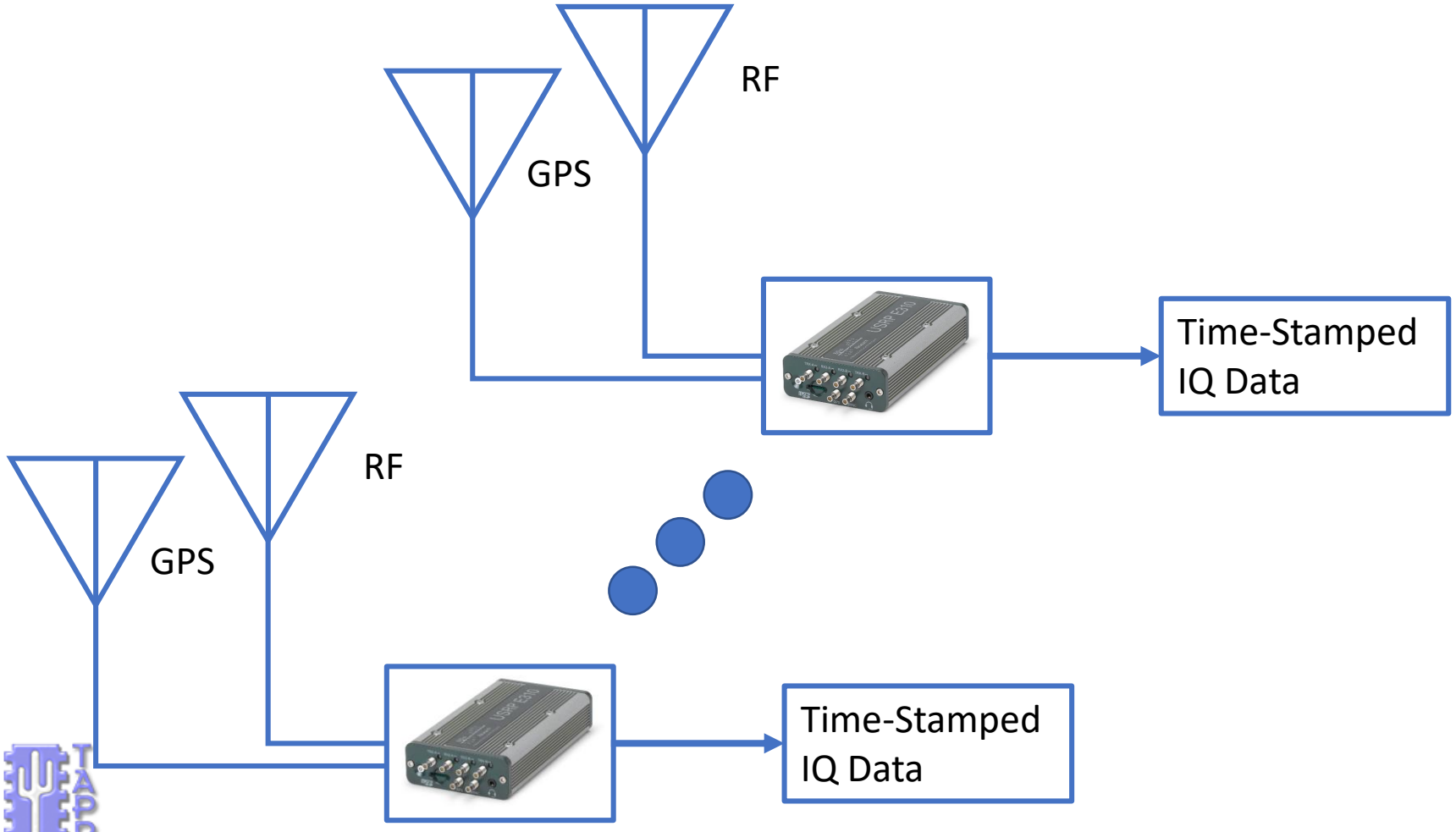
Beamforming: Local



We can form any beam we want in post-processing!

Can also steer NULLS to notch out noise sources

Beamforming: Distributed



Could we build a large scale distributed receiver for HAM experimentation over the internet?

