Classical and Modern Modulation Techniques

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Outline:

1. Wireless Telegraphy (Spark and CW)
2. Amplitude Modulation (AM)
3. Single Side-band (SSB) Modulation
4. Frequency Modulation (FM)
5. Digital Modulation (ASK, FSK, PSK, QAM)

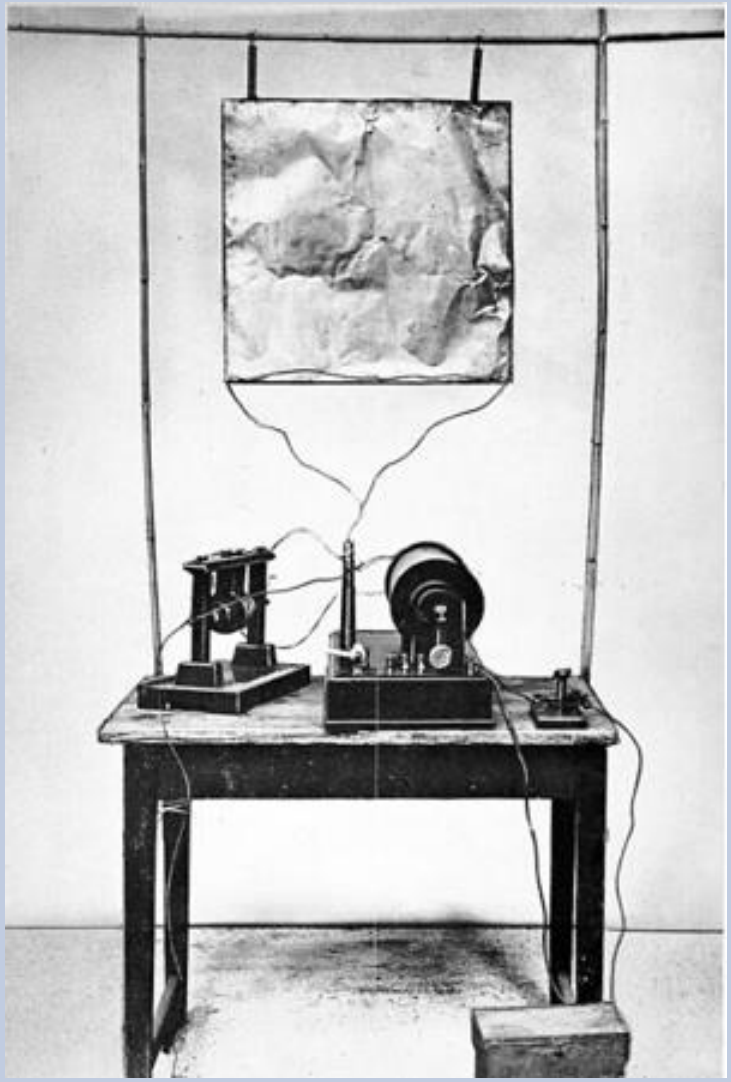
Category	Modulation Type	Key Features	Example Uses
Analog Modulation	AM	Varies Amplitude of Carrier	AM Radio
	FM	Varies Frequency of Carrier	FM and Two-way Radio
	PM	Varies Phase of Carrier	Analog TV and Satellite
Digital Modulation	ASK	Amplitude represents binary data	RFID, Optical Comm
	FSK	Frequency shift encodes data	Modems, Bluetooth
	PSK	Phase of carrier encodes bits	Wi-Fi, Satellite
	QPSK	4 phase states: two bits per symbol	DVB, LTE
	QAM	Both amplitude and phase vary; can transmit multiple bits	Cable TV, Wi-Fi
	OFDM	Multiple carriers, each modulated separately	4G/5G, Wi-Fi
Pulse Modulation	PWM	Pulse width represents amplitude	Motor Control, Audio
	PPM	Pulse position within a time slot represents data	Optical Comm., Radar
Spread Spectrum	DSSS	Signal bandwidth spread using code sequence	CDMA, GPS
	FHSS	Carrier hops between different frequencies	Bluetooth, Military

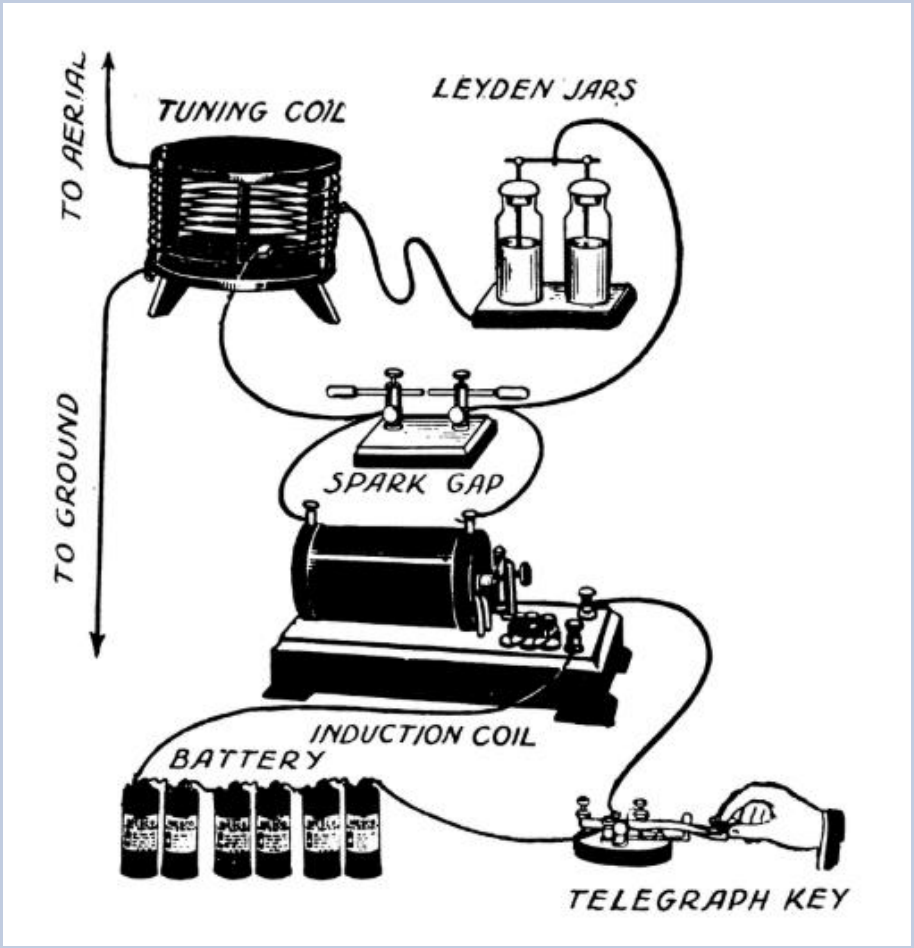
Wireless Telegraphy

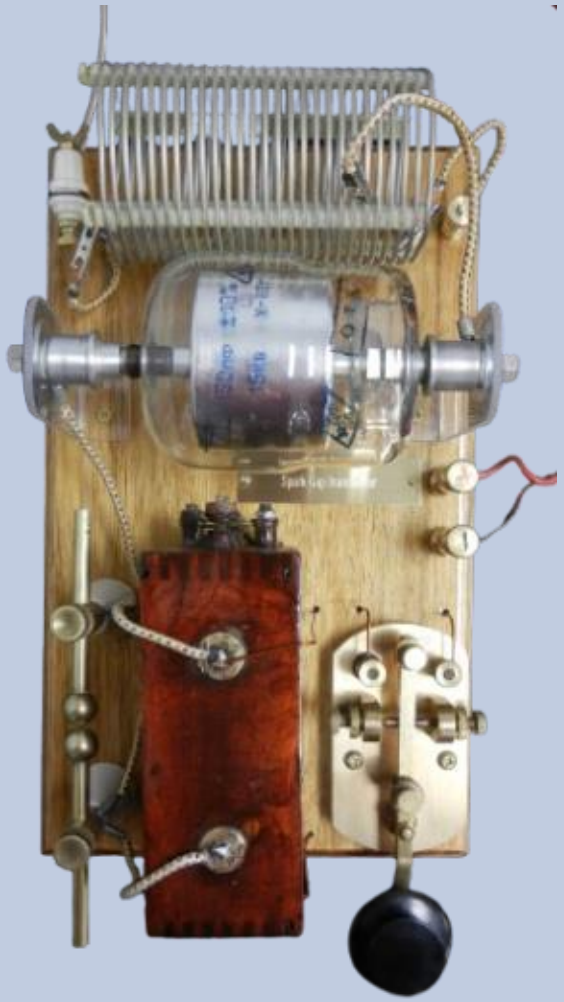


Guglielmo Marconi (1874-1937)

Wireless Telegraphy

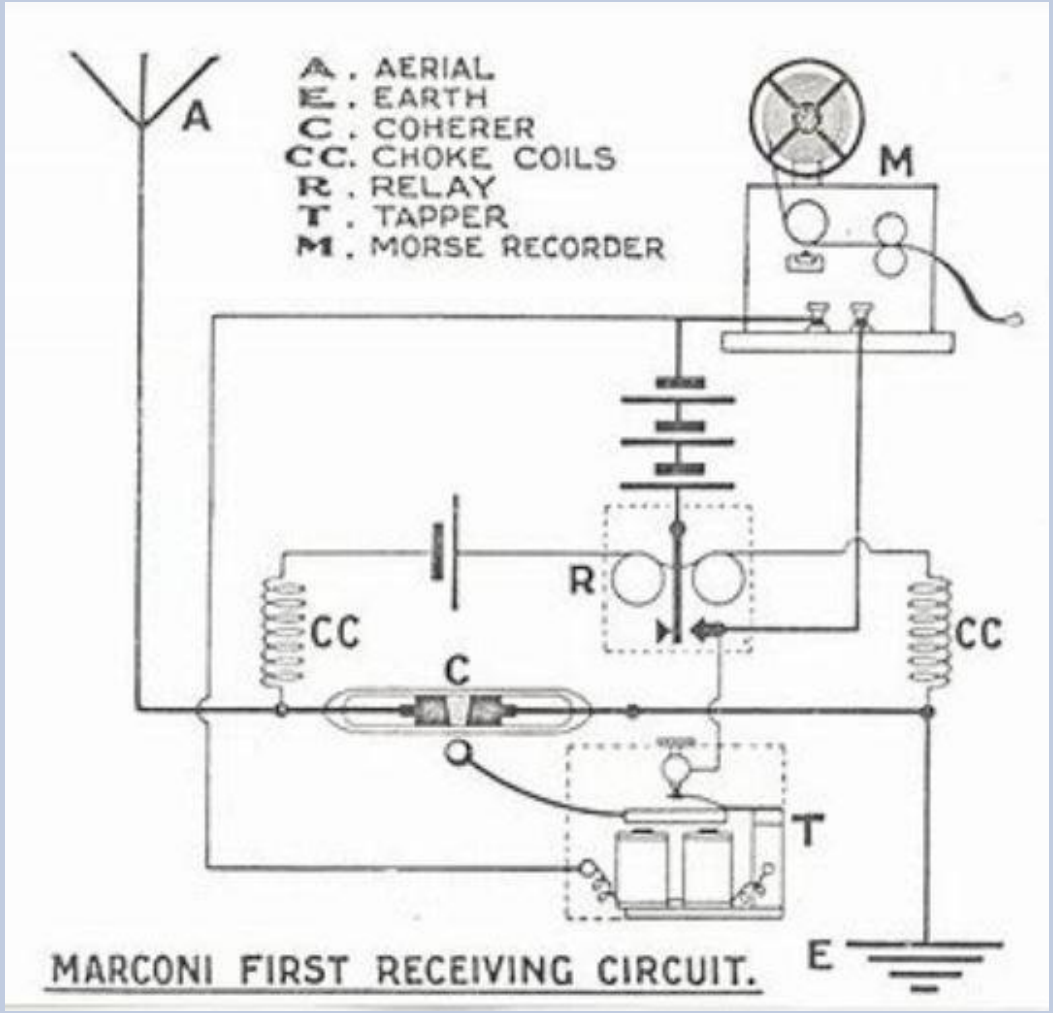






Marconi's first spark transmitter with a monopole antenna, a schematic from a 1917 boy's hobby book, and my 2017 replica

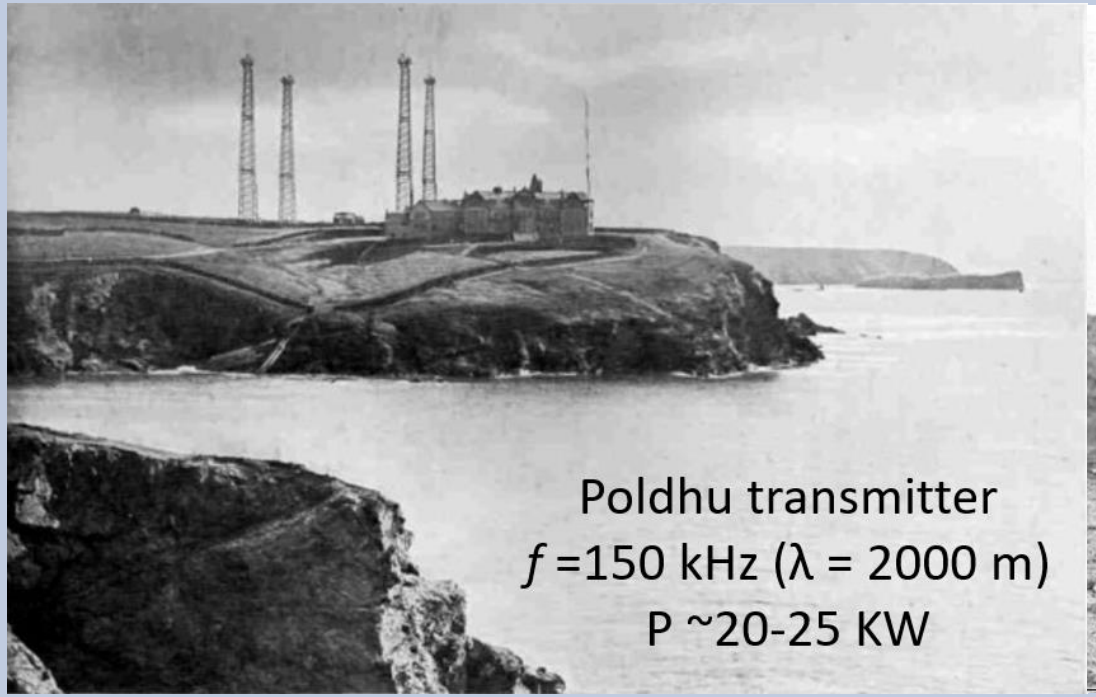
Wireless Telegraphy

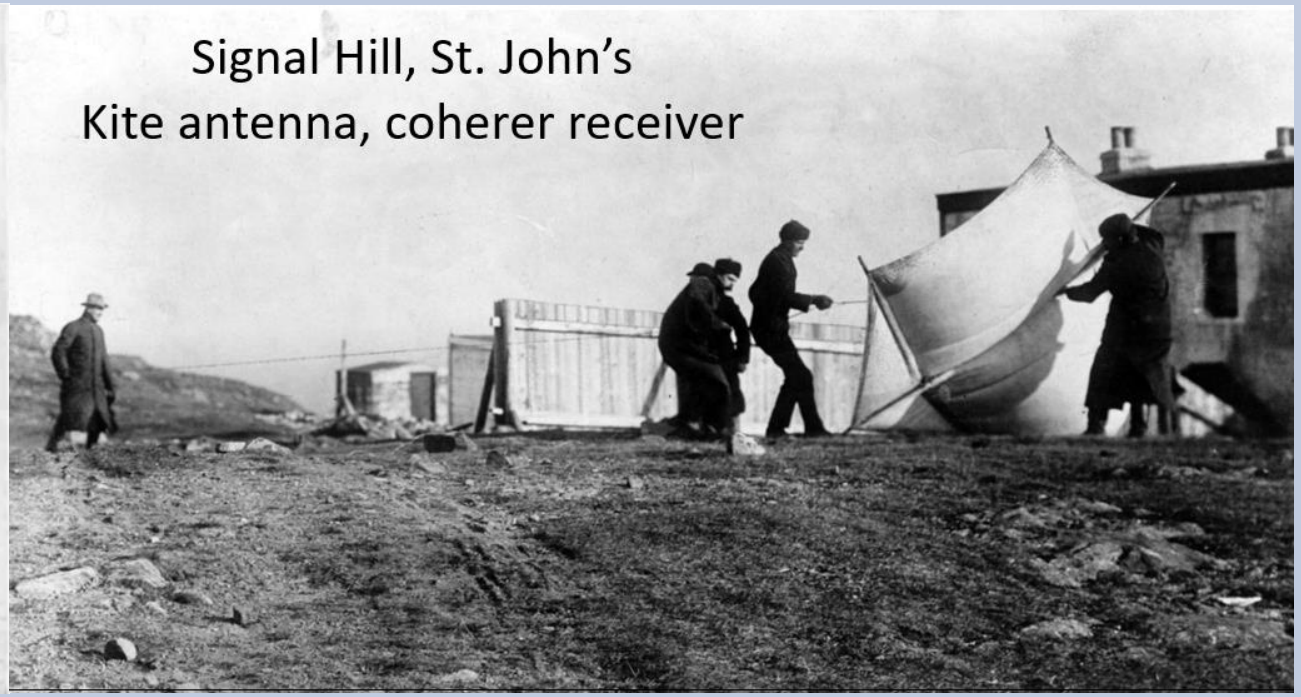




Marconi's first receiving circuit schematic, and my 2017 replica

Wireless Telegraphy

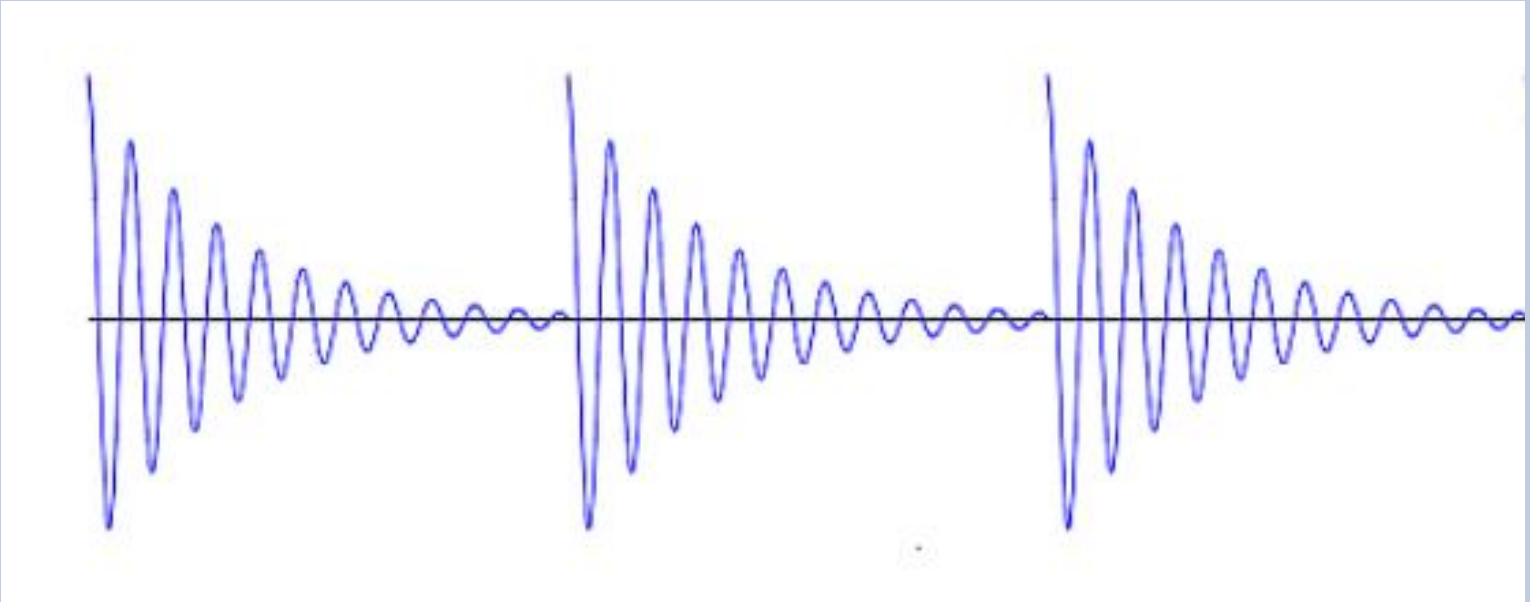




The first transatlantic telegraphic wireless (radio) transmission, achieved by Guglielmo Marconi on **December 12, 1901**, marked a pivotal moment in global communication history.
He received at St. John's, Newfoundland, Canada, signals transmitted across the Atlantic Ocean from Poldhu in Cornwall, England over 3500 Km away: a series of three "bips", Morse code for the letter "S." Marconi used a basic set-up : 'syntonic' or tuned circuits patented by him one year ago, self-restoring mercury coherer detector in series with a telephone earpiece, as an alternative method of reception to Morse paper tape recorder. This ingenious arrangement took advantage of the ability of the human ear to tell the difference between the signal clicks and the crackle of the atmospheric, which the Morse recorder could not do.

Wireless Telegraphy

The signal emitted by a typical spark transmitter looks something like this:



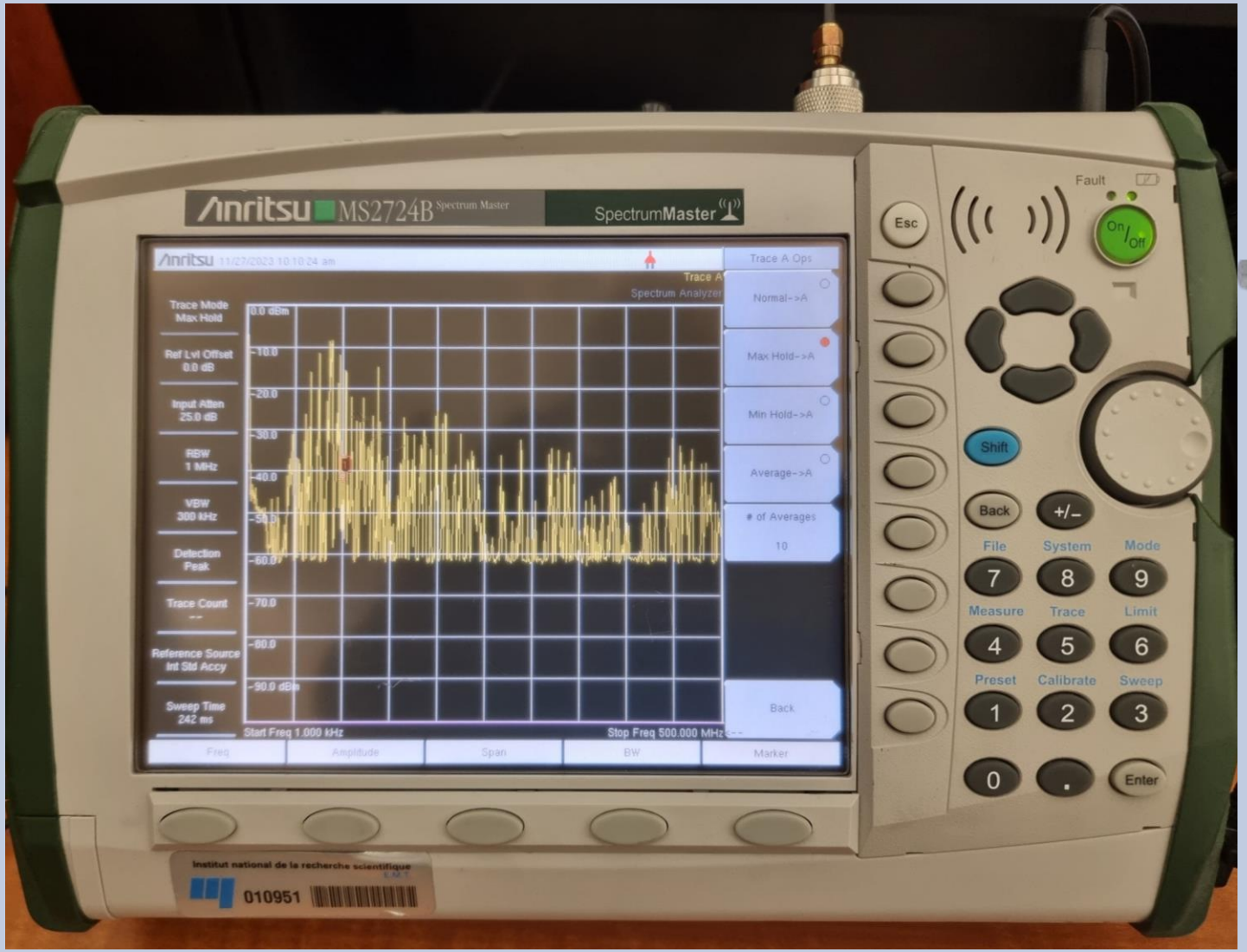
It's a train of damped waves and sounds over the air like a buzz or whine. The multiple waves are created by the multiple openings of the primary interrupter on the induction coil that produces the high voltage for the spark (usually several hundred times per second). How fast the wave decays is a function of the Q of the resonant circuit formed by the antenna and ground system and the spark gap circuitry. The higher the Q of the system the longer the decay time and the closer the wave comes to being continuous (the origin of the abbreviation "CW", for "continuous wave").

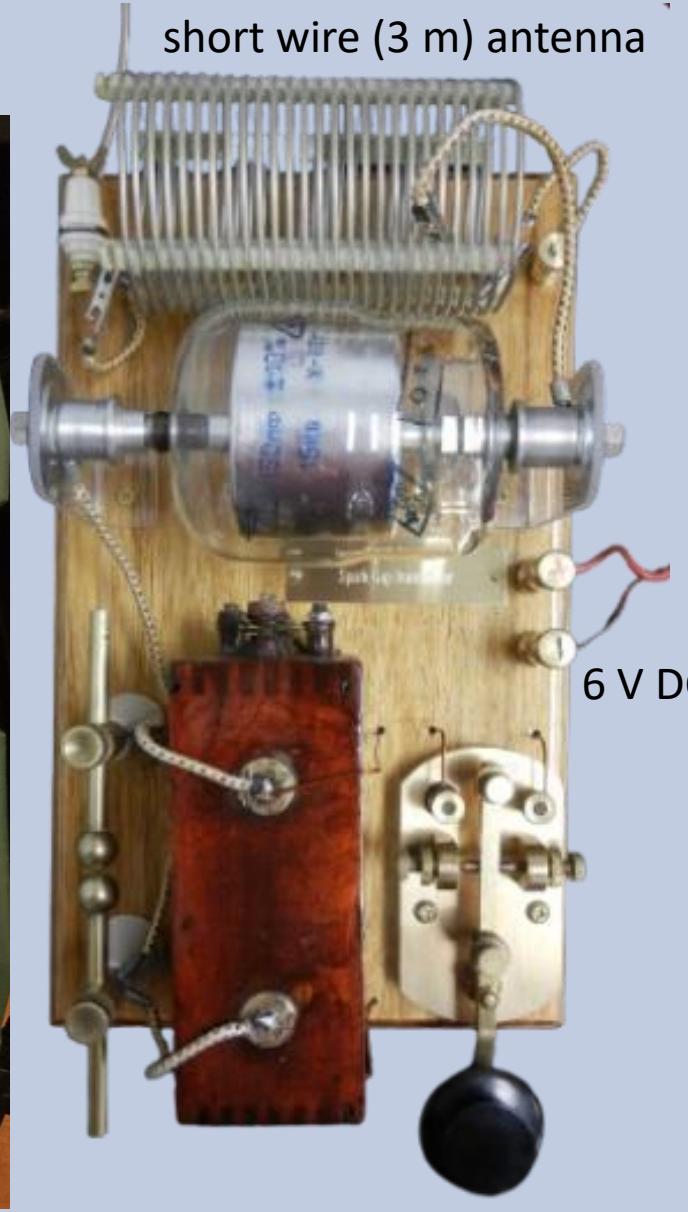
The radiated signal has both amplitude- and phase-modulated components and as such produces multiple sidebands extending either side of the nominal operating frequency.