Hat Tip: Ed James KA8JMW

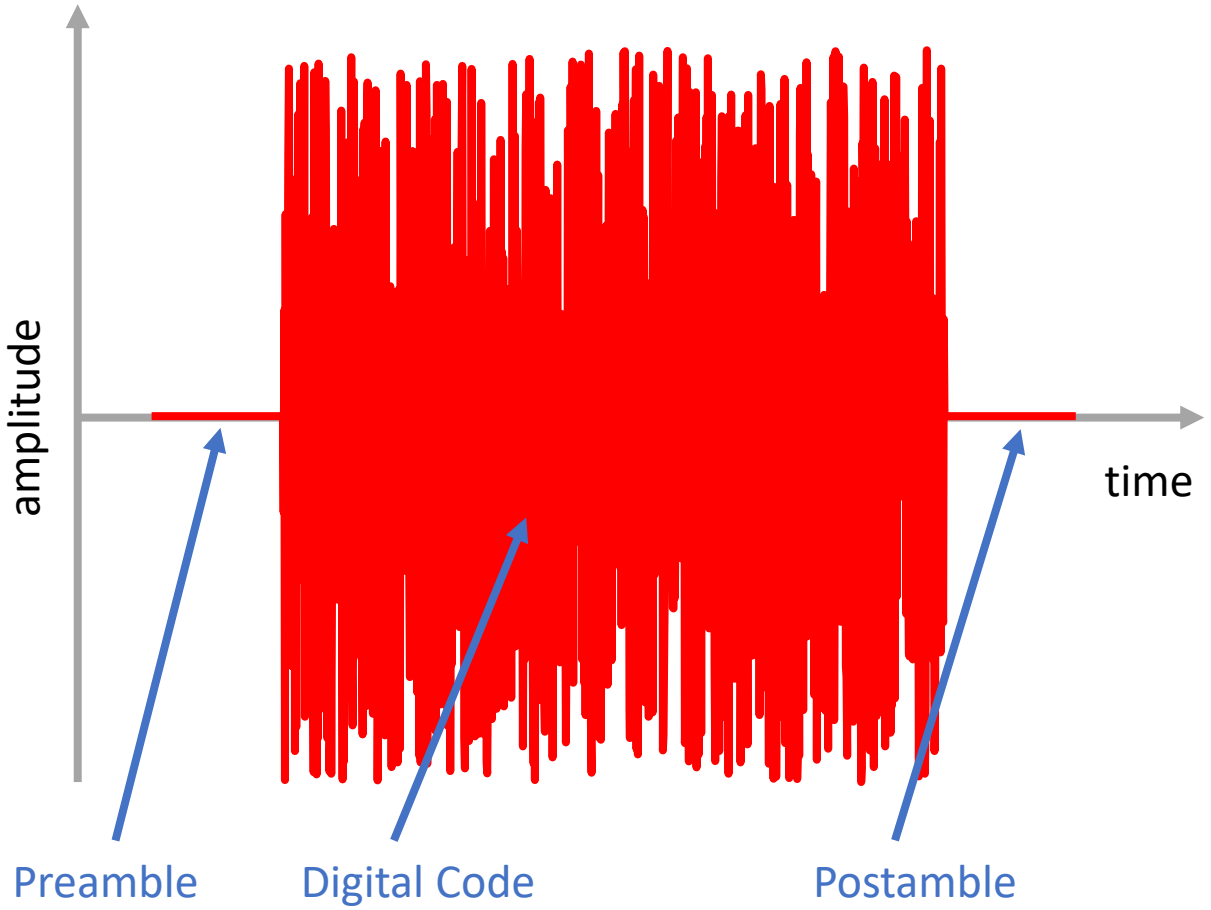
Beamforming: Distributed (Alternative)

- There are many commercial transmitters that have very good time stability
- For example: cell phone towers
- Can we have multiple digital receivers capture a known signal and cross correlate for timing?
  - For instance, the GSM Frequency Correction Channel (FCCH)

Beacon Concept

- Transmit a message consisting of:
  - Preamble
  - Message
  - Postamble
- Steer beam and run a search for preamble and postamble
  - Once detected can use to measure frequency drift
- Demod digital code for verification
- Total probability of false alarm is:

  $PFA = 1 - (1-PFA_{PRE})(1-PFA_{CODE})(1-PFA_{POST})$



Questions?