Wireless Telegraphy

X = 50 MHz/div

Y = 10 dB/div





The spectrum of the RF signal emitted by my spark transmitter replica, recorded with a modern Spectrum Analyser at 3 m distance, all over the band (1 kHz - 500 MHz). This capture shows memory records of 20 s continuous transmission.

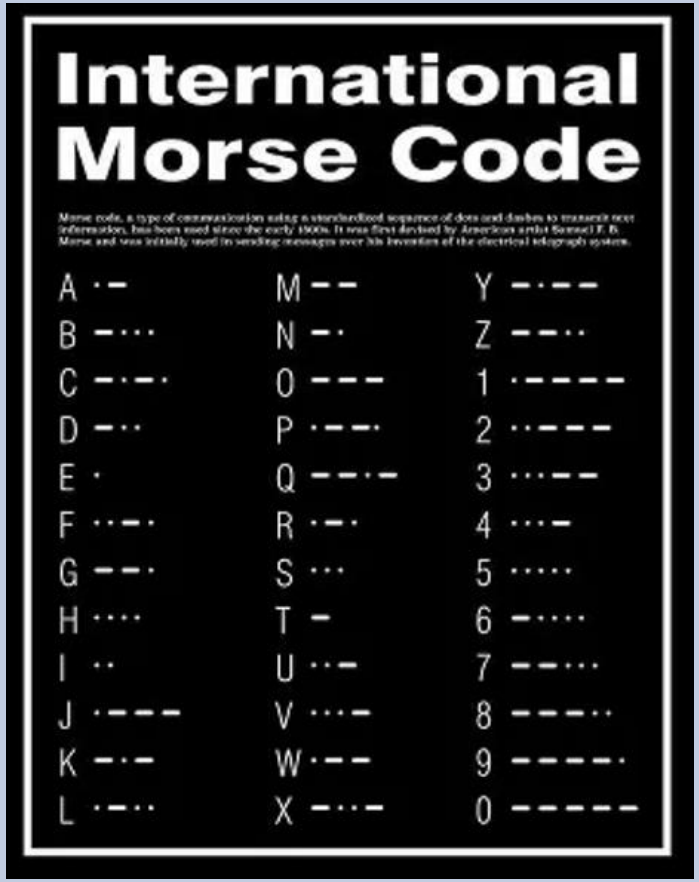
Continuous Wave Wireless Telegraphy (CW)

After 1905 new types of radiotelegraph transmitters were invented which transmitted code using a new modulation method: continuous wave (CW).

As long as the telegraph key was pressed, the transmitter produced a continuous sinusoidal wave of constant amplitude. Since all the radio wave's energy was concentrated at a single frequency, CW Tx could transmit further with a given power, and also caused virtually no interference to transmissions on adjacent frequencies.

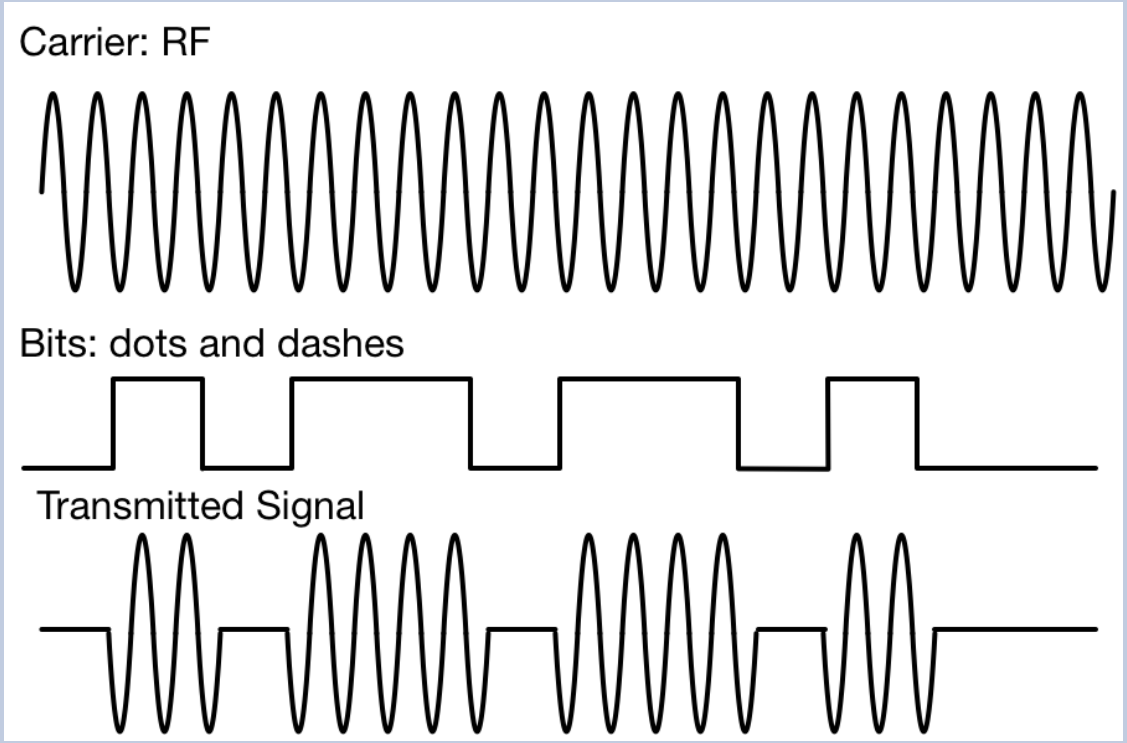
The first transmitters able to produce continuous wave were the arc converter (Poulsen arc) transmitter, invented by Danish engineer Valdemar Poulsen in 1903, and the Alexanderson alternator, invented by Reginald Fessenden and Ernst Alexanderson (1906–1912). These slowly replaced the spark transmitters in high power radiotelegraphy stations.

Because **the CW signal produced** while the key is pressed **is just an unmodulated carrier wave**, it made no sound in a receiver's earphones. This problem was solved by **Reginald Fessenden in 1901**. In his receiver, the incoming radiotelegraph signal is mixed in the receiver's detector crystal or vacuum tube with a constant sine wave generated by an oscillator in the receiver called a **beat frequency oscillator (BFO).** Thus, the Morse code is audible as musical "beeps" in the earphones.

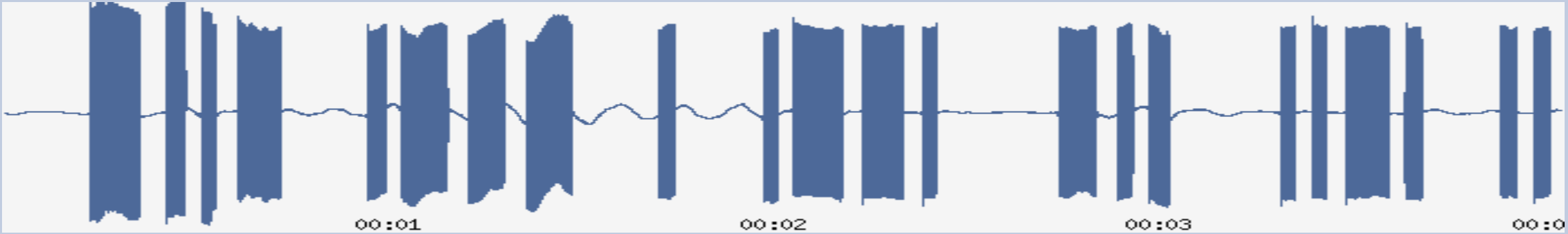


However, **BFO reception would not become practical for a decade after it was invented**, because it required a method for producing a **stable local signal**, which would not become available until the development of the first practical electronic oscillator, the vacuum tube feedback oscillator, in **1913 by Edwin Armstrong**.

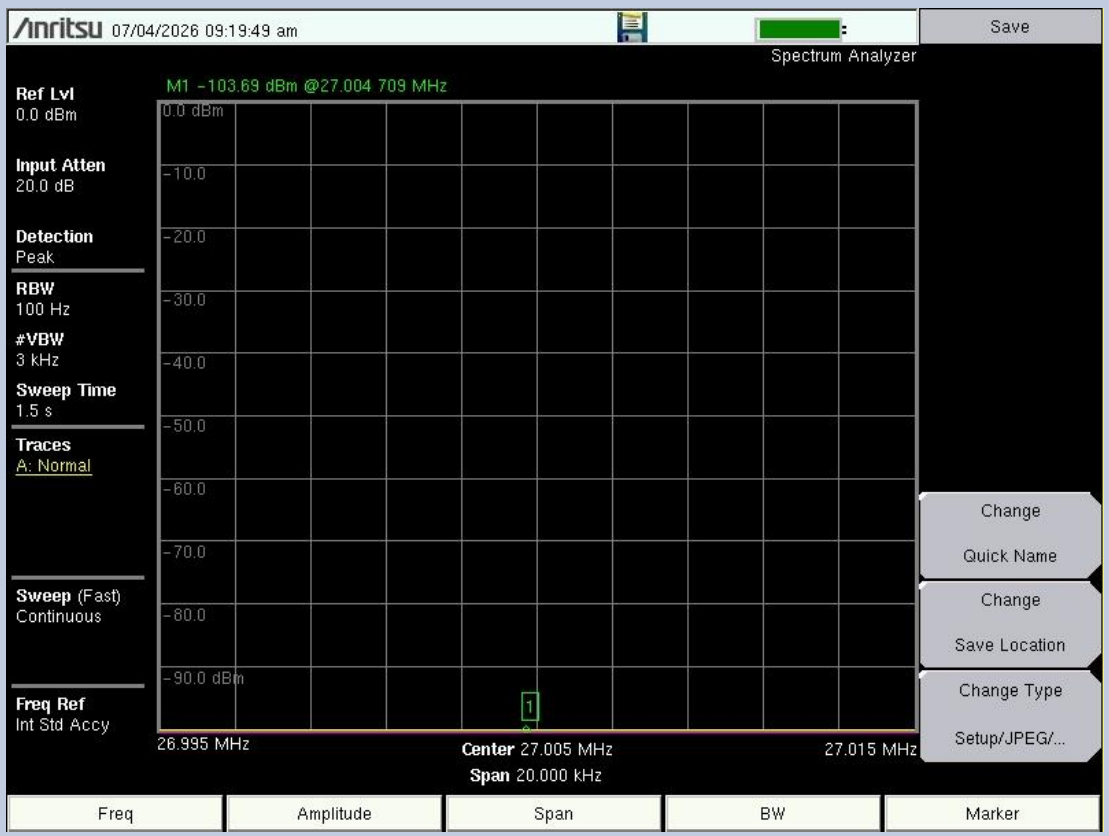
Continuous Wave Wireless Telegraphy (CW)

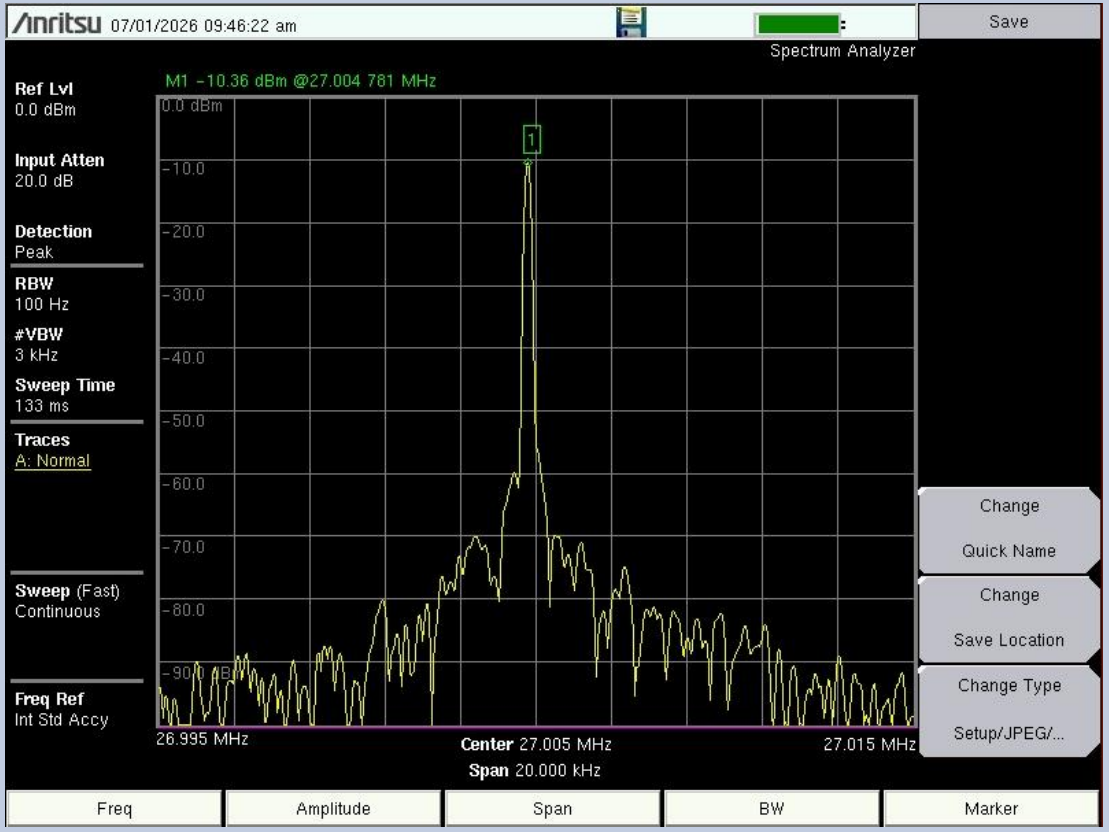


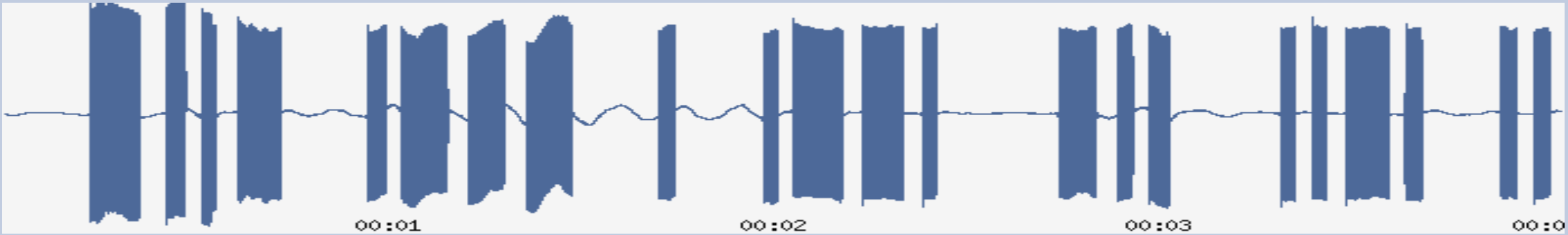




Continuous Wave Wireless Telegraphy (CW)







Spectrum of the CW signal when transmitting dots or dashes (right) and the noise level in stand–by (left)

Amplitude Modulation

Reginald Aubrey Fessenden was a Canadian-American electrical engineer and inventor who received hundreds of patents in fields related to radio and sonar between 1891 and 1936.

Most significant inventions are: amplitude modulation (1900), the beat frequency oscillator (1901), heterodyne (1905), and Fessenden oscillator (1912).

He pioneered developments in radio technology, including the foundations of AM radio. His achievements included the first transmission of speech by radio (1900), and the first two-way radiotelegraphic communication across the Atlantic Ocean (1906). He did a majority of his work in the United States and also claimed U.S. citizenship through his American-born father.

On **December 24, 1906**, he made **the first audio broadcast of entertainment and music to a general audience**, from Brant Rock on the coast of Massachusetts. Starting at 9:00 pm, wireless operators on the Atlantic coast, as far away as Norfolk, Virginia, were startled to hear speech and music through their own receivers. The program included Fessenden playing the song O Holy Night on the violin and reading a passage, Luke Chapter 2, from the Bible.

Fessenden used a specially-built high-speed 50 kHz alternator to create a continuous RF waveform, and inserted a carbon microphone in the antenna circuit to modulate the signal. This is considered the beginning of AM broadcasting.



Reginald Aubrey Fessenden
October 6, 1866 – July 22, 1932

Amplitude Modulation



Canada Post commemorative stamp honors 100 years of radio broadcasting, a SQCRA initiative; 1922 Marconi model C



XWA station, William street, Montreal, 1920

Amplitude Modulation

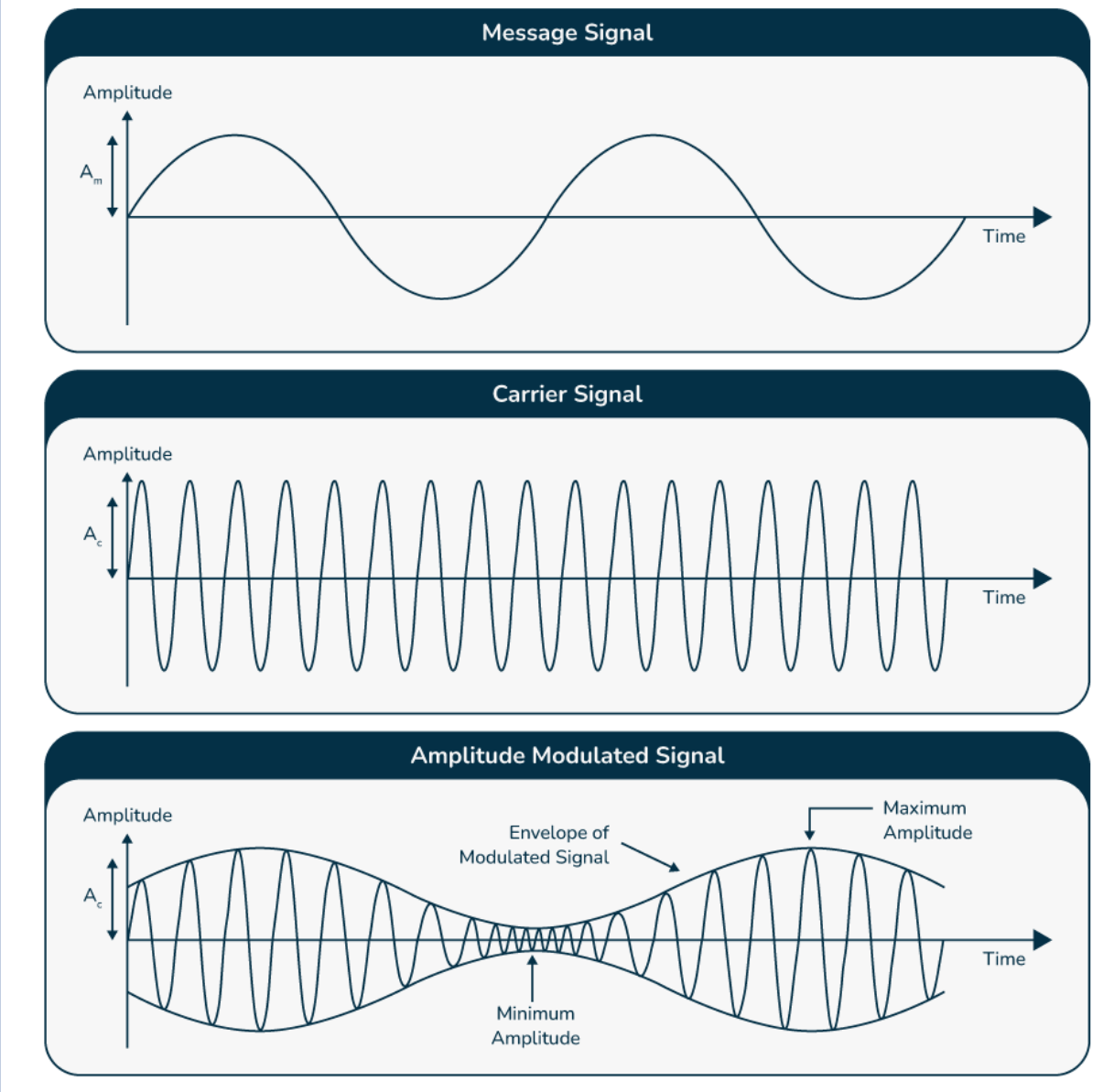
Amplitude modulation (AM) is a technique where the amplitude of a high-frequency carrier wave is varied in proportion to the instantaneous amplitude of a message signal to transmit information.

To include speech information or data information to the carrier wave which can be interpreted, another wave needs to be imposed, called an input signal, on top of the carrier wave. This input signal is known as the modulating signal.

Modulation is defined as the process of superimposing a low-frequency signal which is coined as the input signal or modulating signal on a high-frequency carrier signal whose data or speech needs to be interpreted.

Modulation index:

$$m = \frac{(A_{max} - A_{min})}{(A_{max} + A_{min})} \text{ x } 100\ \%$$



Amplitude Modulation

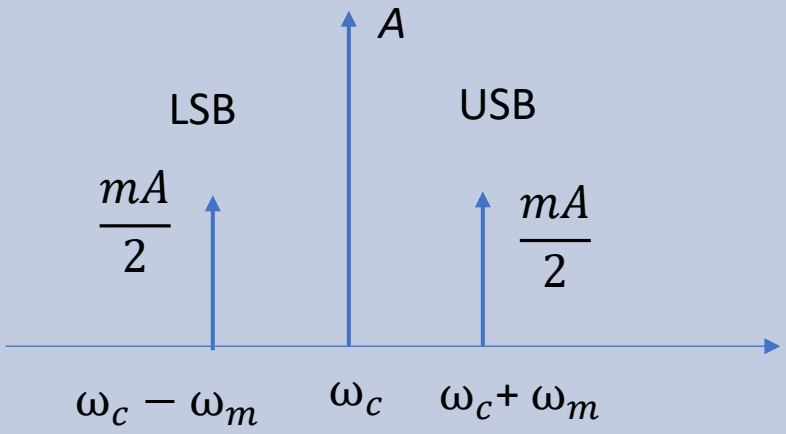
The AM signal produced by a sinusoidal carrier of frequency ω_c, modulated by an audio tone of frequency ω_m with amplitude A, can be written as:

$$s(t) = A[1 + m\cos(\omega_m t)]\cos(\omega_c t) = A\cos(\omega_c t) + m\frac{A}{2}\cos[(\omega_c + \omega_m)] + m\frac{A}{2}\cos[(\omega_c - \omega_m)]$$

$$A_{max} = A(1+m)$$
$$A_{min} = A(1-m)$$

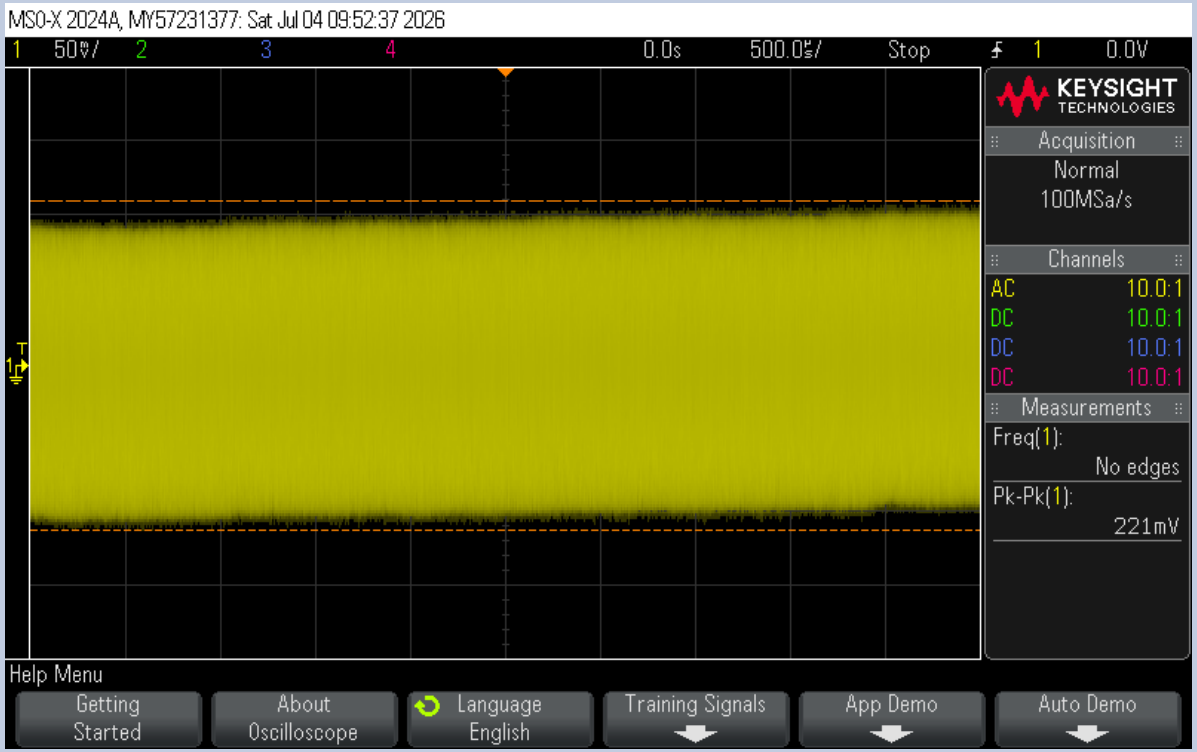
$$A_{max} - A_{min} = 2mA$$
$$A_{max} + A_{min} = 2A$$

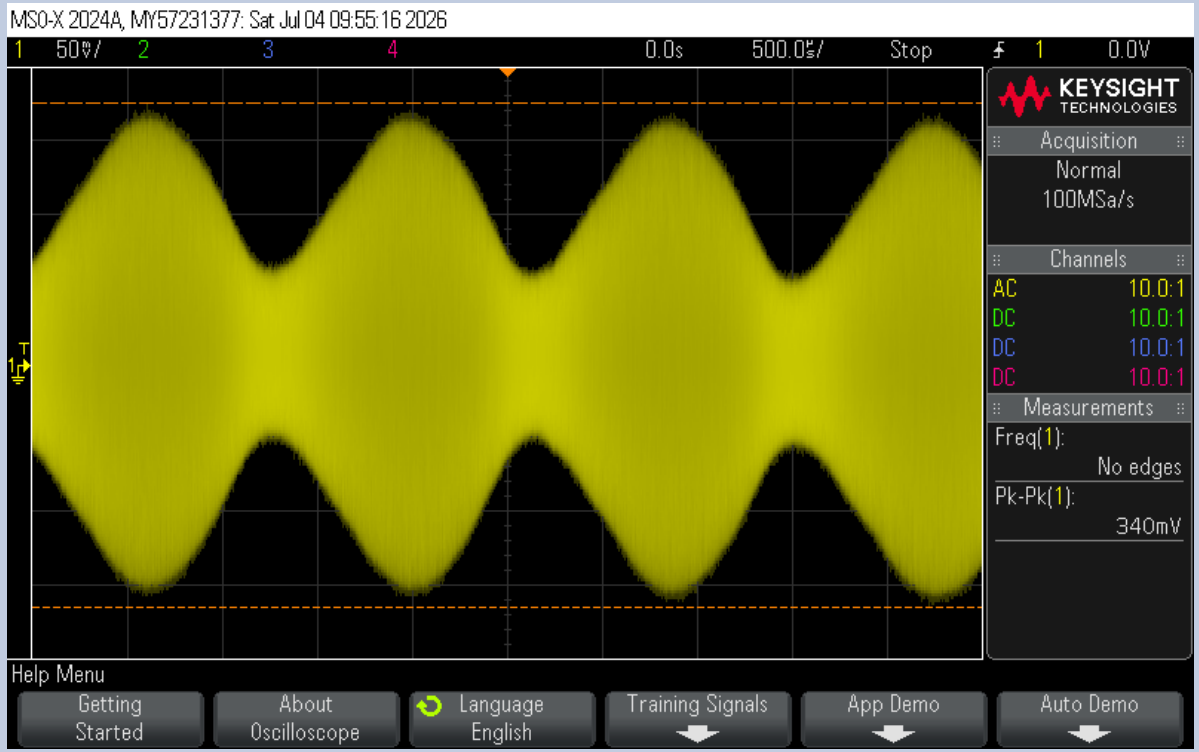
$$m = \frac{(A_{max} - A_{min})}{(A_{max} + A_{min})} \times 100\ \%$$



m	$\frac{P_{SB}}{P_c} = \frac{m^2}{4}$	$10lg\left(\frac{P_{SB}}{P_c}\right)$	$\frac{P_{USB+LSB}}{P_c} = \frac{m^2}{2}$	$\frac{P_{USB+LSB}}{P_c + P_{USB+LSB}} = \frac{m^2}{2+m^2}$
1	0.25	-6 dBc	0.5	0.3333= 33.33 %
0.9	0.2025	-6.93 dBc	0.405	0.2882= 28.82 %
0.8	0.16	-7.96 dBc	0.32	0.2424= 24.24%
0.7	0.1225	-9.12 dBc	0.245	0.1967=19.67 %
0.6	0.09	-10.45 dBc	0.18	0.1525= 15.25 5
0.5	0.0625	-12 dBc	0.125	0.1111= 11.11 %
0.4	0.04	- 14 dBc	0.08	0.0740= 7.4 %
0.3	0.0225	-16.5 dBc	0.045	0.0430= 4.3 %
0.2	0.01	-20 dBc	0.02	0.0196= 1.96 %
0.1	0.0025	-26 dBc	0.005	0.004975 = 0.4975 %

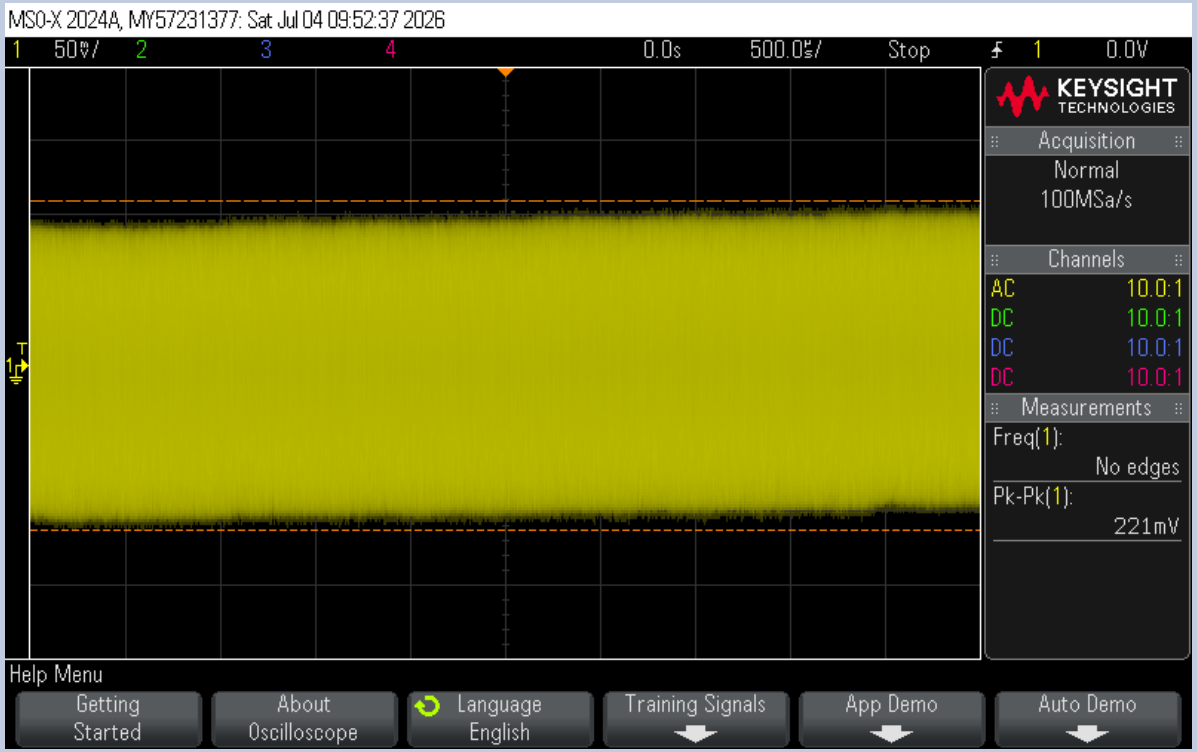
Amplitude Modulation

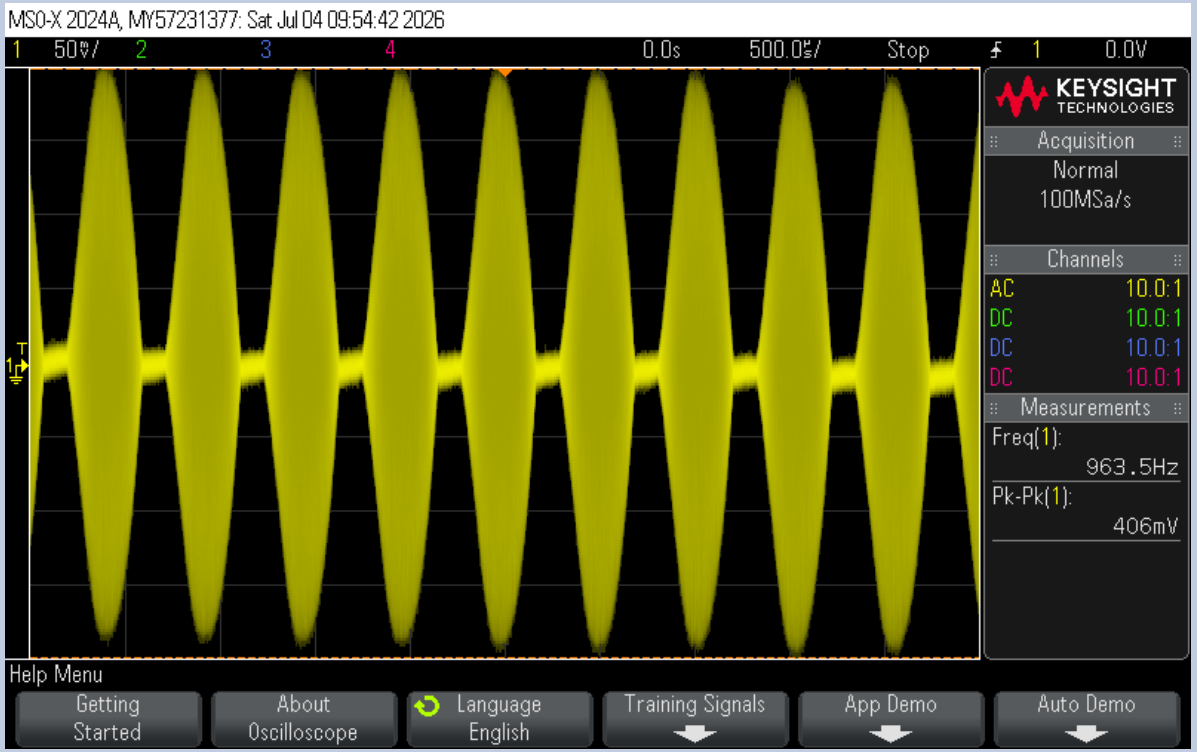




Oscilloscope print screen: carrier wave and AM, modulation index 50 %

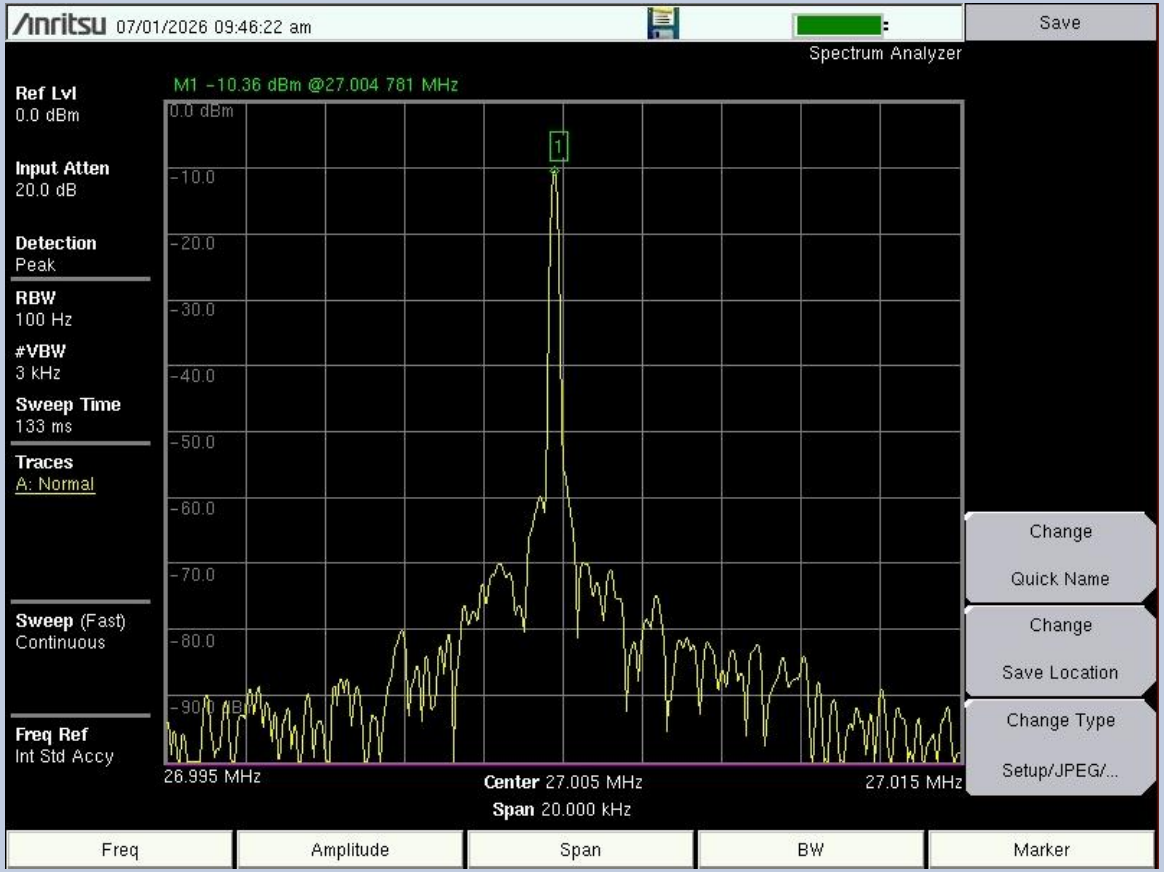
Amplitude Modulation

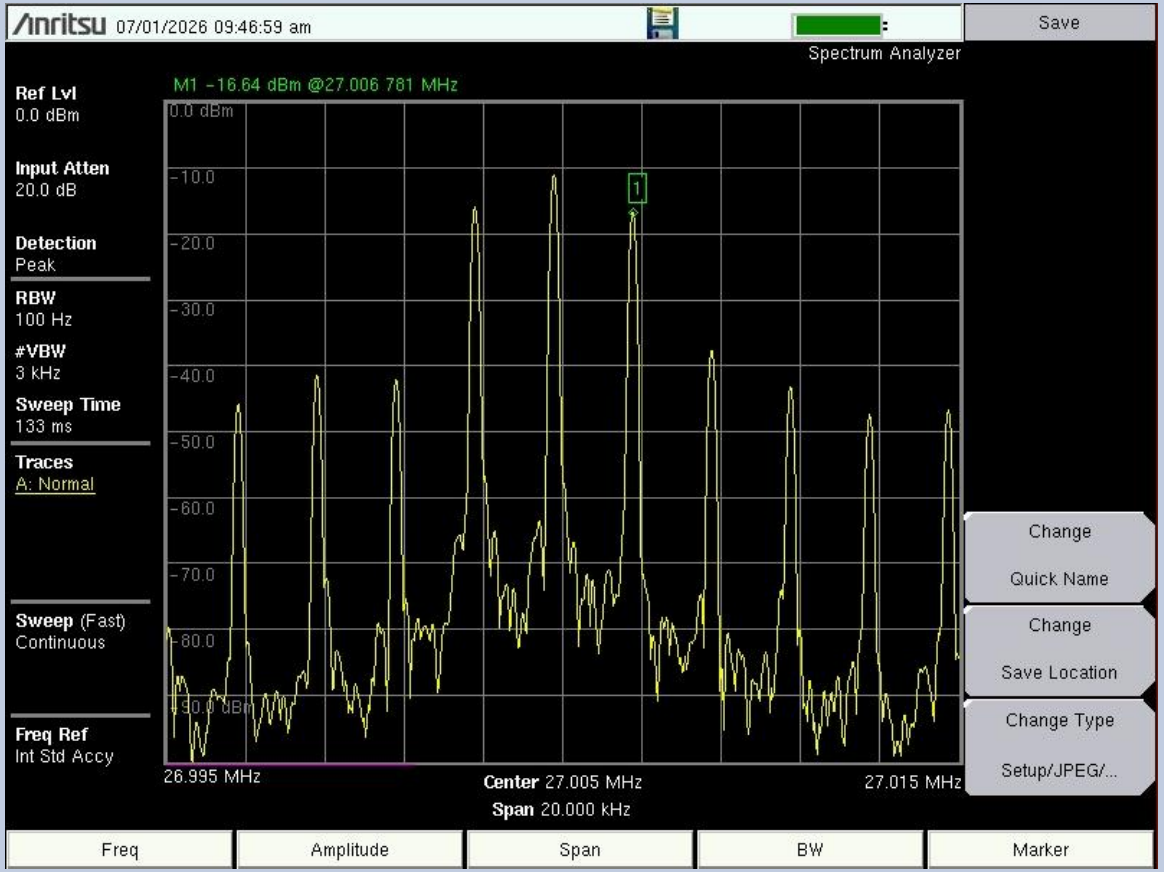




Oscilloscope print screen: carrier wave and overmodulated AM

Amplitude Modulation





AM unmodulated carrier (left) and the spectrum of a 100 % modulated signal: modulation tone = 2 kHz, very close to a perfect sinus; fundamental at – 6 dBc, harmonics are 20 dB lower than the modulation tone (right).

Amplitude Modulation

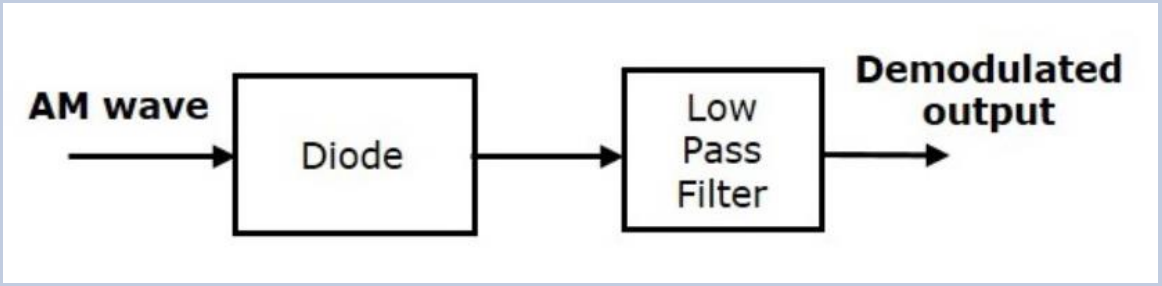
Envelope Detection: This is the most commonly used method due to its simplicity and efficiency, especially in low-frequency applications like radio broadcasting

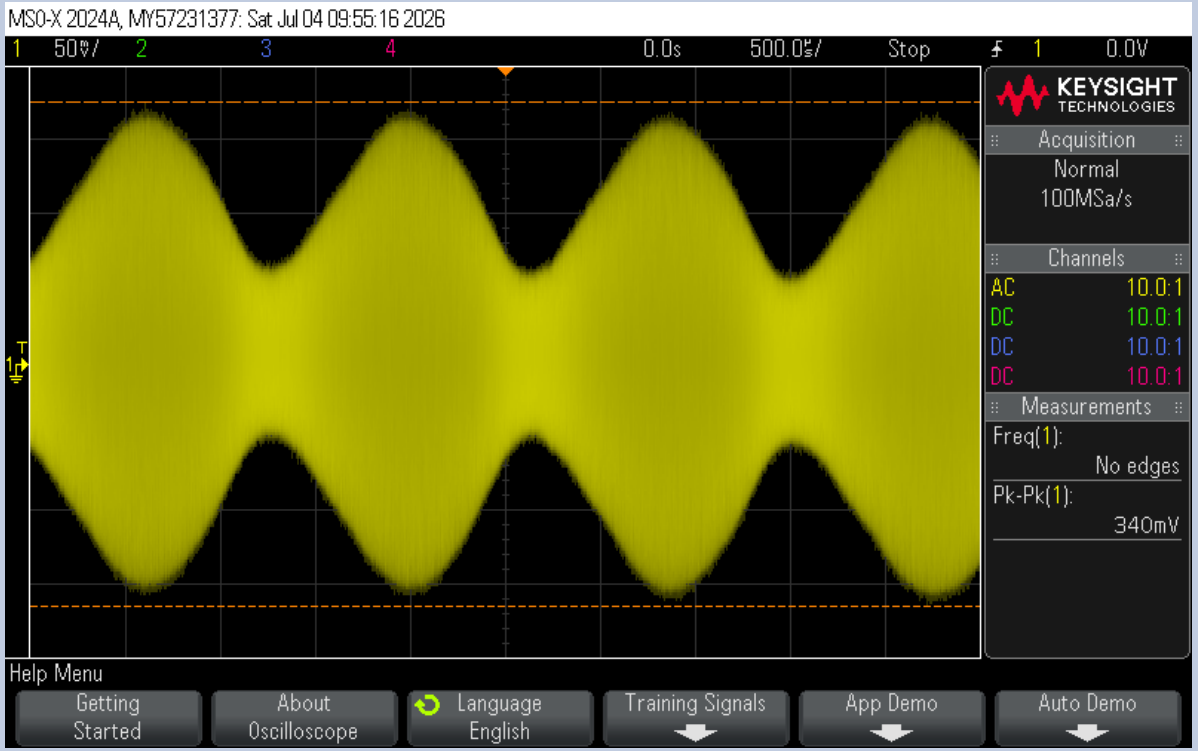
Coherent Demodulation: This technique involves using a local oscillator to mix the received signal with a reference signal, allowing for better performance in terms of noise and distortion

Peak Detection: A simple method that uses a peak detector circuit to extract the envelope of the AM signal

Synchronous Detection: This method uses a phase-locked loop (PLL) to synchronize with the carrier frequency, improving the demodulation accuracy

Product Demodulation: This technique multiplies the AM signal with a local oscillator signal to recover the original message





Single-sideband Modulation (SSB)

John Renshaw Carson was an American transmission theorist for early communications systems. Carson was born in Pittsburgh, Pennsylvania, and, together with his twin brother Joseph, attended Princeton University, graduating in 1907 with a Bachelor of Science degree. John attended the Massachusetts Institute of Technology from 1907 to 1908, before returning to Princeton to receive his electrical engineering degree in 1909 and a Master of Science degree in 1912. He **invented single-sideband (SSB) modulation** and developed the Carson bandwidth rule for estimating frequency modulation (FM) bandwidth.

In 1922, he defined instantaneous frequency in a mathematical treatment of FM, and introduced the Carson bandwidth rule. In his 1922 paper, Carson presented a negative opinion of narrowband FM, which occurs when the maximum frequency swing is made narrower than the audio bandwidth. Later, Edwin Armstrong managed to demonstrate that FM can be advantageous if the frequency swing is significantly wider than the audio bandwidth.

Carson received the ***1924 IRE Morris N. Liebmann Memorial Award*** "in recognition of his valuable contributions to alternating current circuit theory and, in particular, to ***his investigations of filter systems and of single side band telephony***." He received an honorary Doctor of Science degree from Brooklyn Polytechnic Institute in 1937 and the 1939 Elliott Cresson Medal from the Franklin Institute. In 2013, Carson was inducted into the Electronic Design Hall of Fame for his contributions to communications.



John Renshaw Carson,
June 28, 1886 – October 31, 1940

Single-sideband Modulation (SSB)

Single-sideband modulation (SSB) **modulation is an efficient form of amplitude modulation that transmits only one sideband**, reducing bandwidth and power usage while preserving the full information of the original signal.

SSB is a refinement of standard AM where only one of the two sidebands is transmitted, and the carrier is usually suppressed.

In conventional AM, the carrier and both sidebands are transmitted, but the carrier carries no information, and each sideband contains identical information. By removing one sideband and the carrier, SSB halves the bandwidth requirement and concentrates transmitter power into the remaining sideband, improving efficiency.

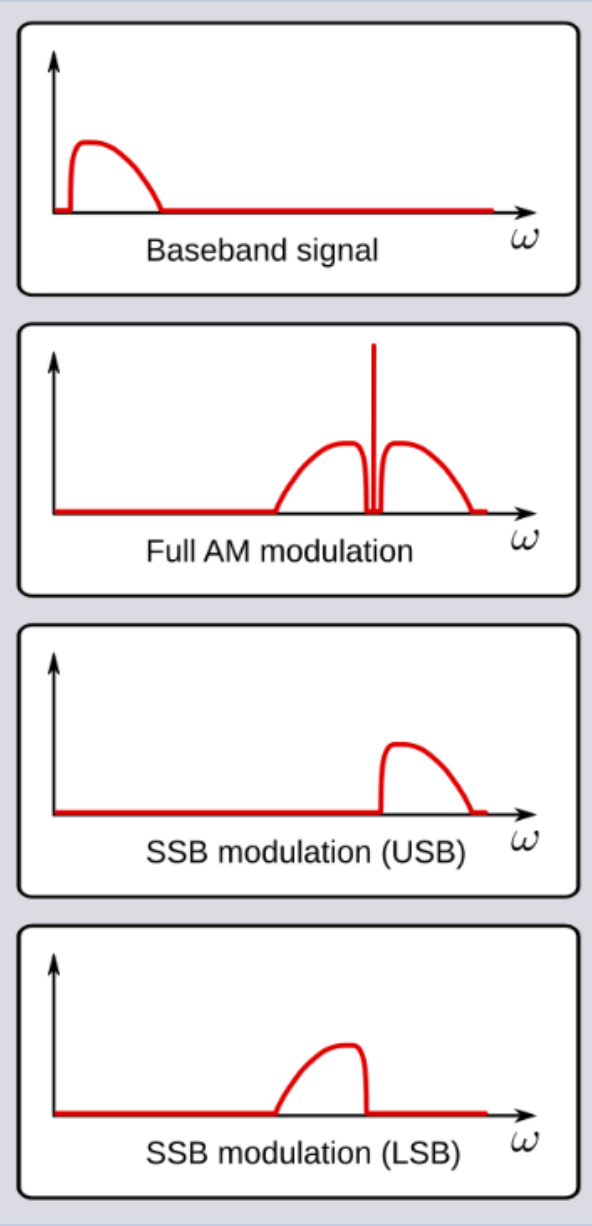
Compared with AM, SSB requires approximately half the bandwidth and uses transmitter power more efficiently.

SSB signals are typically generated at low power using filtering or phase-cancellation techniques and then amplified linearly.

AM can be generated and received with relatively simple equipment, while **SSB is used primarily where efficiency and range are important.**

Because the carrier is suppressed, **SSB reception requires reinsertion of a locally generated carrier and greater frequency stability than AM**.

In amateur radio, prior to widespread digital voice, most HF voice operation moved from AM to SSB.



Single-sideband Modulation (SSB)

Advantages of SSB modulation:

It allows multiple signals to transmit.
SSB technique requires less bandwidth as compared to DSB technique.
Less power is consumed.
It allows transmission of the high-power signals.
It provides less interference to noise due to the reduction in bandwidth.

Disadvantages of SSB modulation:

Implementation of SSB holds complex nature.
It is expensive.
SSB technique requires a transmitter and receiver to be highly frequency stable. As some slight change in frequency will deteriorate the quality of the signal.

Applications of SSB modulation:

It is needed in all such applications where power saving and low bandwidth is required.
The technique is utilized in point-to-point communication.
It is also used in land and air mobile communication.
It also finds its applications in telemetry and radar communication.

Quartz crystals are mostly used in the manufacturing of filters that are employed in the SSB modulation system.

Single-sideband Modulation (SSB)

Mathematical representation of SSB

Let's say the base-band message signal is:
$m(t) = A_m \cos(2\pi f_m t)$

And the carrier signal is:
$c(t) = A_c \cos(2\pi f_c t)$

For **DSB-SC** (double sideband suppressed carrier), the modulated wave looks like:

$$s(t) = A_m A_c \cos(2\pi f_c t) \cos(2\pi f_m t) = (1/2) A_m A_c \{ \cos[2\pi(f_c+f_m)t] + \cos[2\pi(f_c-f_m)t] \}$$

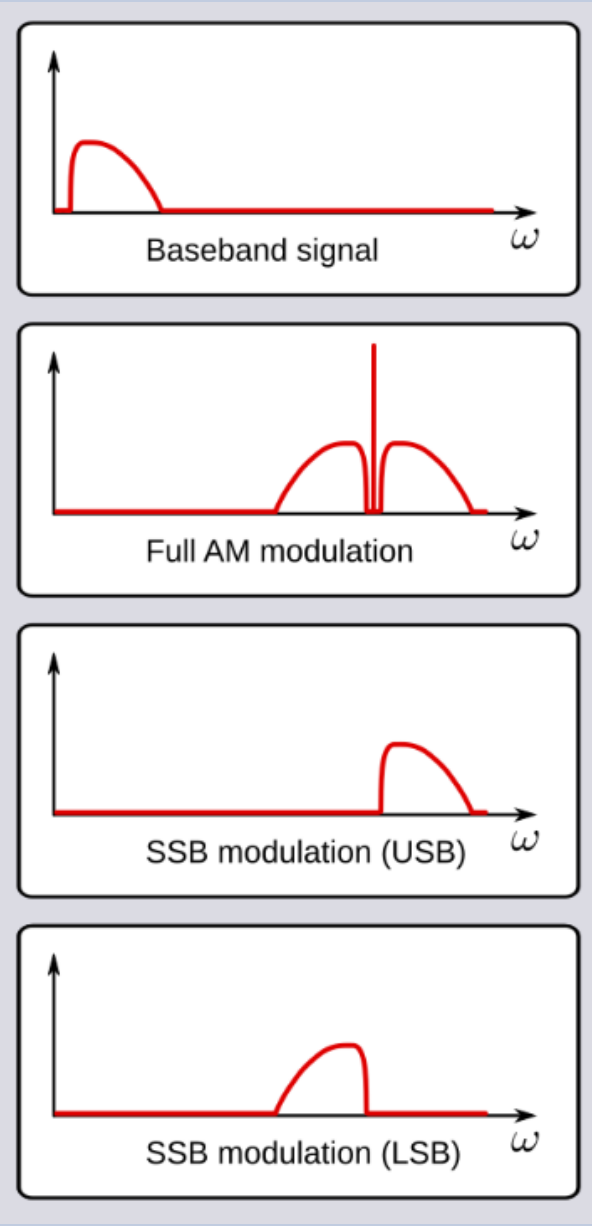
If you expand that, you get two frequency components:

USB: $f_c + f_m$
LSB: $f_c - f_m$

SSB just keeps one of those:

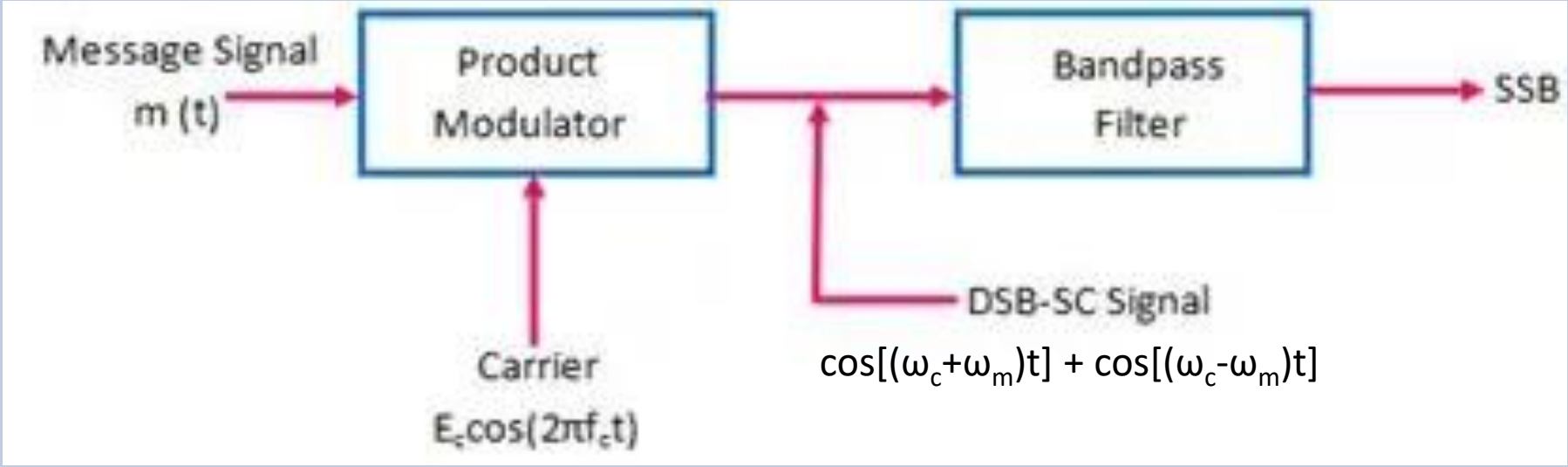
For USB: $s_{USB}(t) = (1/2) A_m A_c \cos[2\pi(f_c + f_m)t]$

For LSB: $s_{LSB}(t) = (1/2) A_m A_c \cos[2\pi(f_c - f_m)t]$

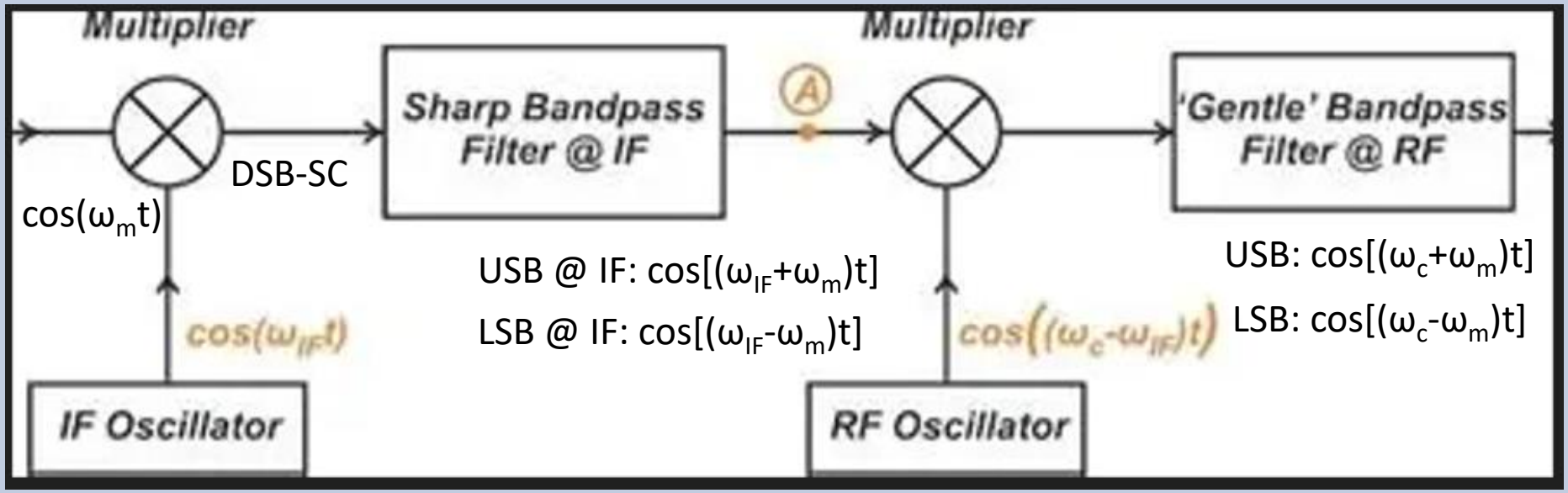


Single-sideband Modulation (SSB)

Generic @ RF

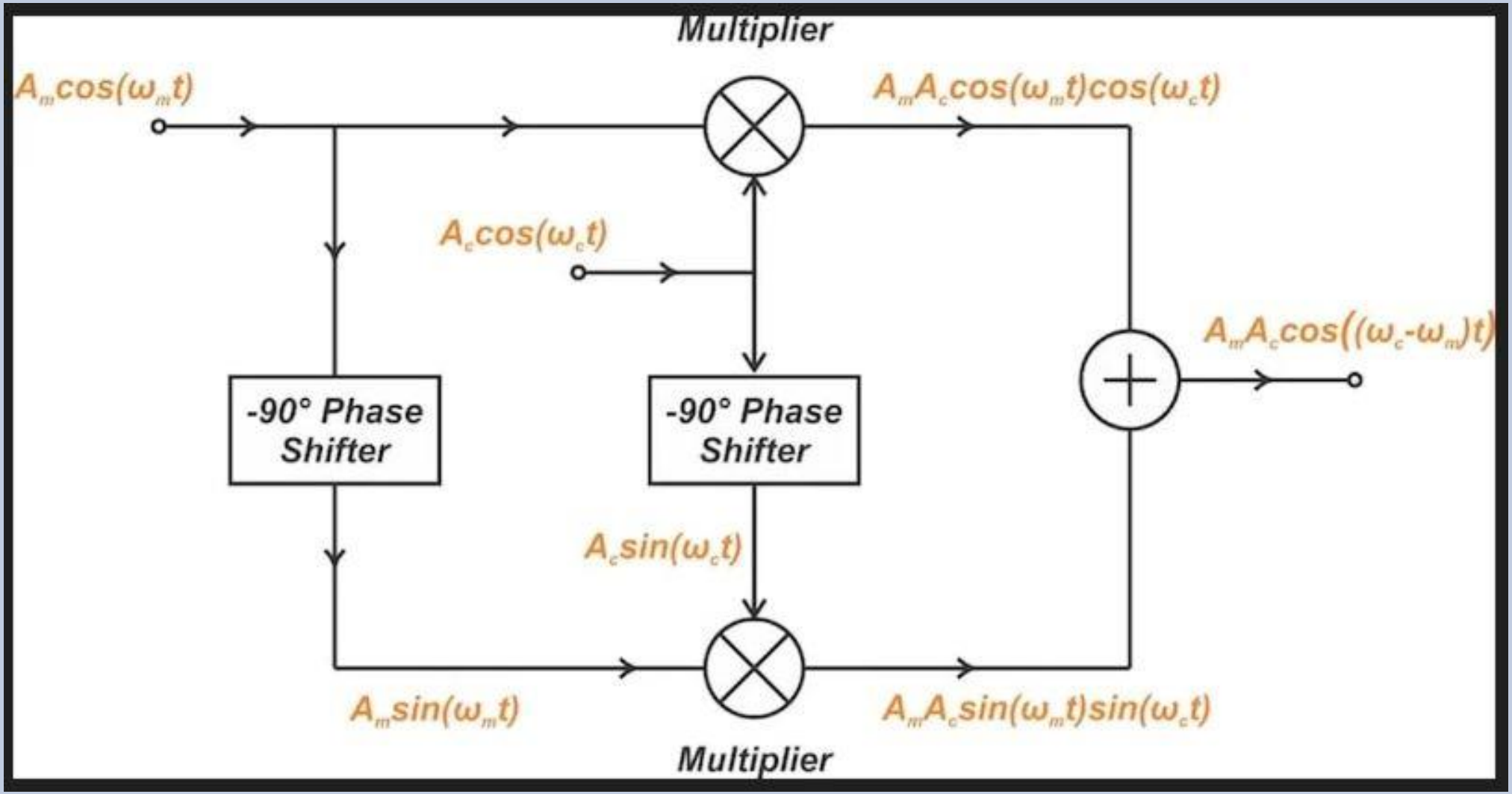


Sharp quartz filter @ IF
& up-converting @ RF



The Filter Method for SSB Generation

Single-sideband Modulation (SSB)

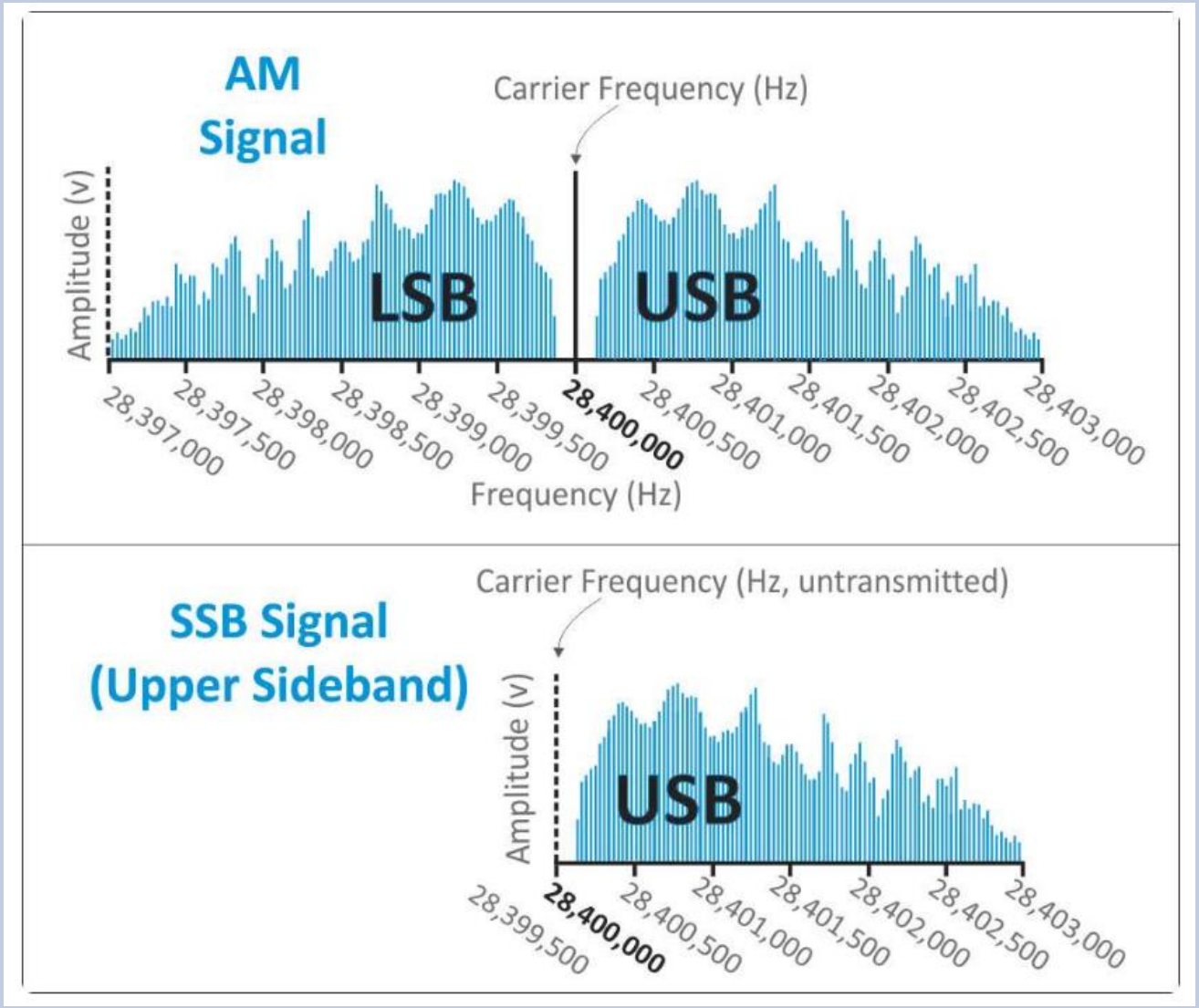


The Phasing Method and Hilbert Transforms for SSB Generation

Single-sideband Modulation (SSB)



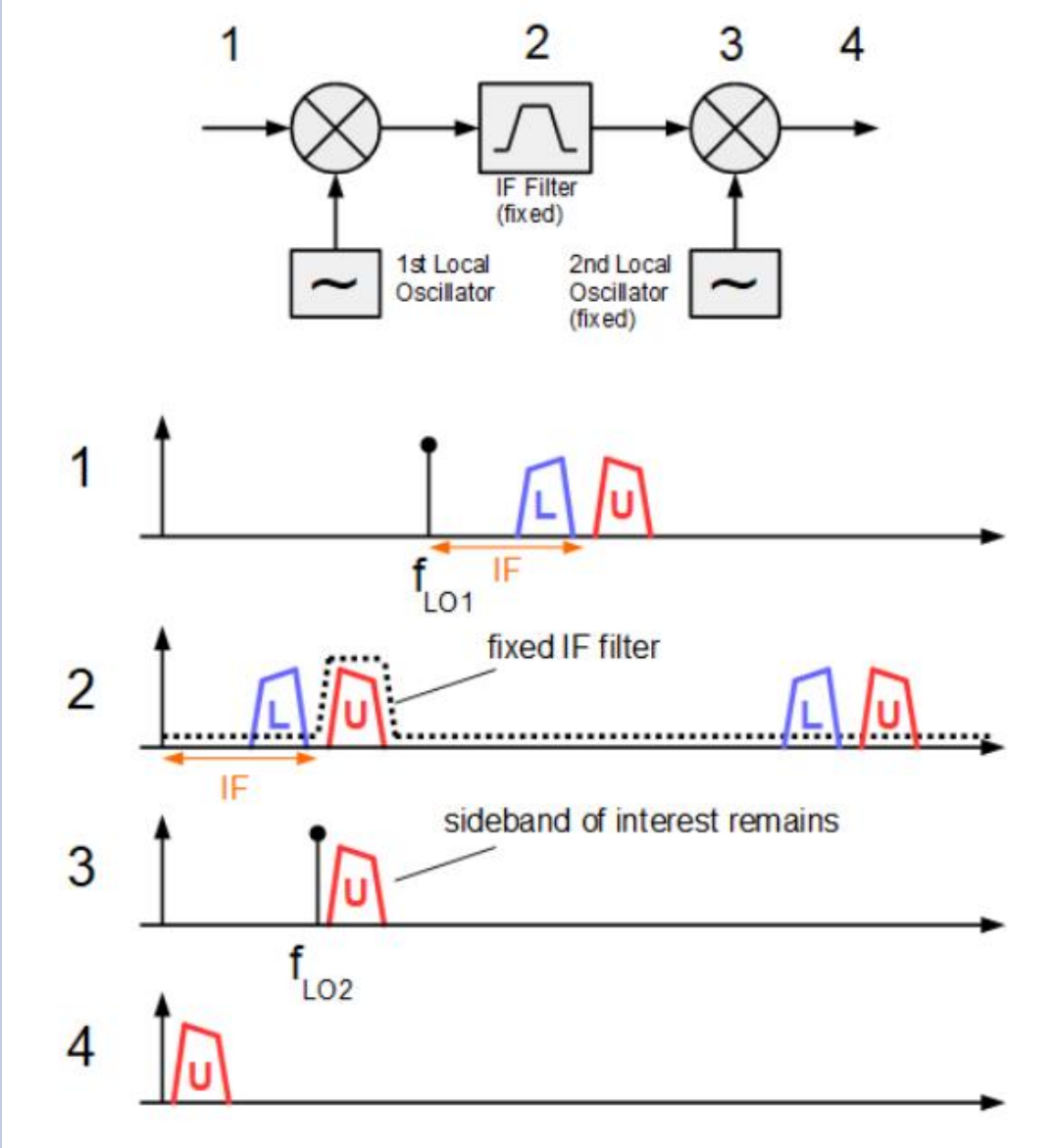
Single sideband is the predominant phone mode used for over-the-horizon skip propagation via the ionosphere. It offers a broader range of radio contact opportunities, including long distance and international communications.



Single-sideband (SSB) Demodulation

1. The Filtering Method

The filtering method **is the traditional SSB reception method in analog superheterodyne receivers**.
Typically, a first mixer translates the signal to an intermediate frequency (IF) first. At the IF a sharp band-pass filter with fixed frequency response simply selects only one of the two sidebands and suppresses the other one.
Then the second mixer converts the remaining sideband to audio frequencies. If required, the audio spectrum can be inverted by using high-side local oscillator injection in one of the mixer stages.
The filtering method **requires the availability of very sharp filters at the IF** and is widely spread in the analog domain, where **quartz filters are used**. Sideband suppression is determined by the sharpness and attenuation of the filter for the unwanted sideband.

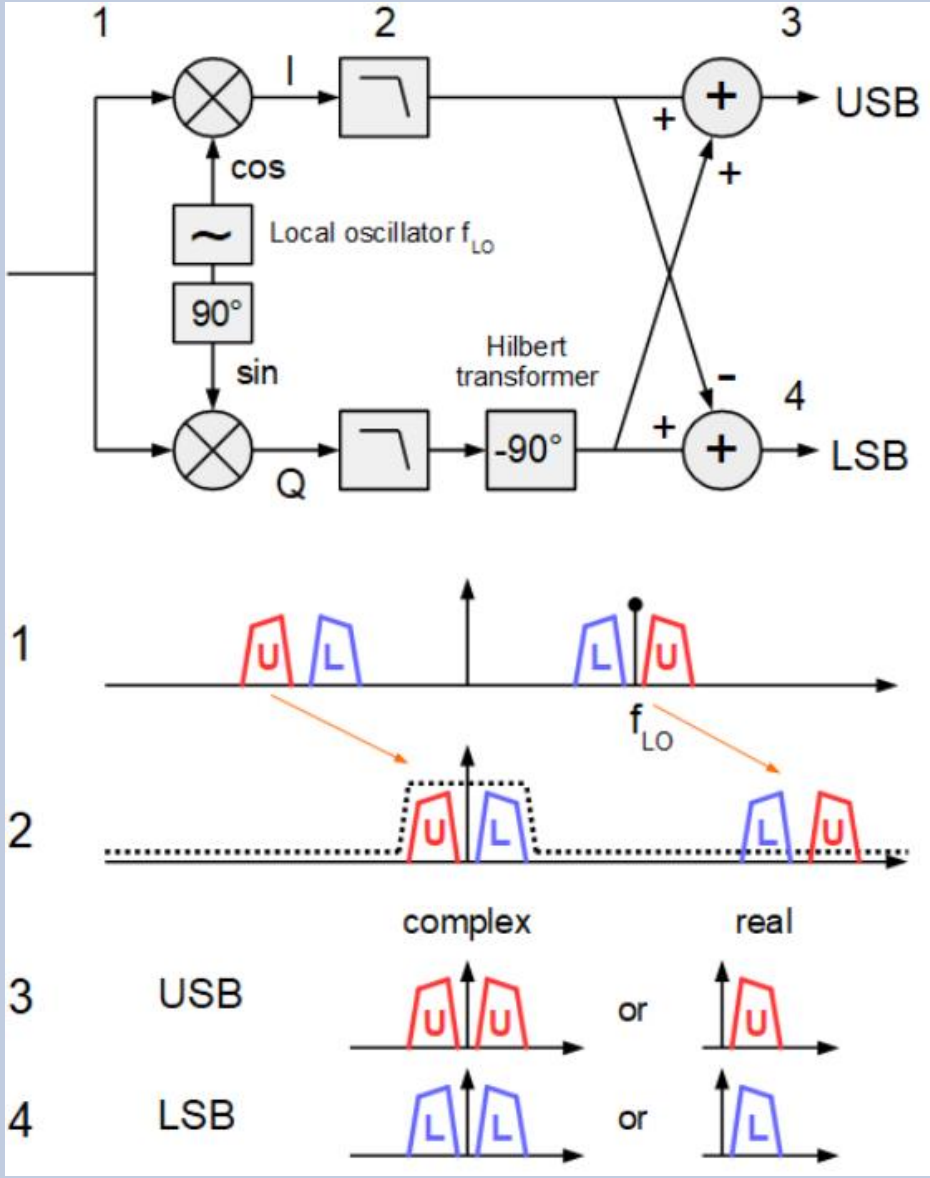


Single-sideband (SSB) Demodulation

2. The Phasing Method (Direct Conversion)

The phasing method **uses complex IQ processing to resolve the superposition of lower and upper sideband at AF**. The complex mixer directly converts the incoming signal to AF ands creates I and Q components (zero-IF or direct conversion receiver). The complex mixer stage consists of a sine and cosine local oscillator (a phase shift of 90°) and two mixers. The following low-pass filters with a width of one sideband determines the final bandwidth. After filtering a Hilbert transformer shifts the Q component by 90° before it can be added or subtracted to the I component to select one of the two sidebands.

To realize acceptable sideband suppression, the 90° phase shift for the LO and the 90° shift between I and Q, as well as their amplitude have to be matched exactly. This **is hardly practical with analog components**. However, in the digital domain, the LO phase shift can easily be realized by a sine and cosine look-up table. Also, amplitude variations are not a problem in digital processing, if the 90° phase shift for Q is distributed between both I and Q path with a 45° and -45° phase shifter. This makes the phasing method **interesting for implementation in a software defined radio (SDR).**



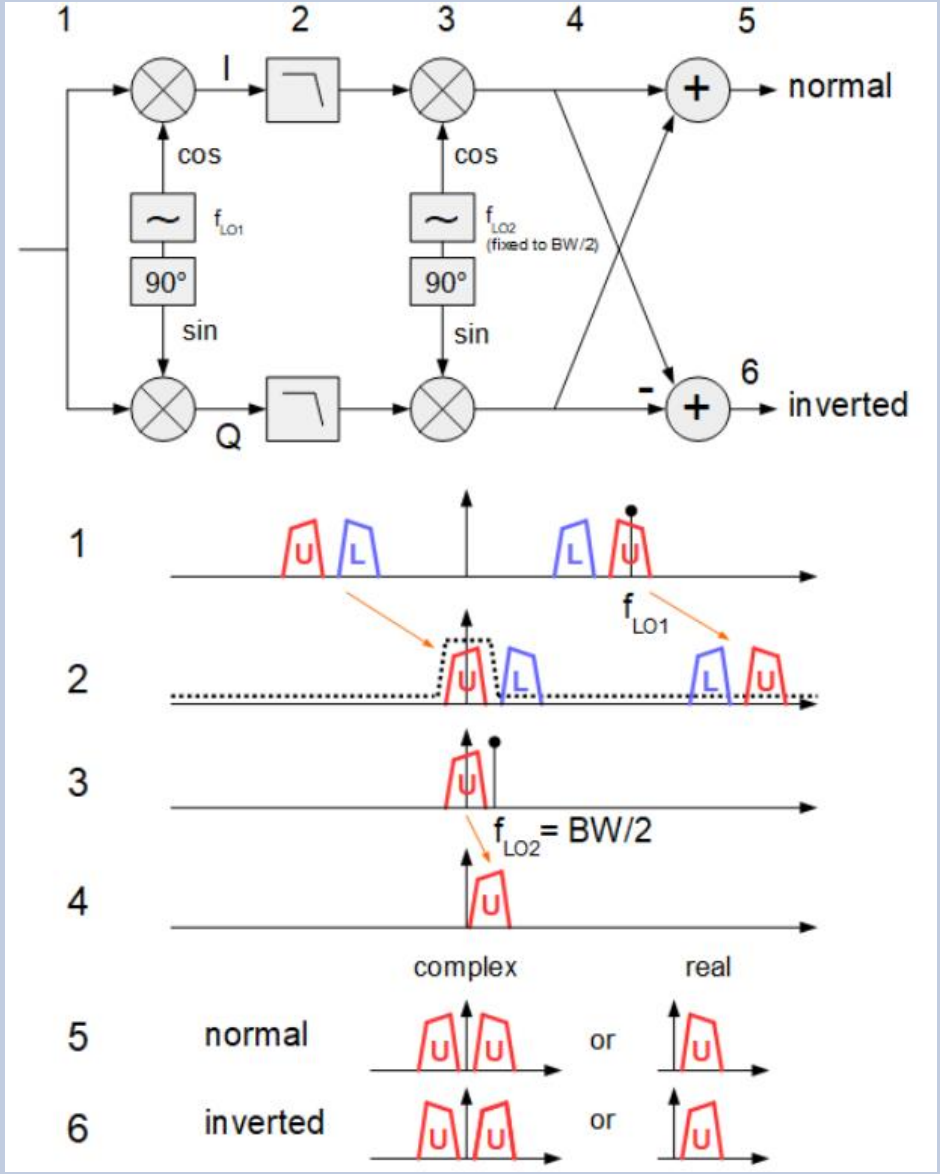
Single-sideband (SSB) Demodulation

3. The Weaver Demodulator

The Weaver demodulator (also called the “Third Method”, besides filtering and phasing techniques) for SSB reception has been introduced by D. Weaver in “A Third Method of Generation and Detection of Single-Sideband Signals”. It differs a little bit from the first two methods since it does not resolve any superposition of lower and upper sideband. Instead, the Weaver simply converts a portion of the spectrum to AF without any ambiguities.

The Weaver demodulator uses two complex mixing stages. The 1st mixer stages translates the signal in order to center the wanted sideband at zero frequency. There the bandwidth is selected by low-pass filters with $BW_{SSB}/2$. A 2nd mixer stage translates the signal in order to align its frequencies with the AF. Summing or subtracting I and Q selects the orientation of the output spectrum (normal or inverted).

This method **is very well suited for SDR**, because digital mixers and their sine and cosine LO signals can be generated with extremely high phase and amplitude accuracy. The same holds for the two identical low-pass filters. Thus, no gain and phase variations occur and the circuit is perfectly balanced for very high performance.



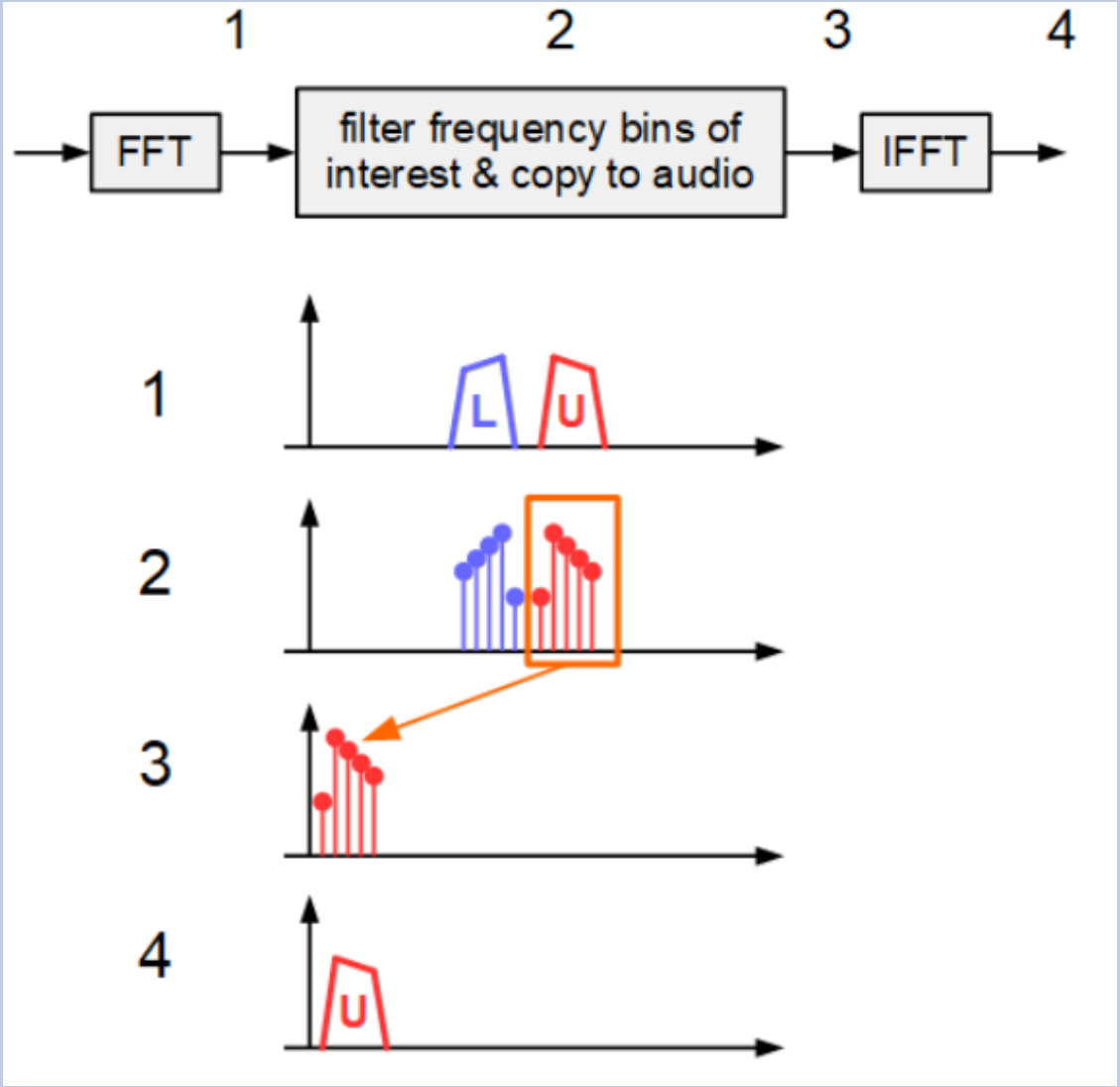
Single-sideband (SSB) Demodulation

4. Fourier based Demodulation

The Fourier approach follows a very intuitive approach: The idea is to simply select the wanted sideband and supress all other signals with a flexible filter prior to down-conversion. This is usually not feasible in the analog domain, because analog filters mostly have a fixed frequency response. However digital signal processing can apply very flexible filtering with almost every frequency response in the spectral (Fourier) domain.

The basic concept of this demodulator is as follows: it first calculates the signal's spectrum (FFT). Then, all frequency bin are set to 0 that do not belong to the sideband of interest. After that the bins are shifted to AF. Finally, an inverse FFT converts back to a time signal.

In practice this approach is slightly more challenging: rectangular filters have an infinite impulse response in the time domain, which cannot be mapped to blocks of finite length. Thus, a better idea is to replace the zero forcing of bins with the application of a finite impulse response (FIR) filter shape, that has a finite length time response.



Frequency Modulation (FM)

"Static" interference – noises caused by sources such as thunderstorms and electrical equipment – bedeviled early radio communication using AM. Many ideas for static elimination were investigated. One approach used FM transmissions. Instead of varying the strength of the carrier wave (AM), the frequency of the carrier was changed to represent the audio signal.

In 1922 John Renshaw Carson of AT&T, inventor of SSB, had published a detailed mathematical analysis which showed that FM transmissions did not provide any improvement over AM. Although the Carson bandwidth rule for FM is important today, Carson's review turned out to be incomplete, as it analyzed only (what is now known as) "narrow-band" FM.

In early 1928 major E.H. Armstrong began researching the capabilities of FM. Working in secret in the basement laboratory of Columbia's Philosophy Hall, **he developed "wide-band" FM**, in the process **discovering significant advantages over the earlier "narrow-band" FM transmissions.**



Edwin Howard Armstrong,
December 18, 1890 – February 1, 1954

Frequency Modulation (FM)

In a "wide-band" FM system, the deviations of the carrier frequency are made to be much larger than the frequency of the audio signal, which can be shown to provide better noise rejection. As the name implies, wide-band FM (WFM) requires a wider signal bandwidth than AM by an equivalent modulating signal; this also makes the signal more robust against noise and interference. FM is also more robust against signal-amplitude-fading phenomena.

As a result, **FM was chosen as the modulation standard for high frequency (VHF), high fidelity radio transmission of music or speech, hence the term "FM radio".**

Mr. E.H. Armstrong was granted five US patents covering the basic features of the new system on December 26, 1933.

FM has better noise (RFI) rejection than AM, as shown in this dramatic *New York publicity demonstration by General Electric in 1940*. The radio has both AM and FM receivers. With a million-volt electric arc as a source of interference behind it, the AM receiver produced only a roar of static, while the FM receiver clearly reproduced a music program from Armstrong's experimental FM transmitter W2XMN in New Jersey.



General Electric FM demonstration in 1940

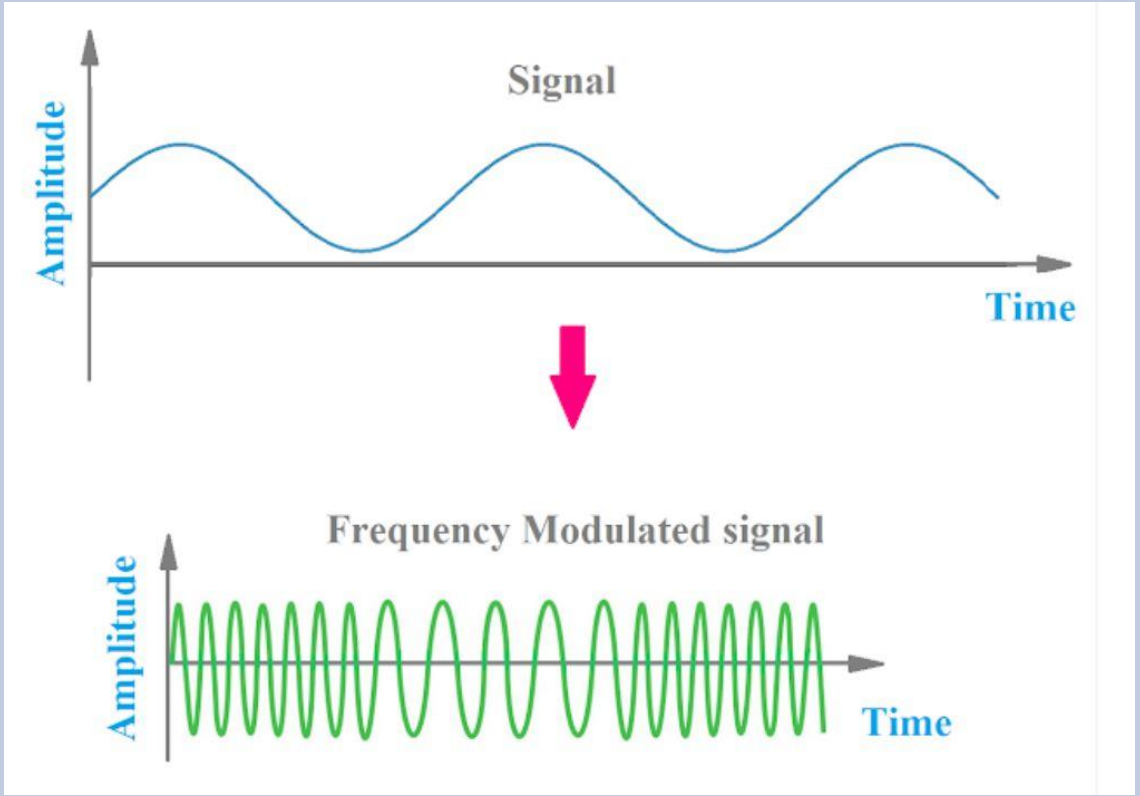
Frequency Modulation (FM)

Definition and Principle

Frequency modulation is a type of angle modulation in which the **instantaneous frequency of a carrier wave changes according to the amplitude of the input** (message) **signal**, while the amplitude of the carrier remains constant. Unlike amplitude modulation (AM), where the carrier's amplitude varies, FM encodes information in the frequency variations of the carrier wave. The instantaneous frequency at any moment reflects the instantaneous value of the modulating signal.

Modulation Index and Frequency Deviation

The modulation index (β) in FM is defined as the ratio of the maximum frequency deviation (Δf) to the frequency of the modulating signal (f_m). It determines how sensitive the carrier frequency is to changes in the message signal. The frequency deviation is the maximum shift of the carrier frequency from its center frequency, directly proportional to the amplitude of the modulating signal.



Frequency Modulation basic principle

Frequency Modulation (FM)

The FM signal produced by a sinusoidal carrier of frequency ω_c, modulated by an audio tone of frequency ω_m with amplitude A, can be written as:

$$s(t) = sin[\omega_c t + kAsin(\omega_m t)]$$

The instantaneous frequency, which describes a frequency varying above and below the carrier frequency at the audio tone frequency, using Carson's time derivative method:

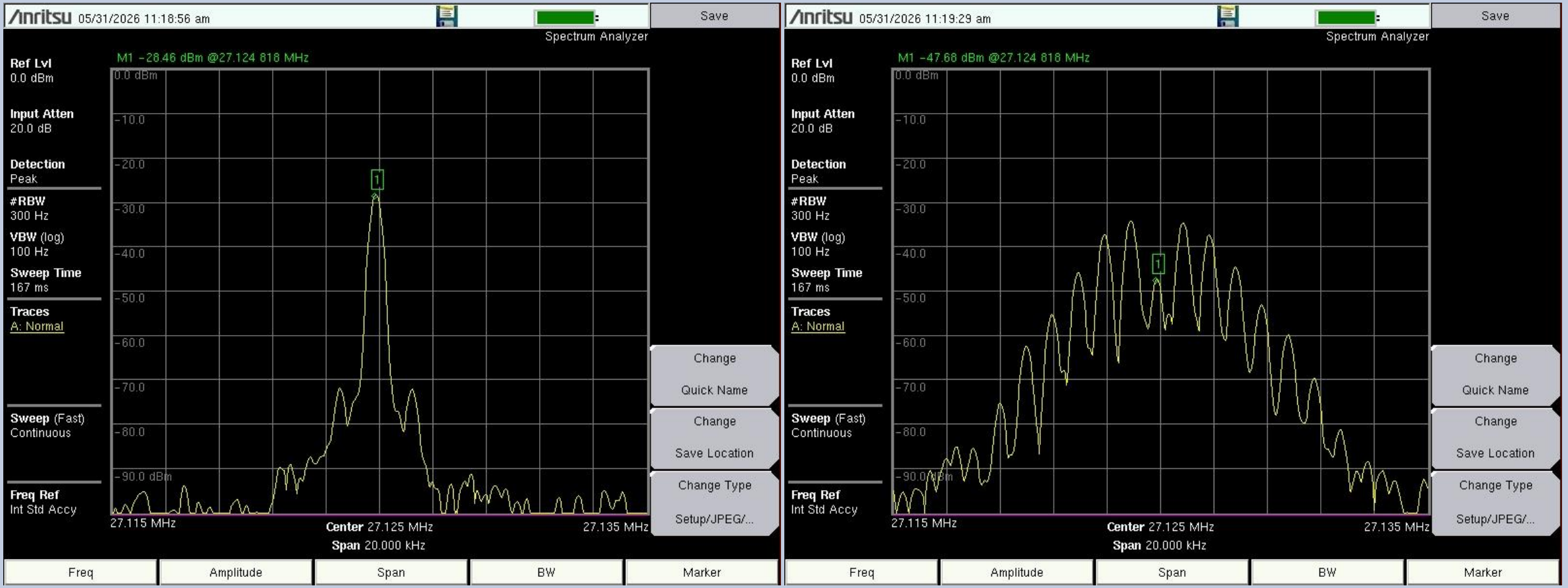
$$\frac{d}{dt}[\omega_c t + kAsin(\omega_m t)] = \omega_c + kA\omega_m cos(\omega_m t)$$

The amplitude factor $kA\omega_m$ defines the maximum frequency deviation around ω_c. Dividing by ω_m, gives us the modulation index $\beta = kA$, which "is the ratio of the amount of frequency deviation to the audio modulating frequency."

While most of the energy of the signal is contained within fc ± Δf, it can be shown by Fourier analysis that a wider range of frequencies is required to precisely represent an FM signal. The frequency spectrum of an actual FM signal has components extending infinitely, although their amplitude decreases and higher-order components are often neglected in practical design problems.

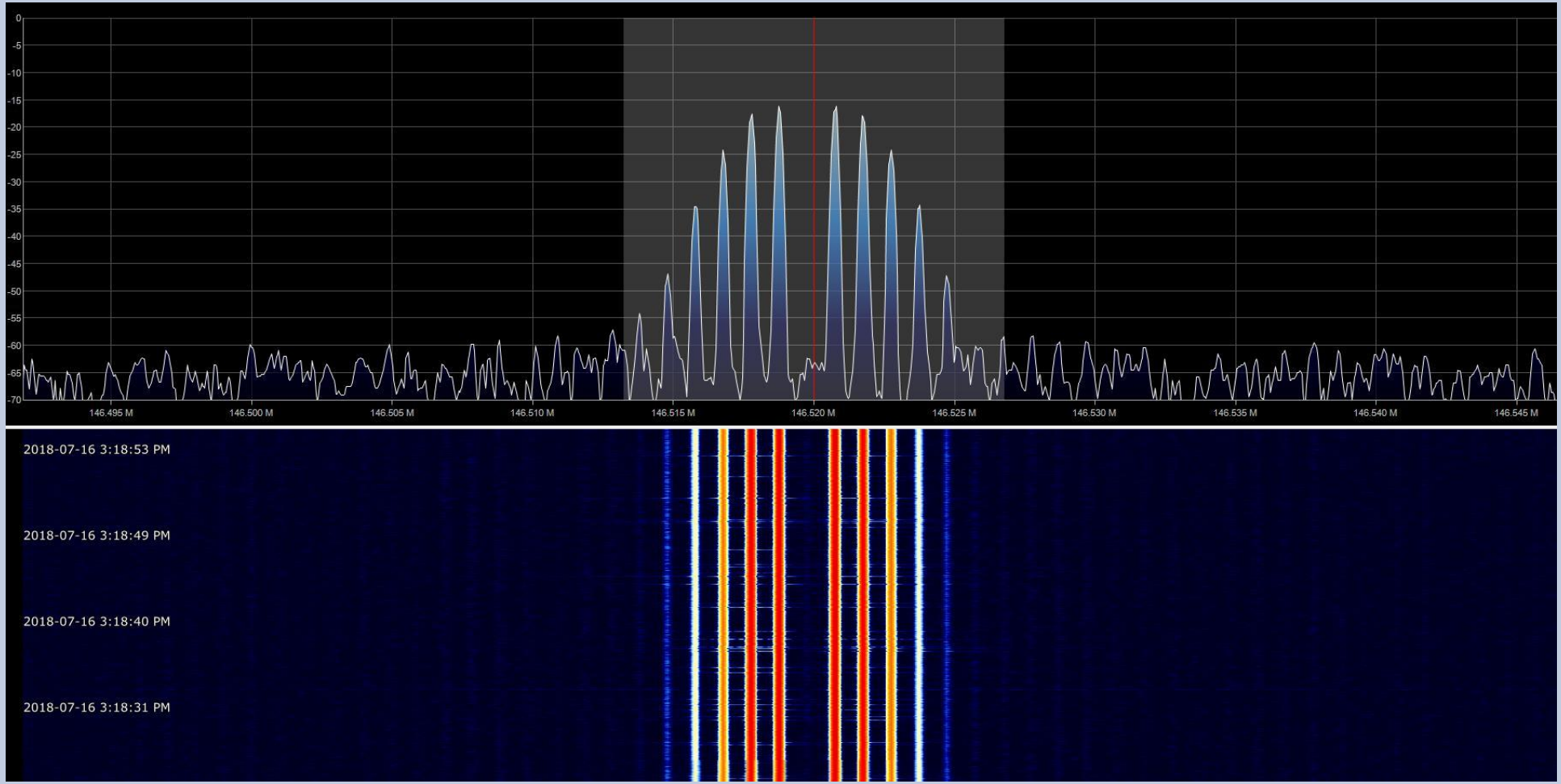
In his 1922 FM paper, Carson pointed out an infinite number of side frequencies are generated when a carrier frequency is modulated by a signal frequency, the amplitudes expressed as Bessel functions. The separation is determined by the frequency of the modulating signal, and the amplitude dependent upon the modulation index. A table of Bessel functions of the first kind is used to determine the side frequency amplitudes.

Frequency Modulation (FM)



Frequency spectrum of a 27.125 MHz (CB, channel 14) frequency modulated by a 1 kHz tone.
In the FM spectrum (right), the carrier frequency is almost 20 dB lower than for unmodulated CW signal (left).
Several strong sidebands are apparent; in principle an infinite number are produced in FM but the higher-order sidebands are of negligible magnitude.

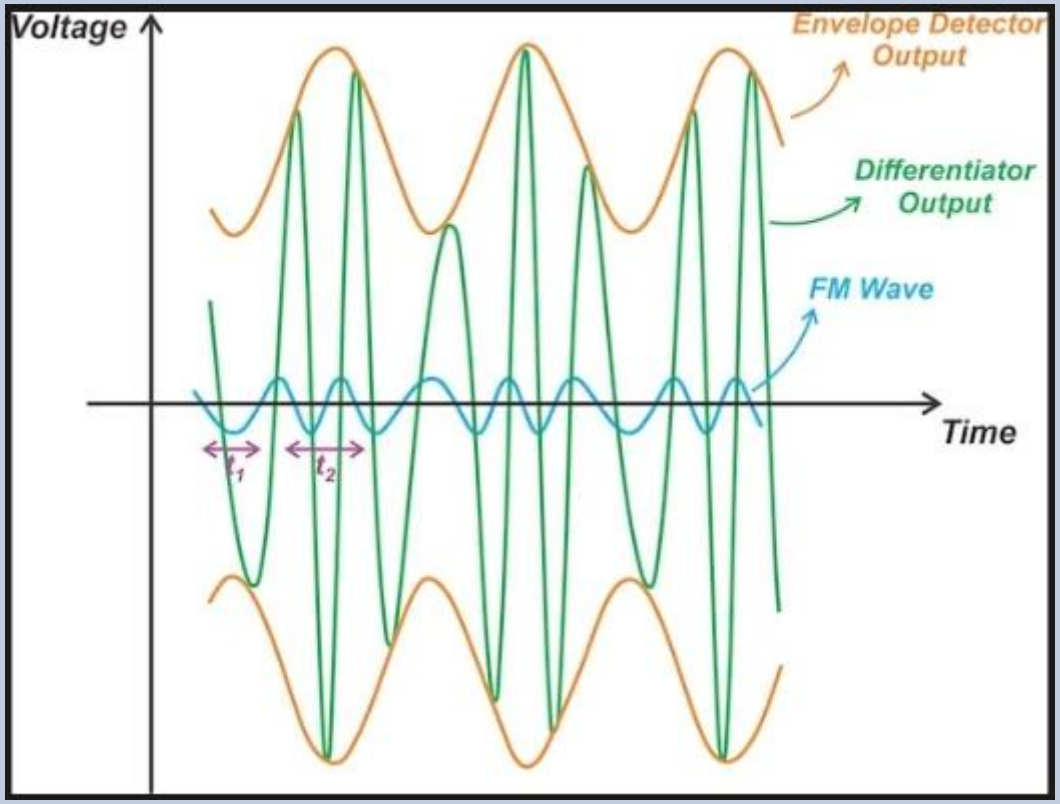
Frequency Modulation (FM)



Frequency spectrum and waterfall plot of a 146.52 MHz carrier, frequency modulated by a 1 kHz tone. The modulation index has been adjusted to around 2.4, so the carrier frequency has small amplitude. Several strong sidebands are apparent; in principle an infinite number are produced in FM but the higher-order sidebands are of negligible magnitude.

FM Demodulation

FM demodulation, also called FM detection or FM discrimination, is essential in any receiver that processes frequency-modulated signals, such as FM radios, walkie-talkies, and other communication devices. The main goal is to extract the original information signal from the FM carrier by converting the frequency deviations of the carrier into amplitude or voltage variations that represent the transmitted message.



Key Principles:

1. Frequency-to-Voltage Conversion: FM demodulators operate by translating frequency changes in the FM signal into voltage changes. When the carrier frequency deviates above or below its nominal value, the demodulator produces a corresponding increase or decrease in output voltage
2. Amplitude Insensitivity: Since FM encodes information in frequency rather than amplitude, the demodulator must ignore amplitude variations and respond only to frequency changes
3. Linearity and Efficiency: The conversion from frequency to voltage should be linear and efficient to accurately reproduce the original modulating signal.

FM Demodulation

Common FM Demodulation Methods:

1. Slope Detector (Frequency Discriminator):

Uses a tuned circuit slightly offset from the carrier frequency.
The amplitude of the output voltage varies with the input frequency deviation.
A diode and RC network then extract the modulating signal, similar to an AM envelope detector.

2. Phase Discriminator:

Converts the FM signal into a combination of AM and FM components using a differentiator.
An envelope detector then recovers the original modulation.
Often implemented with a **multiplier, low-pass filter, and voltage-controlled oscillator (VCO)**

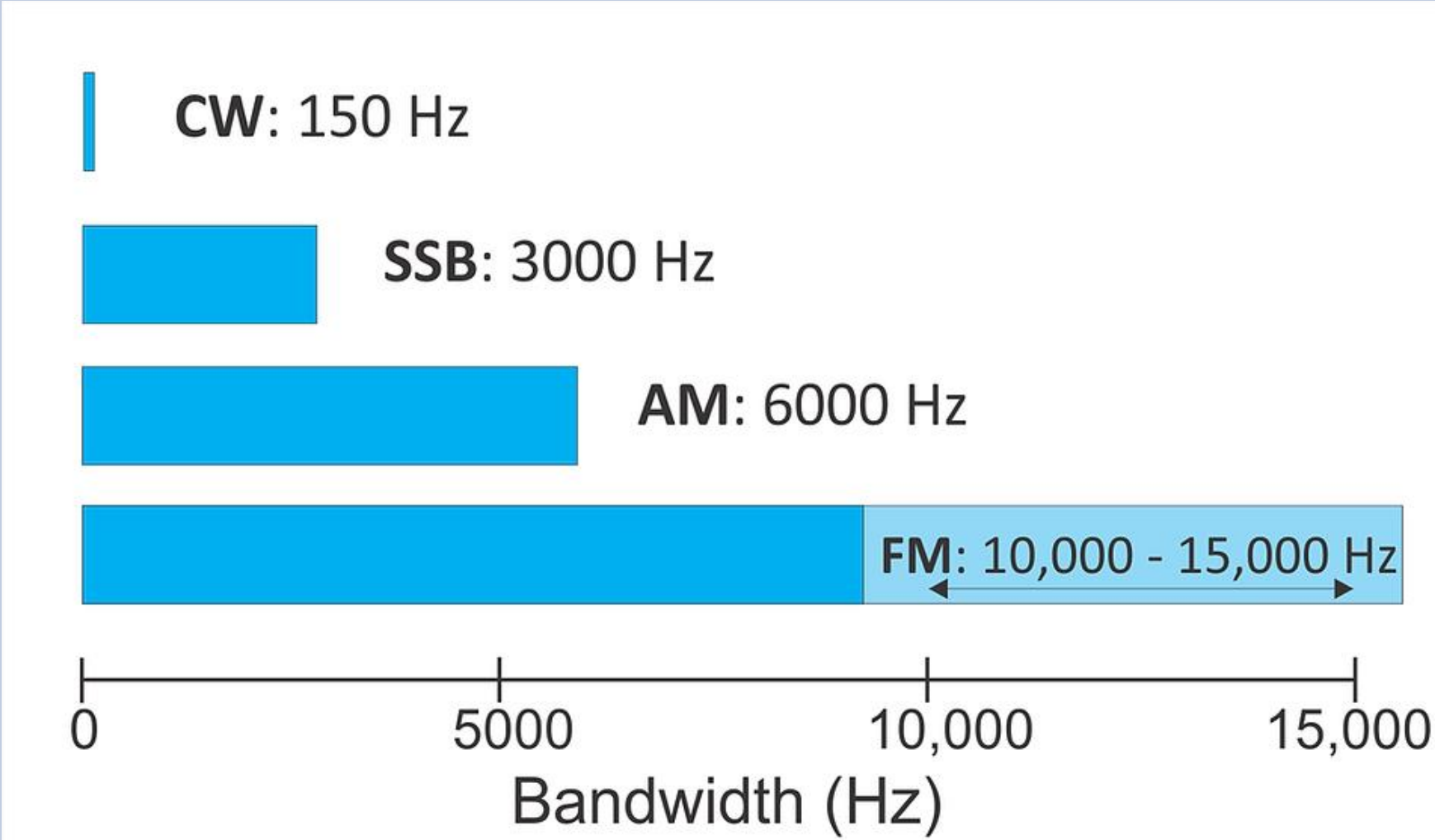
3. Phase-Locked Loop (PLL) Demodulator:

A high-performance method where a PLL locks onto the FM carrier.
The VCO in the PLL tracks the instantaneous frequency of the input signal, and the control voltage of the VCO represents the demodulated output

4. Direct Frequency Discriminator:

Uses a differentiator to produce a signal proportional to the derivative of the FM input.
The resulting amplitude variations are then detected to recover the message signal.

Analog Modulation Summary (Amateur Radio)



US Amateur Radio Bands

US AMATEUR POWER LIMITS — FCC 97.313 An amateur station must use the minimum transmitter power necessary to carry out the desired communications. (b) No station may transmit with a transmitter power exceeding 1.5 kW PEP.

Amateurs wishing to operate on either 2,200 or 630 meters must first register with the Utilities Technology Council online at **https://utc.org/plc-database-amateur-notification-process/** You need only register once for each band.

2,200 Meters (135 kHz)



630 Meters (472 kHz)

5 W EIRP maximum, except in Alaska within 496 miles of Russia where the power limit is 1 W EIRP.



160 Meters (1.8 MHz)

Avoid interference to radiolocation operations from 1.900 to 2.000 MHz



80 Meters (3.5 MHz)

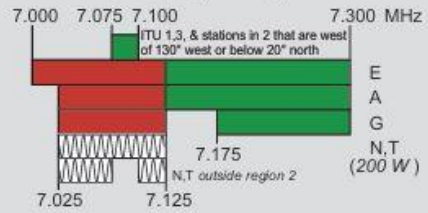


60 Meters (5.3 MHz)



General, Advanced, and Extra licensees may operate on a secondary basis with a maximum ERP of 100 W (relative to a half-wave dipole antenna).

40 Meters (7 MHz)



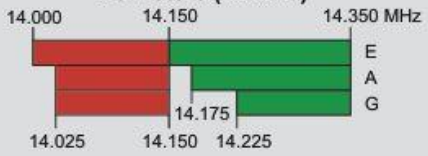
See Sections 97.305(c), 97.307(f)(11) and 97.301(e).These exemptions do not apply to stations in the continental US.

30 Meters (10.1 MHz)

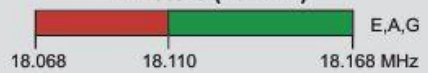
Avoid interference to fixed services outside the US.



20 Meters (14 MHz)



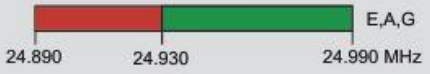
17 Meters (18 MHz)



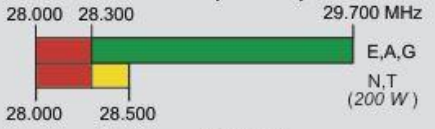
15 Meters (21 MHz)



12 Meters (24 MHz)



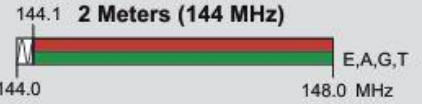
10 Meters (28 MHz)



6 Meters (50 MHz)



2 Meters (144 MHz)



1.25 Meters (222 MHz)



*Geographical and power restrictions may apply to all bands above 420 MHz. See FCC Part 97.303 for information about your area.

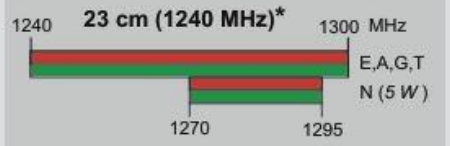
70 cm (420 MHz)*



33 cm (902 MHz)*



23 cm (1240 MHz)*



All licensees except Novices are authorized all modes on the following frequencies:

2300-2310 MHz	10.0-10.5 GHz ‡	122.25-123.0 GHz
2390-2450 MHz	24.0-24.25 GHz	134-141 GHz
3400-3450 MHz	47.0-47.2 GHz	241-250 GHz
5650-5925 MHz	76.0-81.0 GHz	All above 275 GHz

‡ No pulse emissions

ARRL
The National Association for Amateur Radio®

KEY

Note:
CW operation is permitted throughout all amateur bands.

MCW is authorized above 50.1 MHz, except for 144.0-144.1 and 219-220 MHz.

Test transmissions are authorized above 51 MHz, except for 219-220 MHz

- = RTTY and data
- = phone and image
- = CW *only*
- = SSB phone
- = USB phone, CW, RTTY, and data
- = Fixed digital message forwarding systems *only*

E = Amateur Extra
A = Advanced
G = General
T = Technician
N = Novice

See *www.arrl.org/band-plan* for detailed band plans.

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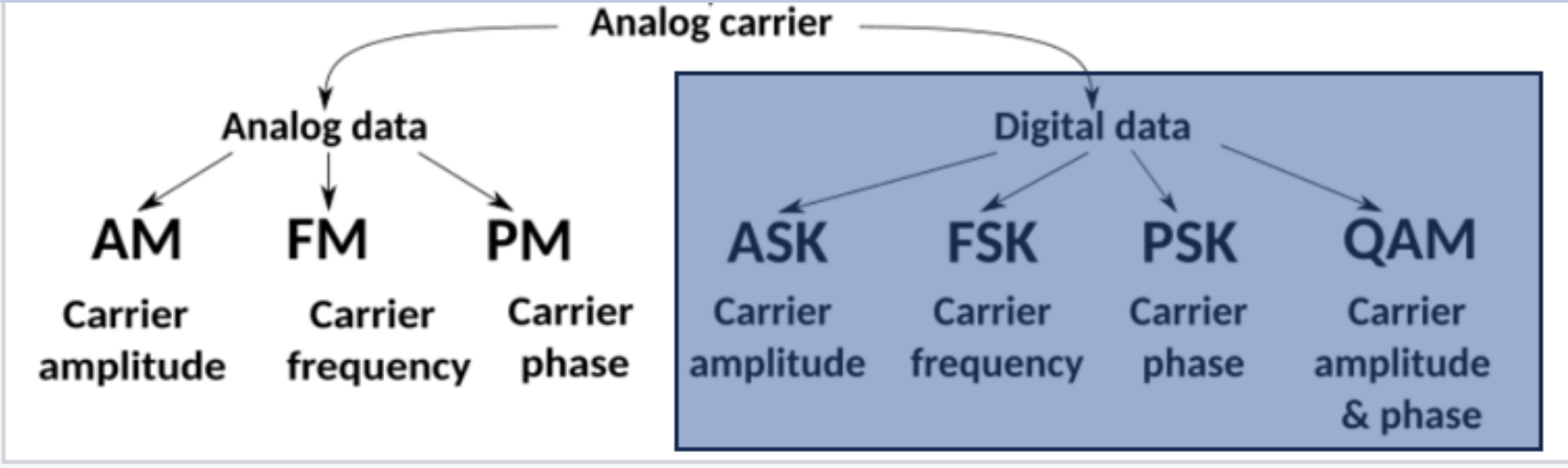
Exams: 860-594-0300 email: vec@arrl.org

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Digital Modulation (Analog Carrier, Digital Data)

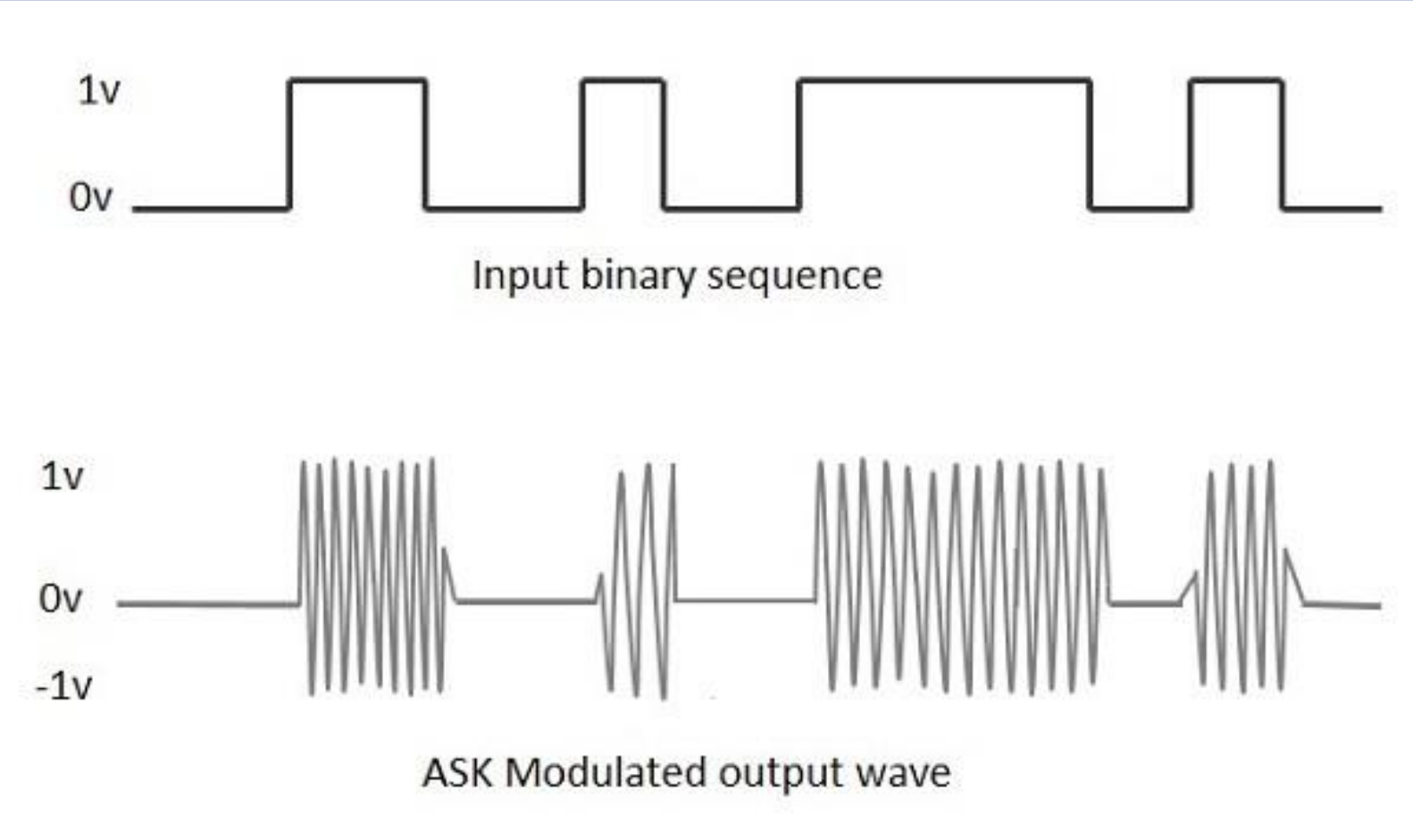
In digital modulation, an analog carrier signal is modulated by a discrete signal. Digital modulation methods can be considered as digital-to-analog conversion and the corresponding demodulation or detection as analog-to-digital conversion. The changes in the carrier signal are chosen from a finite number of M alternative symbols (the modulation alphabet).

The most fundamental digital modulation techniques are based on keying:
ASK (amplitude-shift keying): a finite number of amplitudes are used.
FSK (frequency-shift keying): a finite number of frequencies are used.
PSK (phase-shift keying): a finite number of phases are used.
QAM (quadrature amplitude modulation): a finite number of amplitudes and phases are used.



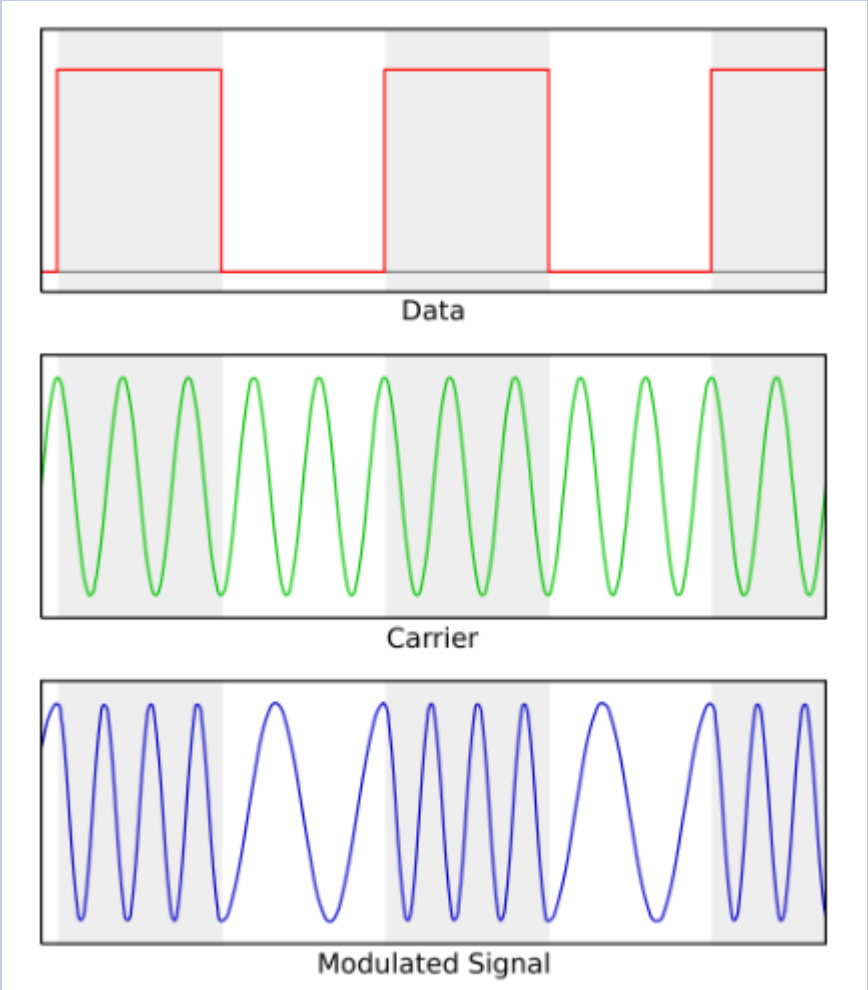
Amplitude Shift Keying (ASK)

Amplitude Shift Keying (ASK) is a digital modulation scheme in which **digital information is transmitted by varying the amplitude of a carrier signal**.



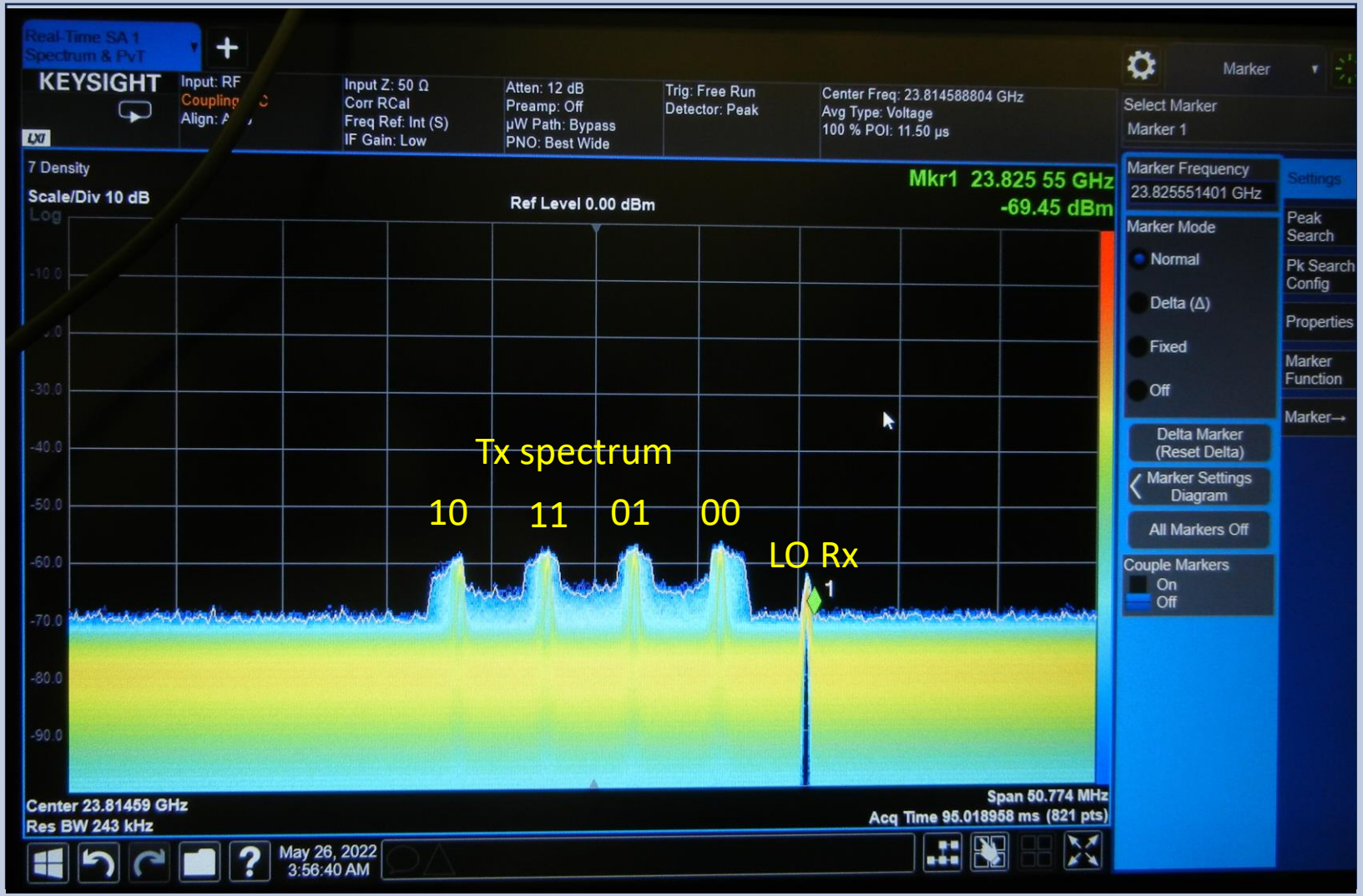
Frequency Shift Keying (FSK)

Frequency Shift Keying (FSK) is a digital modulation scheme in which **digital information is transmitted by varying the frequency of a carrier signal**.
In 1910, Reginald Fessenden invented a two-tone method of transmitting Morse code. Dots and dashes were replaced with different tones of equal length. The intent was to minimize transmission time.
In its simplest form, Binary FSK (**BFSK)**, the carrier switches between two distinct frequencies: one for binary '1' (mark frequency) and another for binary '0' (space frequency).This allows digital data to be encoded efficiently for transmission over communication channels.
An FSK modulator typically uses two oscillators or a single oscillator capable of switching frequencies. The binary input sequence controls which frequency is transmitted at any given time. To avoid abrupt phase discontinuities, a clock signal is often applied to synchronize the frequency switching, ensuring smooth transitions and reducing interference with adjacent channels The resulting waveform alternates between high and low frequencies corresponding to the input digital signal.
FSK signals can be demodulated using coherent (synchronous) or non-coherent (asynchronous) detectors. Coherent detection requires phase synchronization with the carrier, while non-coherent detection does not, making it simpler but slightly less efficient.



Binary FSK (BFSK) modulation

Frequency Shift Keying (FSK)

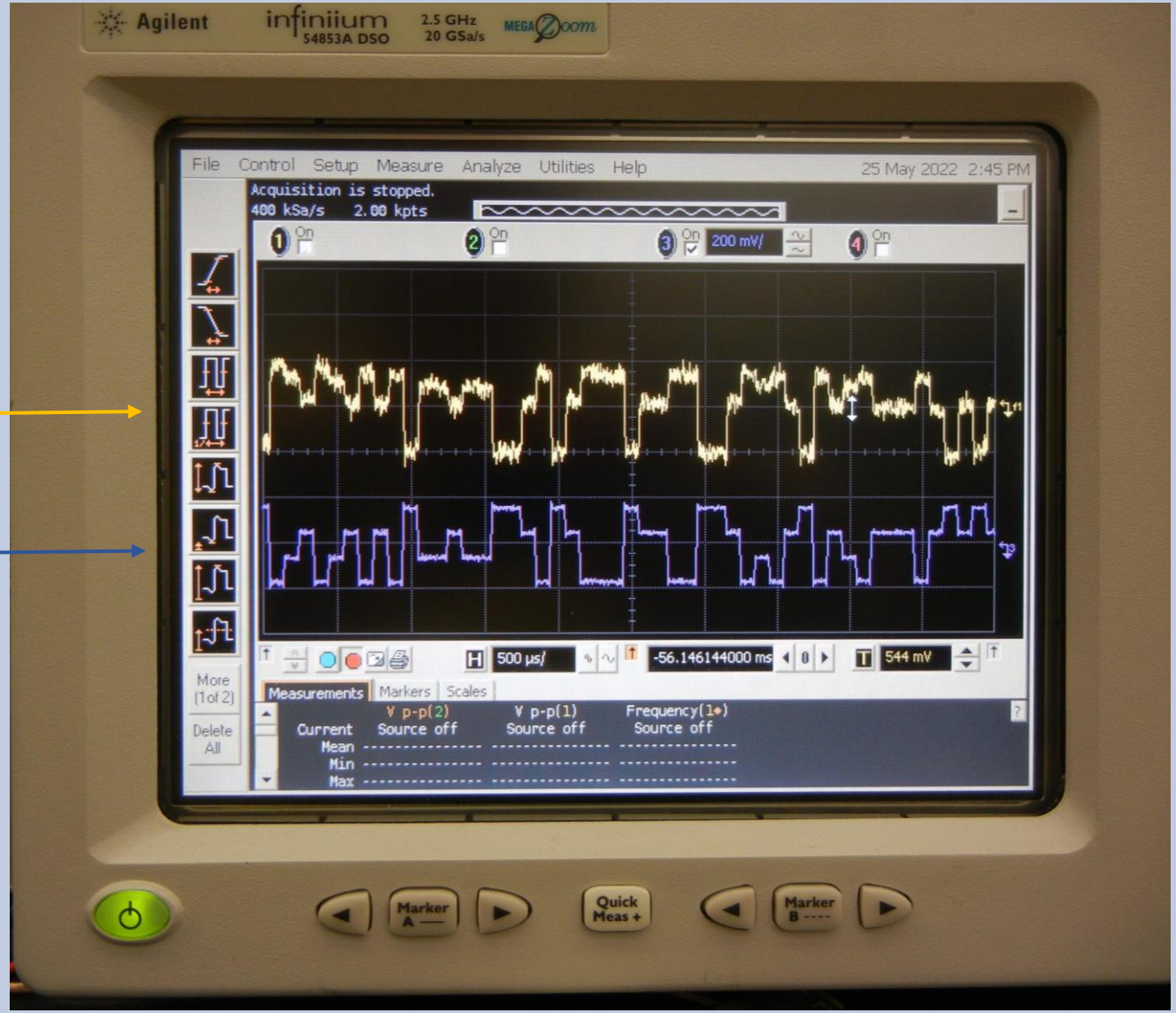


Frequency spectrum of a 4PSK modulated signal at 24 GHz

Frequency Shift Keying (FSK)

Demodulated signal

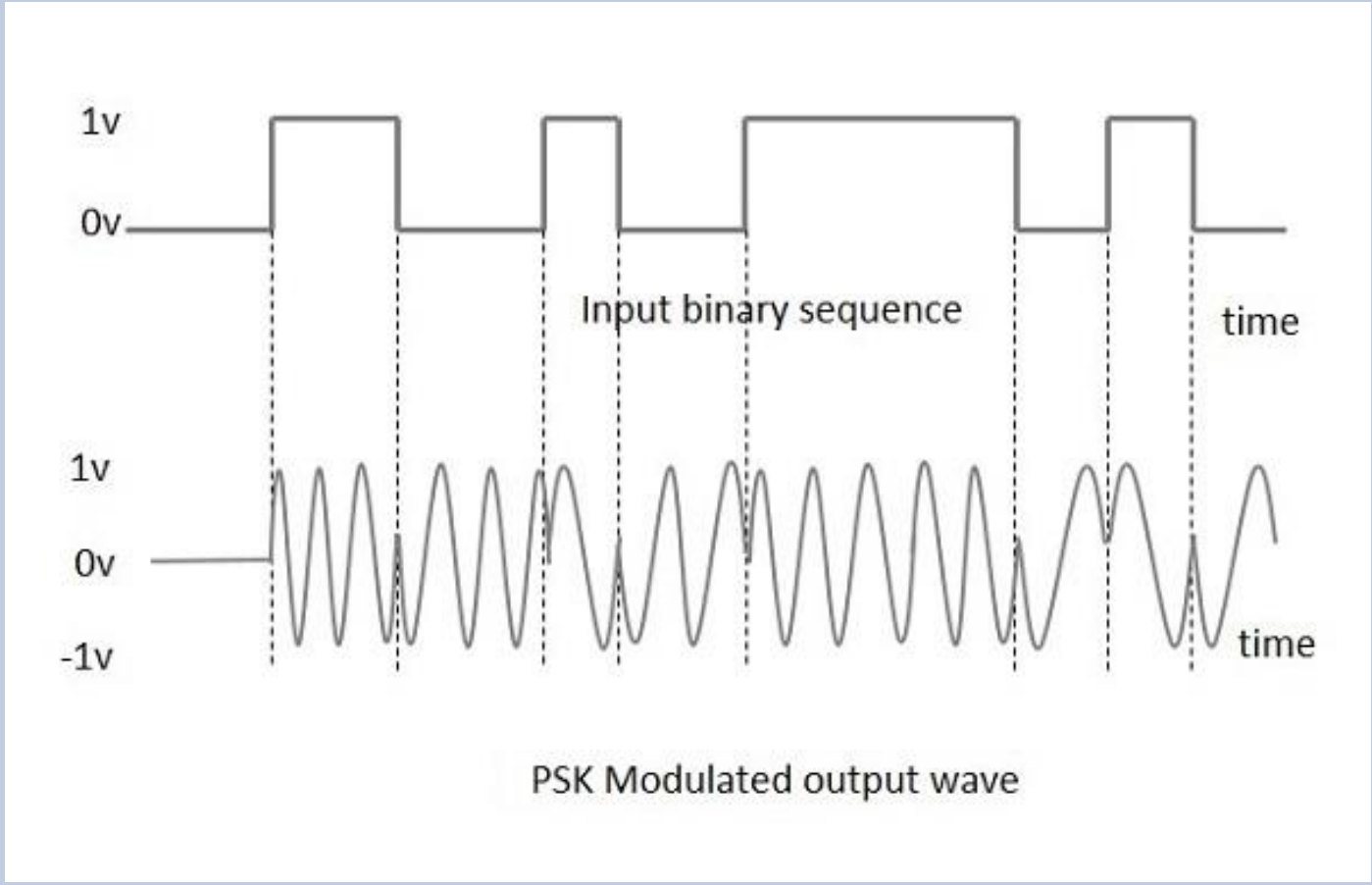
Transmitted signal



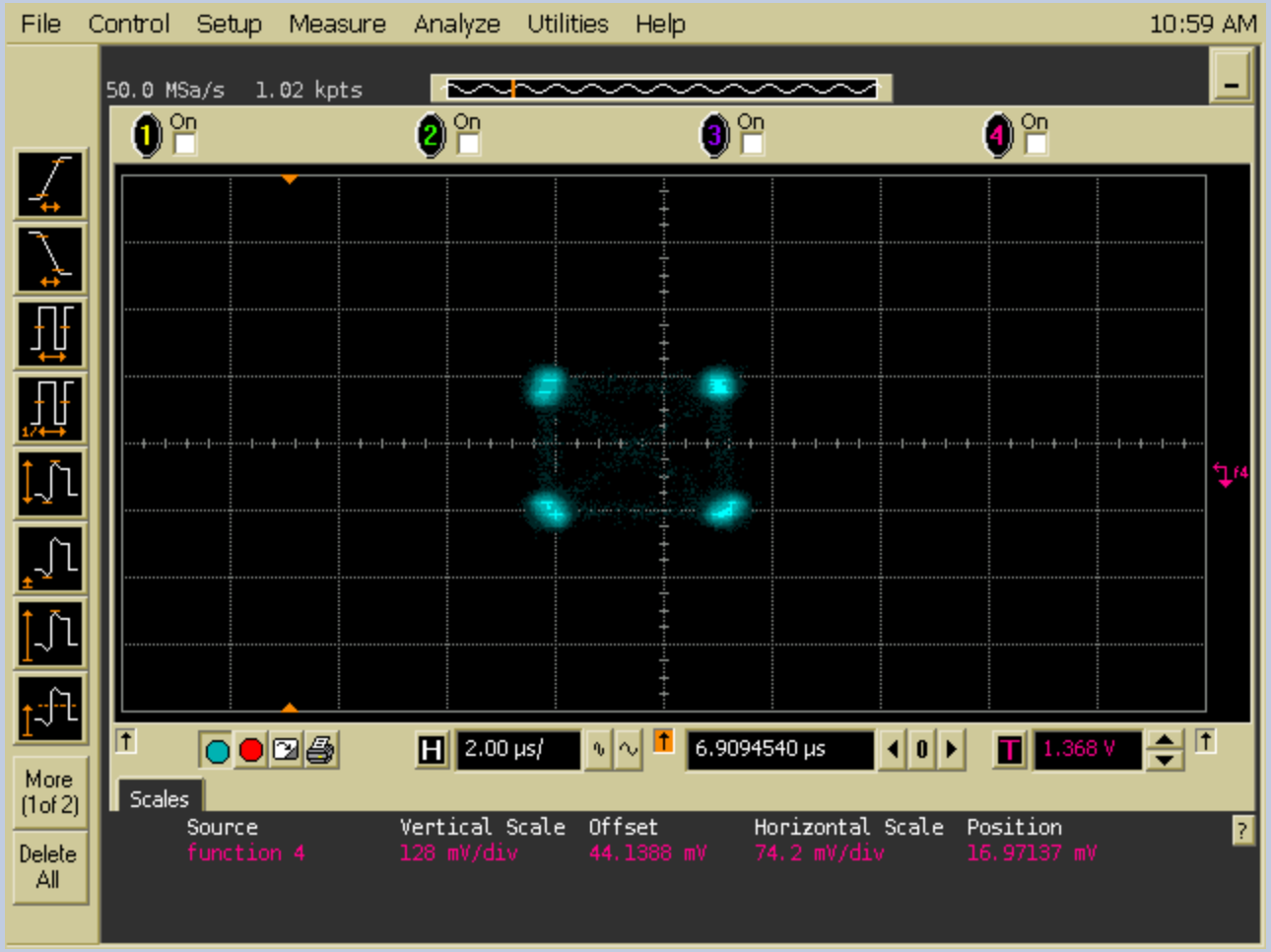
Time domain signal, with 4 voltage levels

Phase Shift Keying (BPSK)

Phase-shift keying (PSK) is a digital modulation process which conveys data by changing (modulating) the phase of a constant frequency carrier wave. The modulation is accomplished by varying the sine and cosine inputs at a precise time. It is widely used for wireless LANs, RFID and Bluetooth communication.

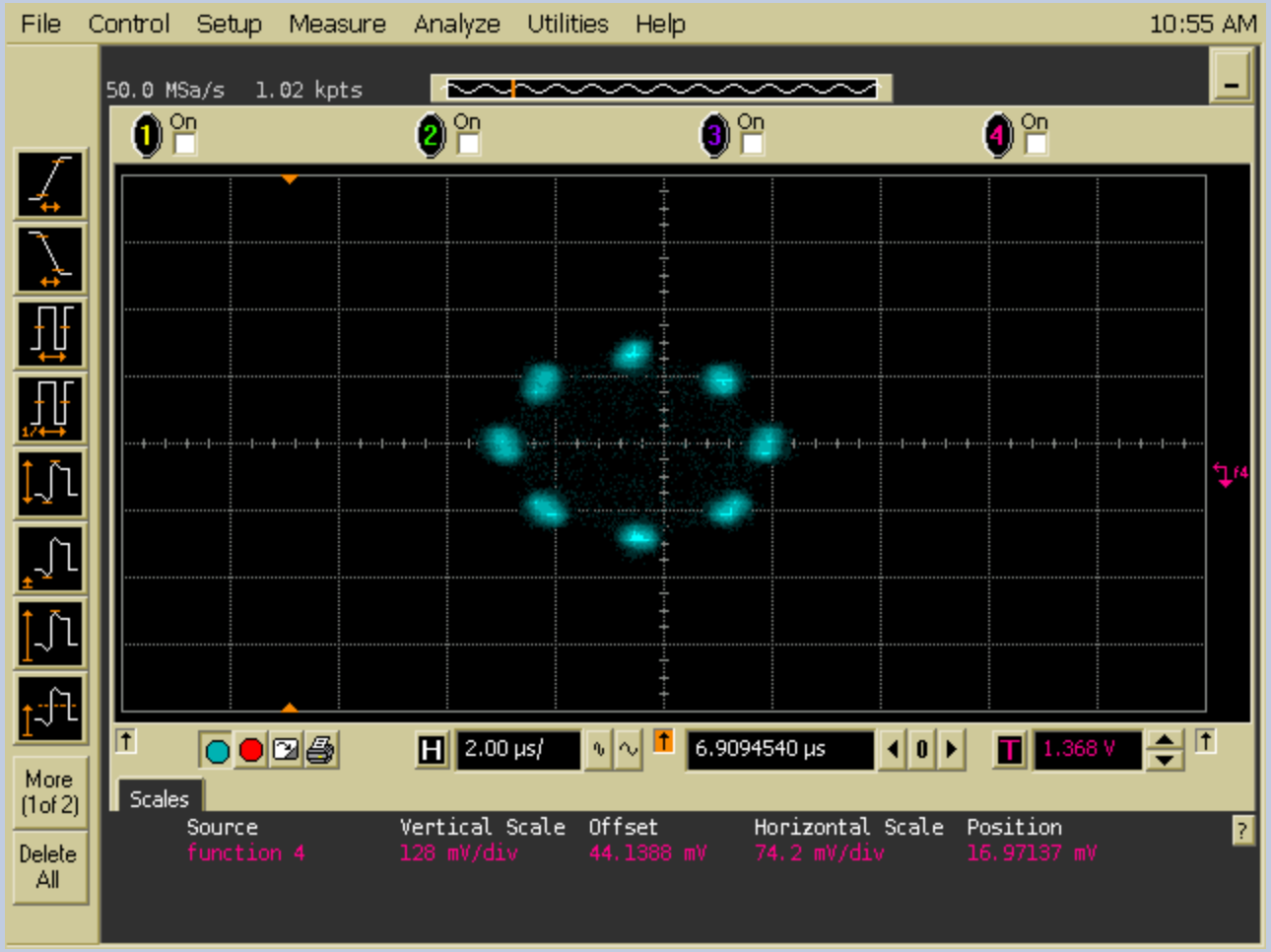


Phase Shift Keying (QPSK)



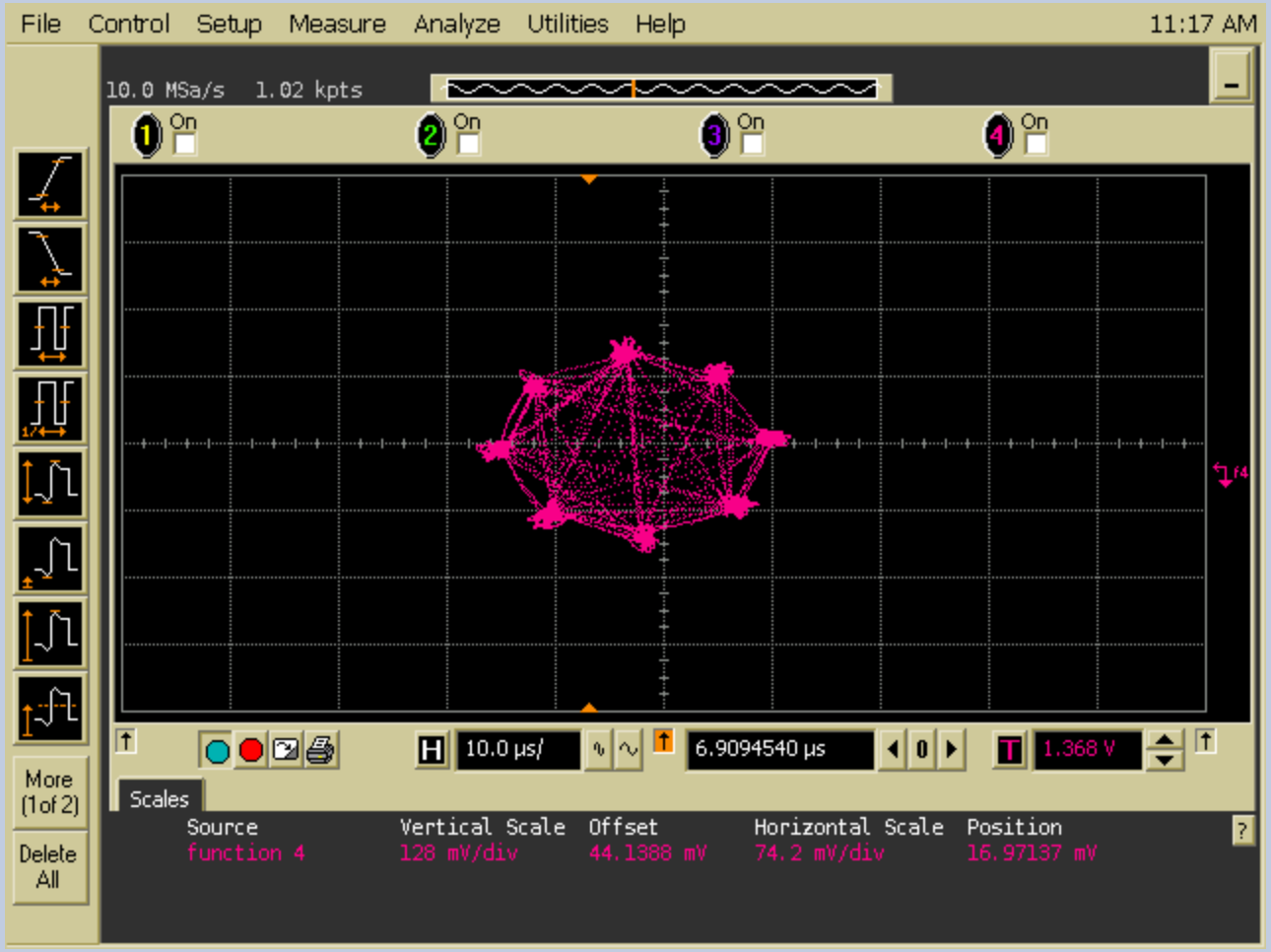
Demodulated 3 GHz carrier, 1 MS/s QPSK

Phase Shift Keying (8PSK)



Demodulated 3 GHz carrier, 1 MS/s 8PSK

Phase Shift Keying (8PSK)



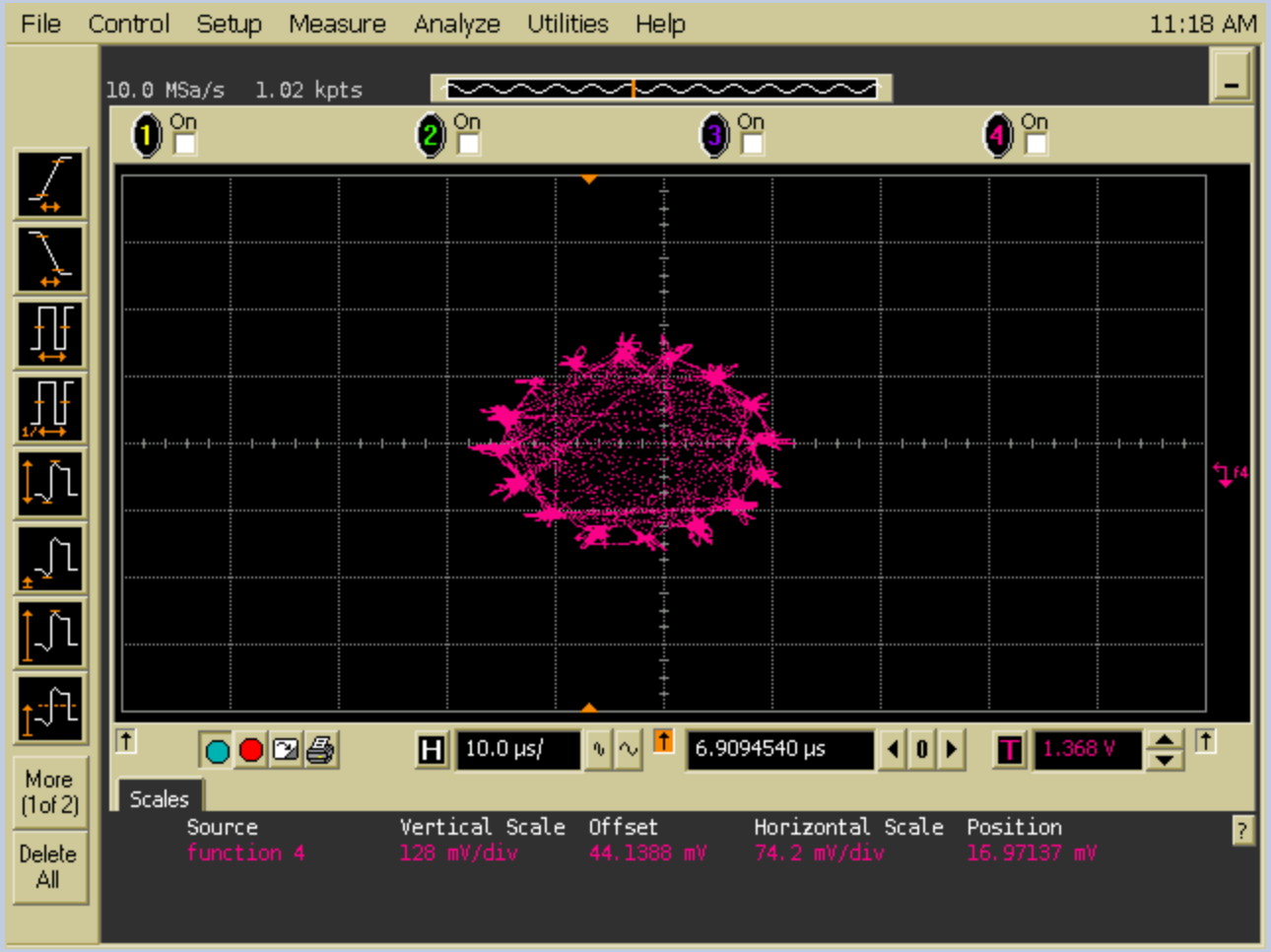
Demodulated 3 GHz carrier, 1 MS/s 8PSK

Phase Shift Keying (16PSK)



Demodulated 3 GHz carrier, 1 MS/s 16PSK

Phase Shift Keying (16PSK)

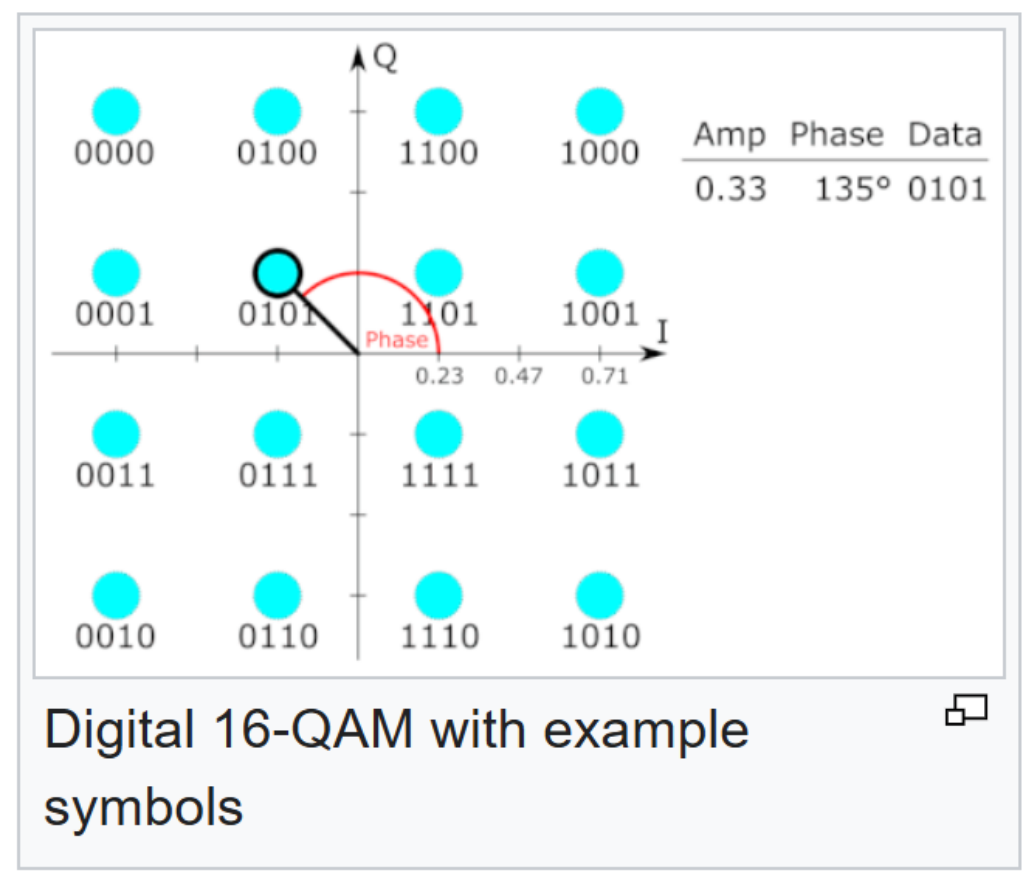


Demodulated 3 GHz carrier, 1 MS/s 16PSK

Quadrature Amplitude Modulation (QAM)

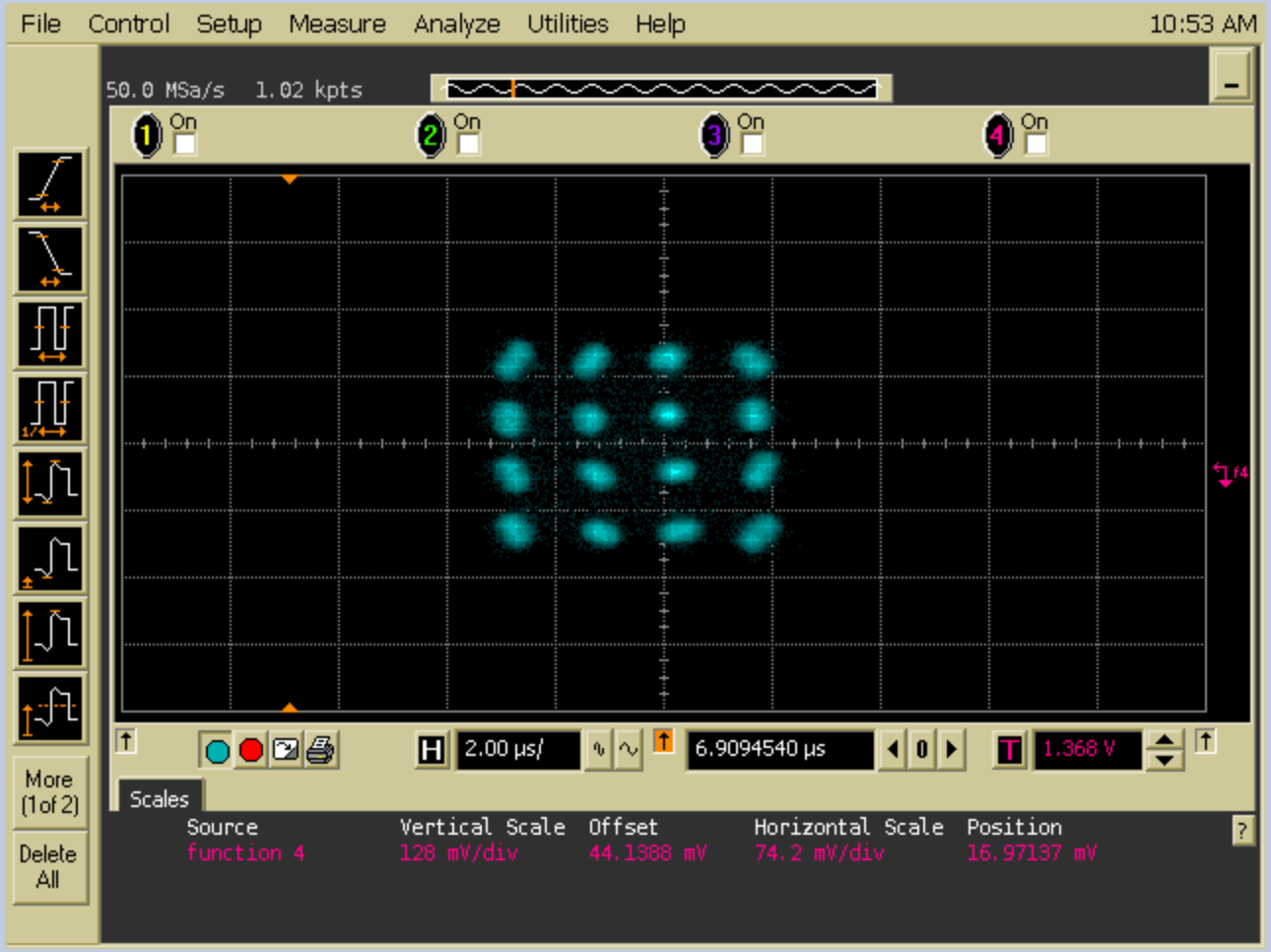
Quadrature amplitude modulation (QAM) is the name of a family of signal modulation methods widely used in modern telecommunications to transmit information. At its core, it conveys two independent analog signals by changing (modulating) the amplitudes of two differently phased versions of a single carrier wave using amplitude modulation. These paired analog signal channels may then be used either directly or to encode digital bit streams using joint amplitude-shift keying across the synchronized channels.

The two carrier waves are of the same frequency and are out of phase with each other by 90°, a condition known as orthogonality or quadrature. The transmitted signal is created by adding the two carrier waves together. At the receiver, the two waves can be coherently separated (demodulated) because of their orthogonality. Another key property is that the modulations are low-frequency/low-bandwidth waveforms compared to the carrier frequency, which is known as the narrowband assumption.



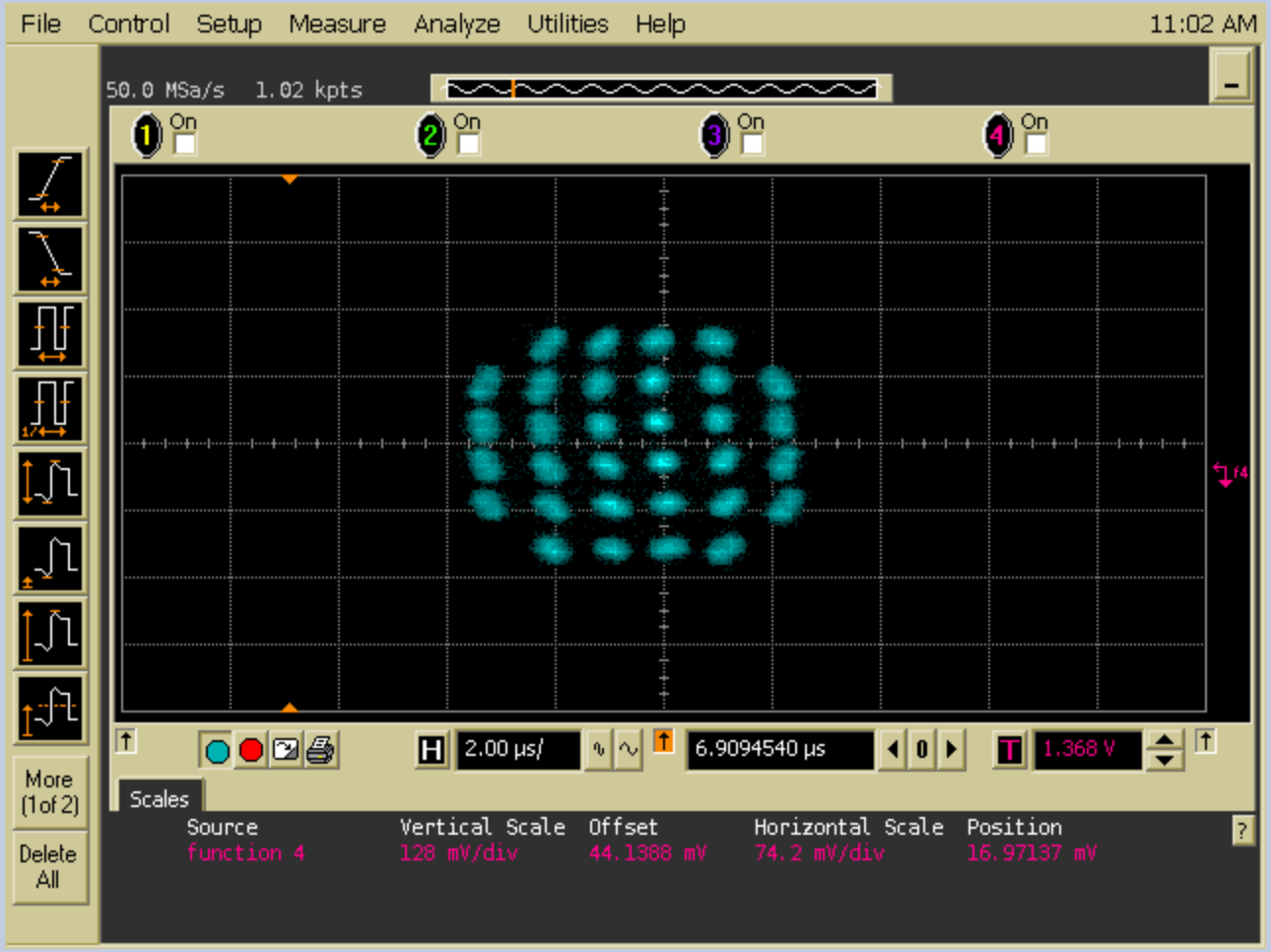
Digital 16-QAM with example symbols

Quadrature Amplitude Modulation (16QAM)



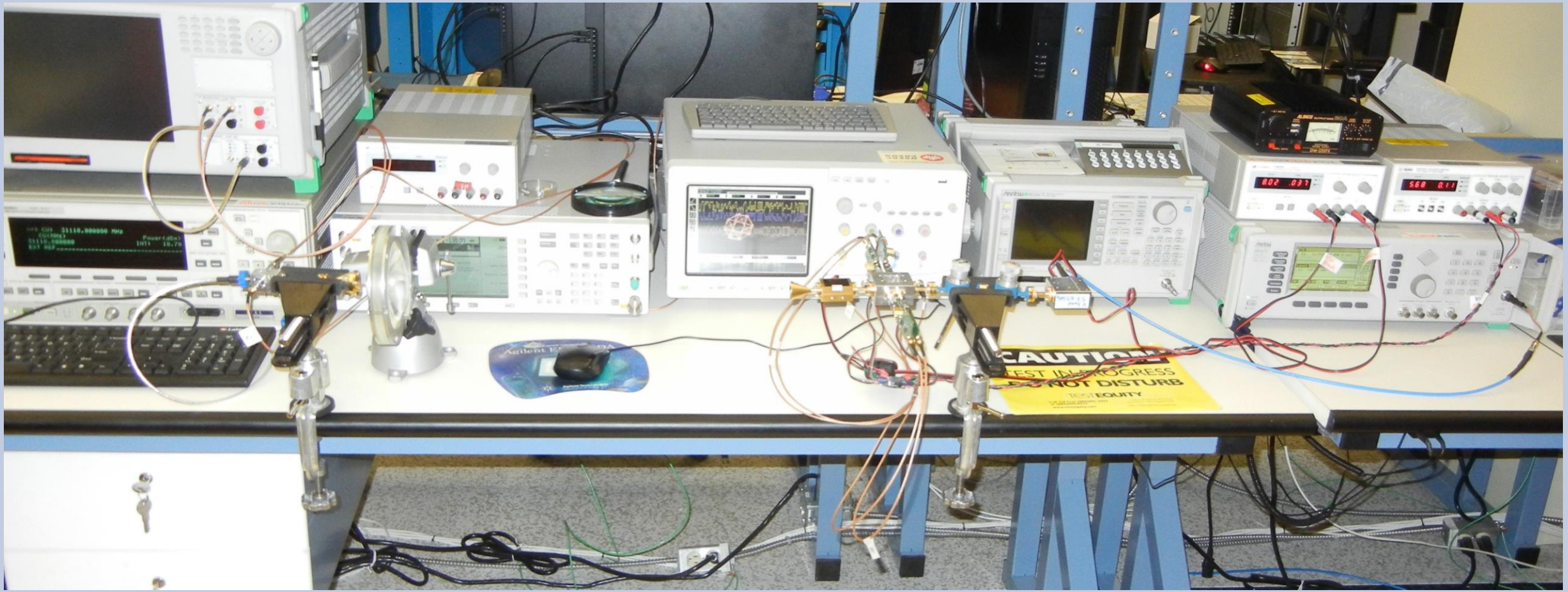
Demodulated 3 GHz carrier, 1 MS/s 16QAM

Quadrature Amplitude Modulation (32QAM)



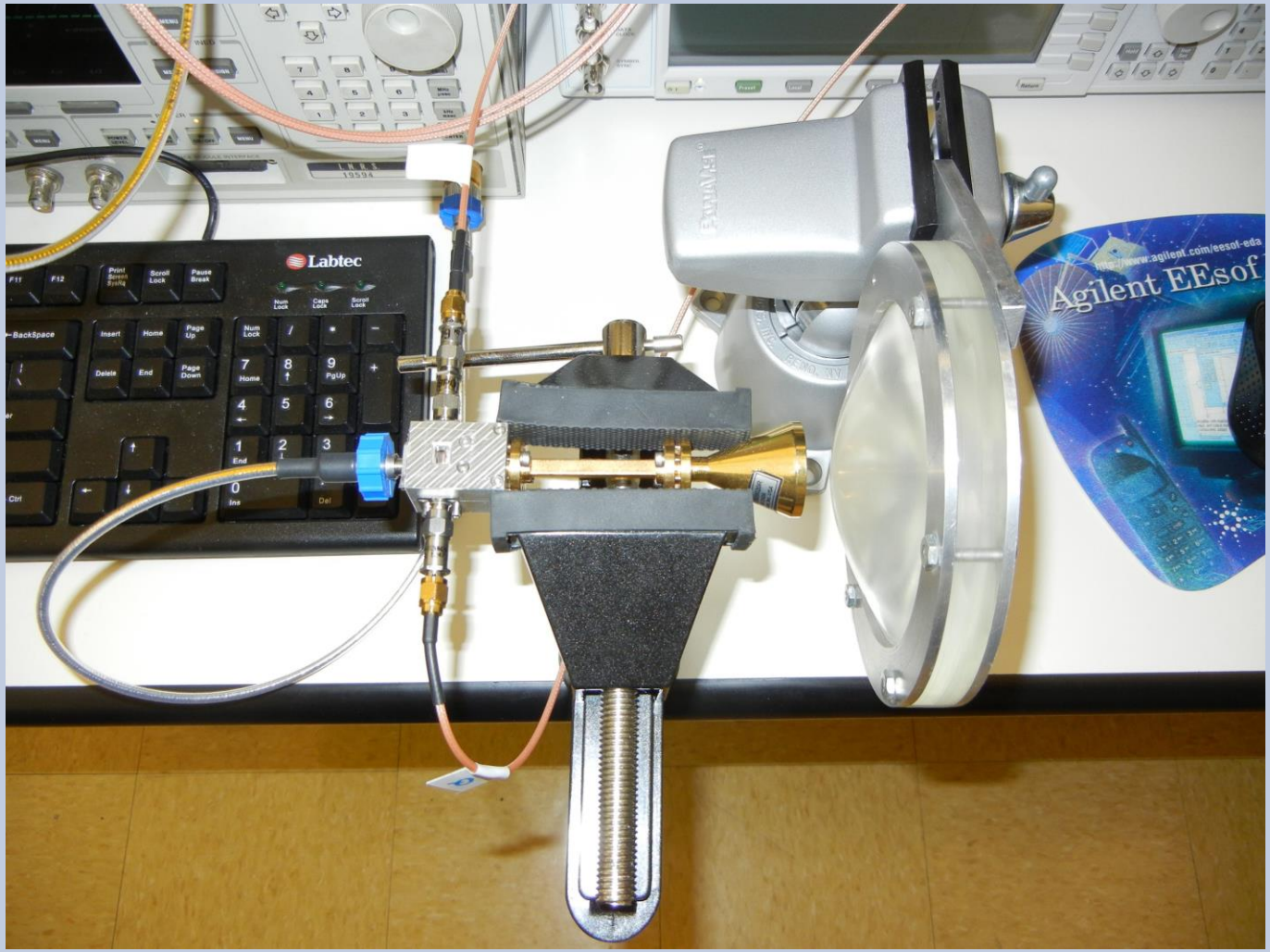
Demodulated 3 GHz carrier, 1 MS/s 32QAM

Mm-wave Digital Modulation



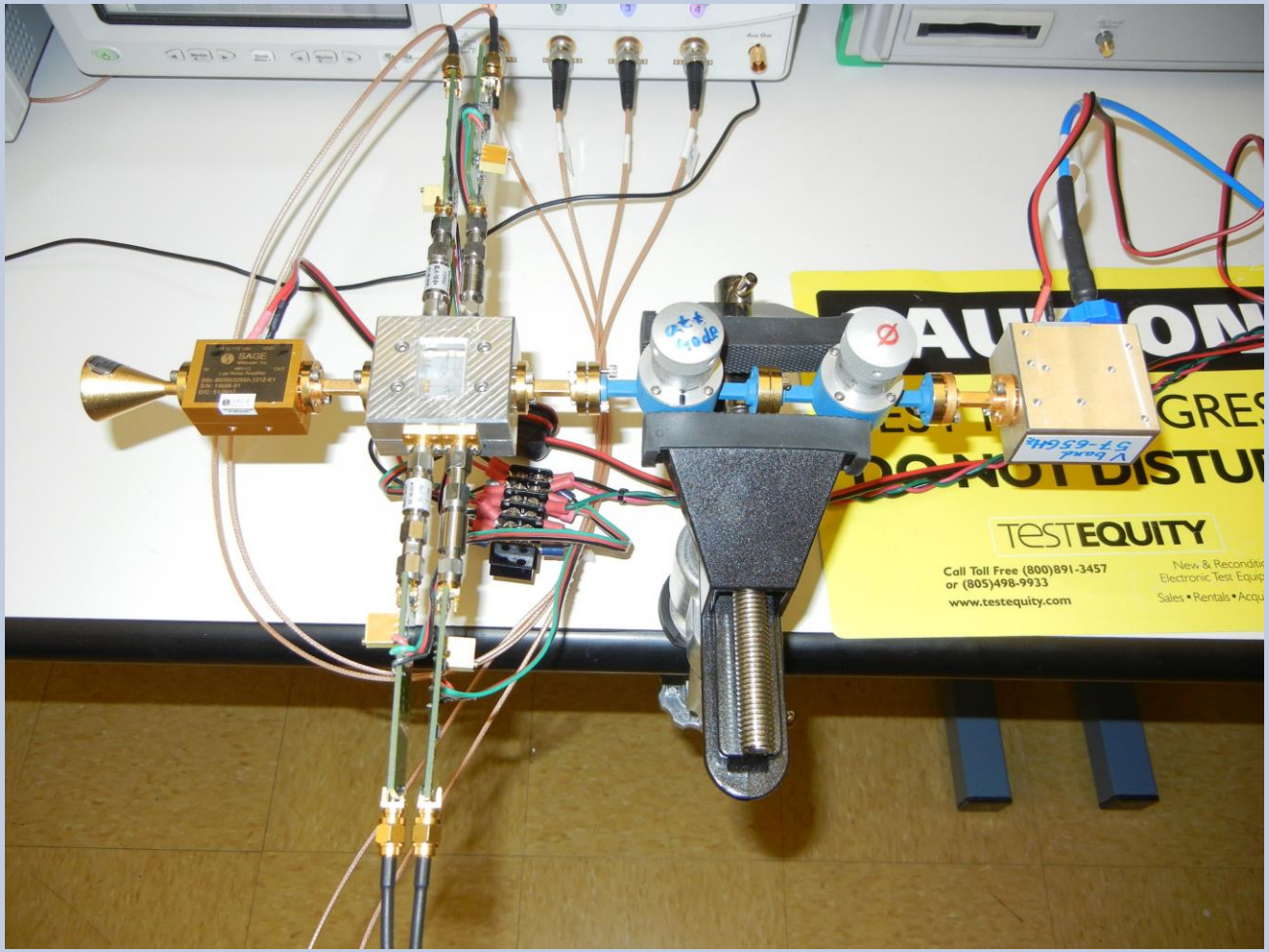
60 GHz test-bench for digital modulation

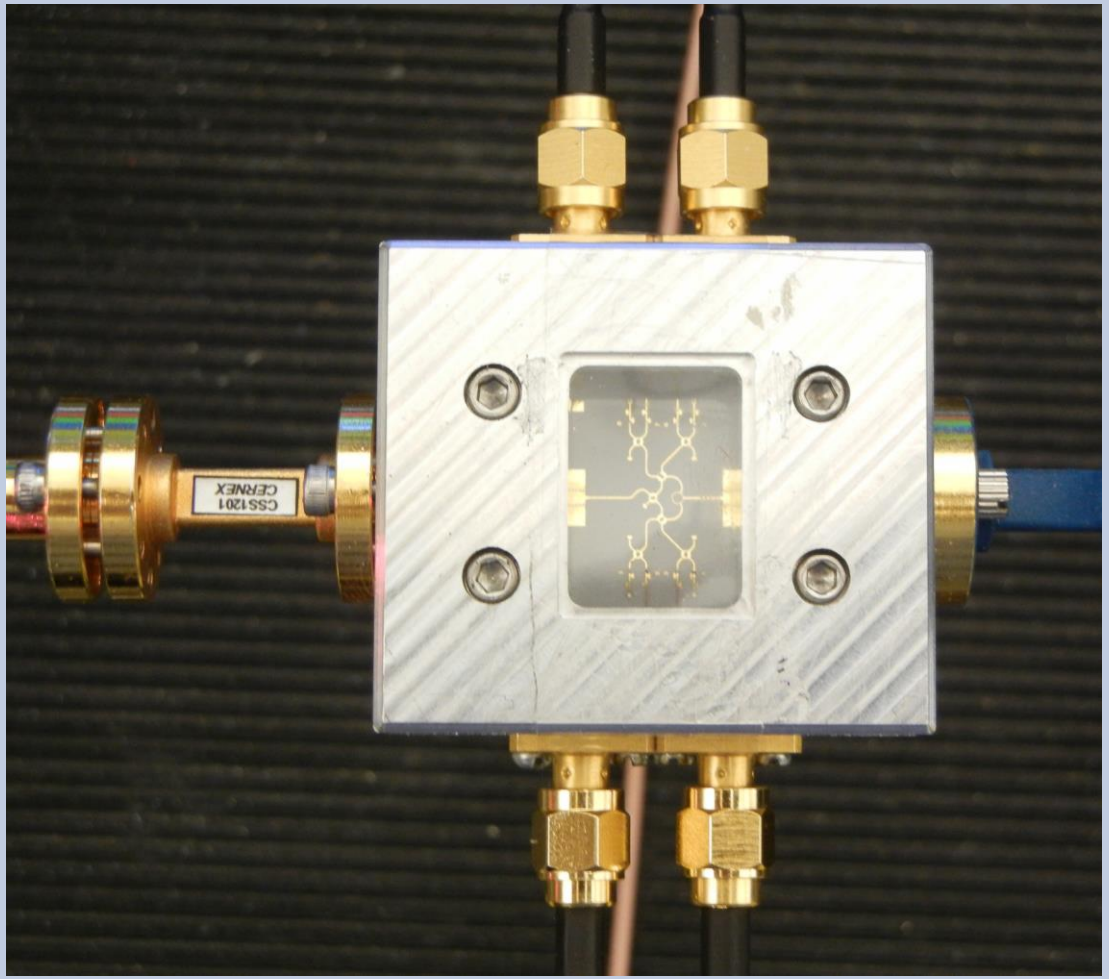
Mm-wave Digital Modulation



60 GHz test-bench for digital modulation: Tx

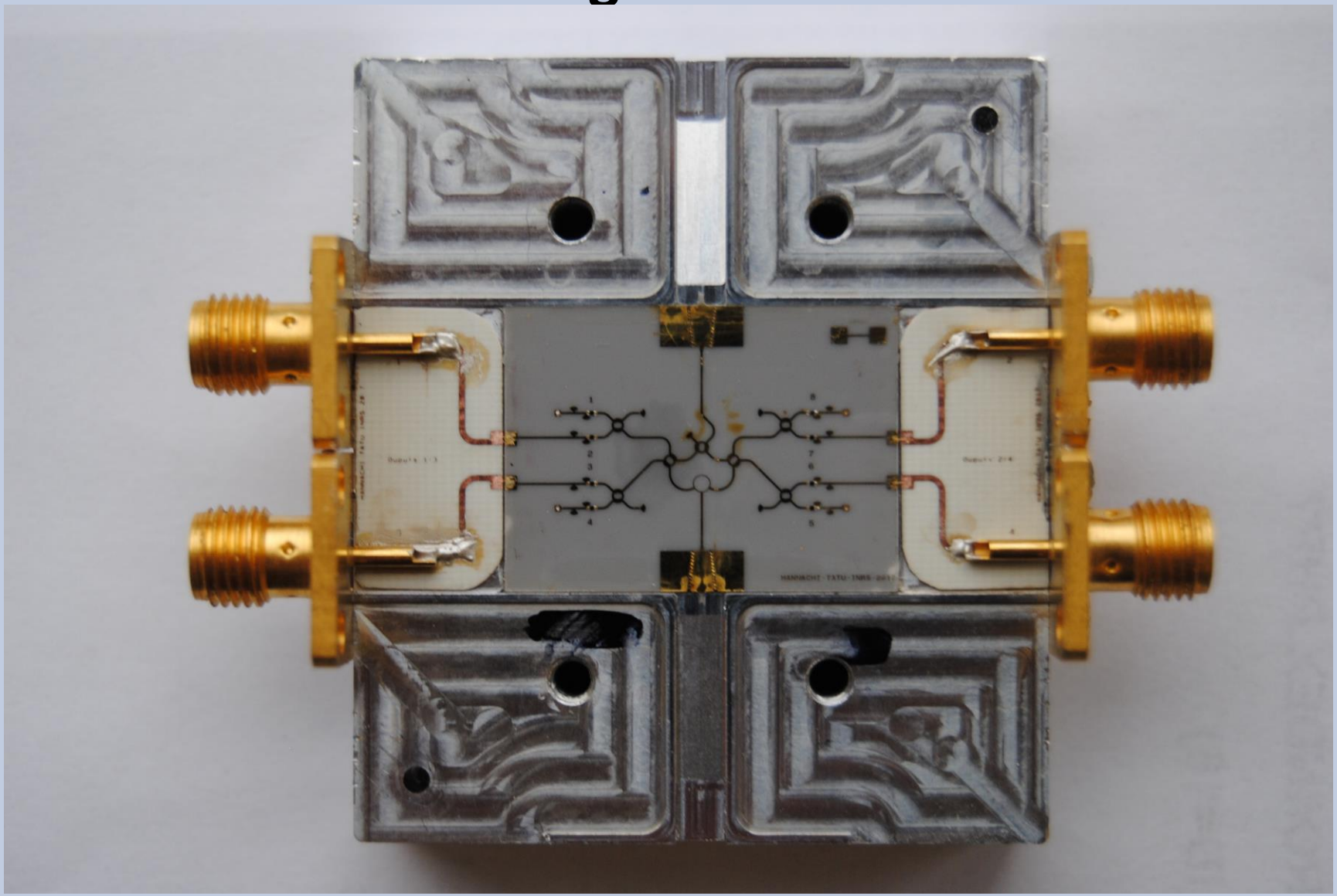
Mm-wave Digital Modulation





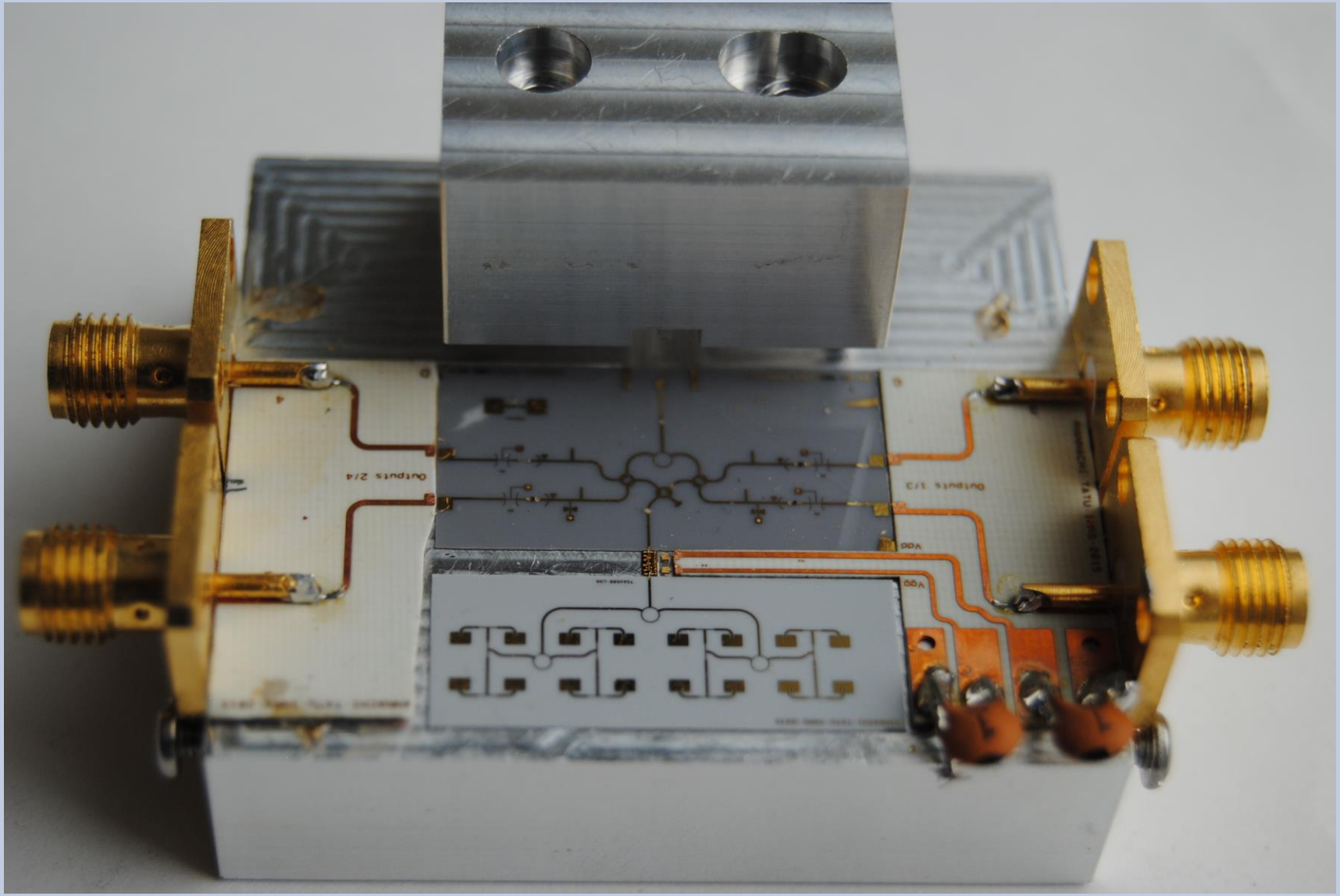
60 GHz test-bench for digital modulation: Rx

Mm-wave Digital Modulation



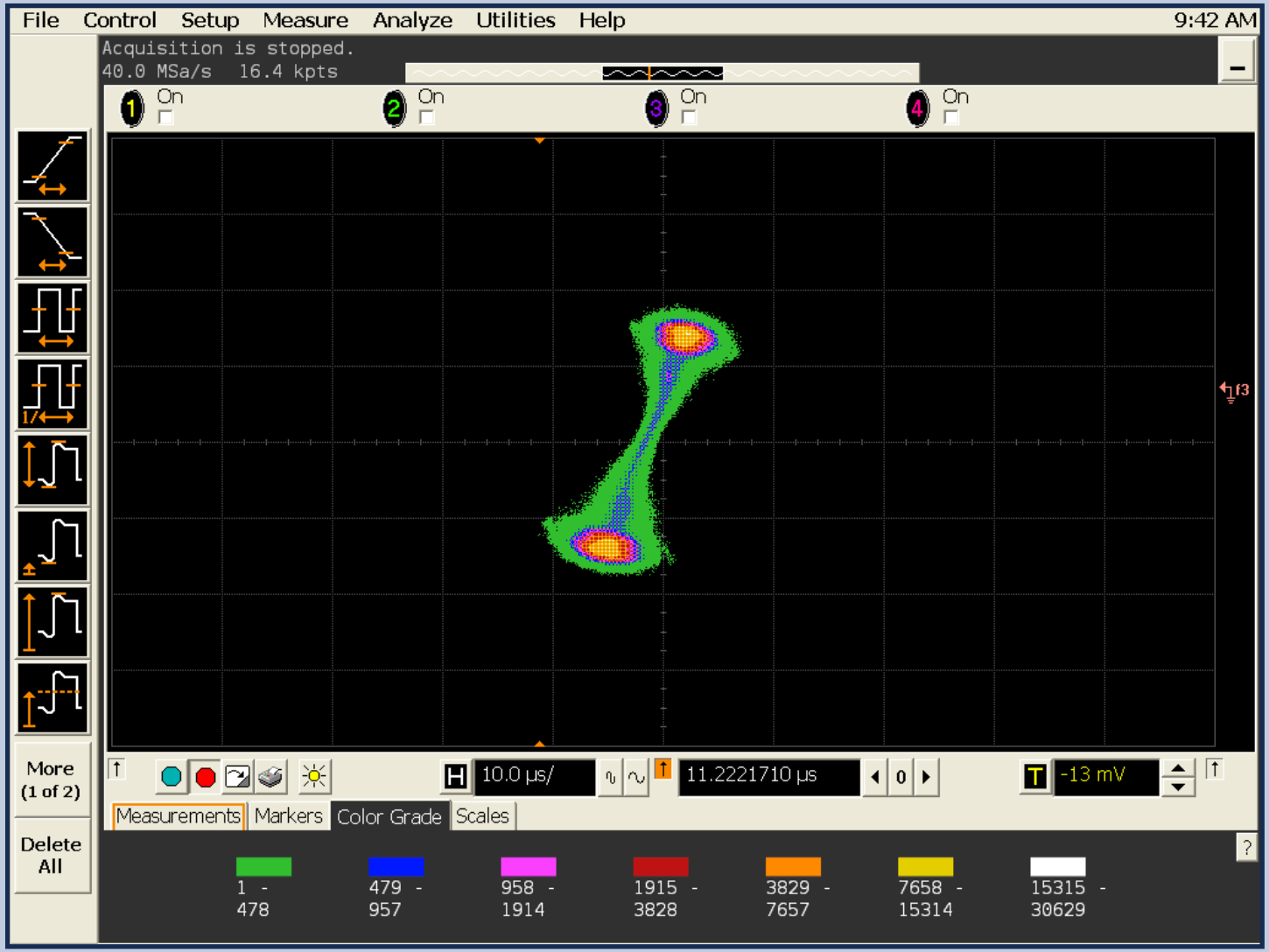
60 GHz test-bench for digital modulation: Rx

Mm-wave Digital Modulation



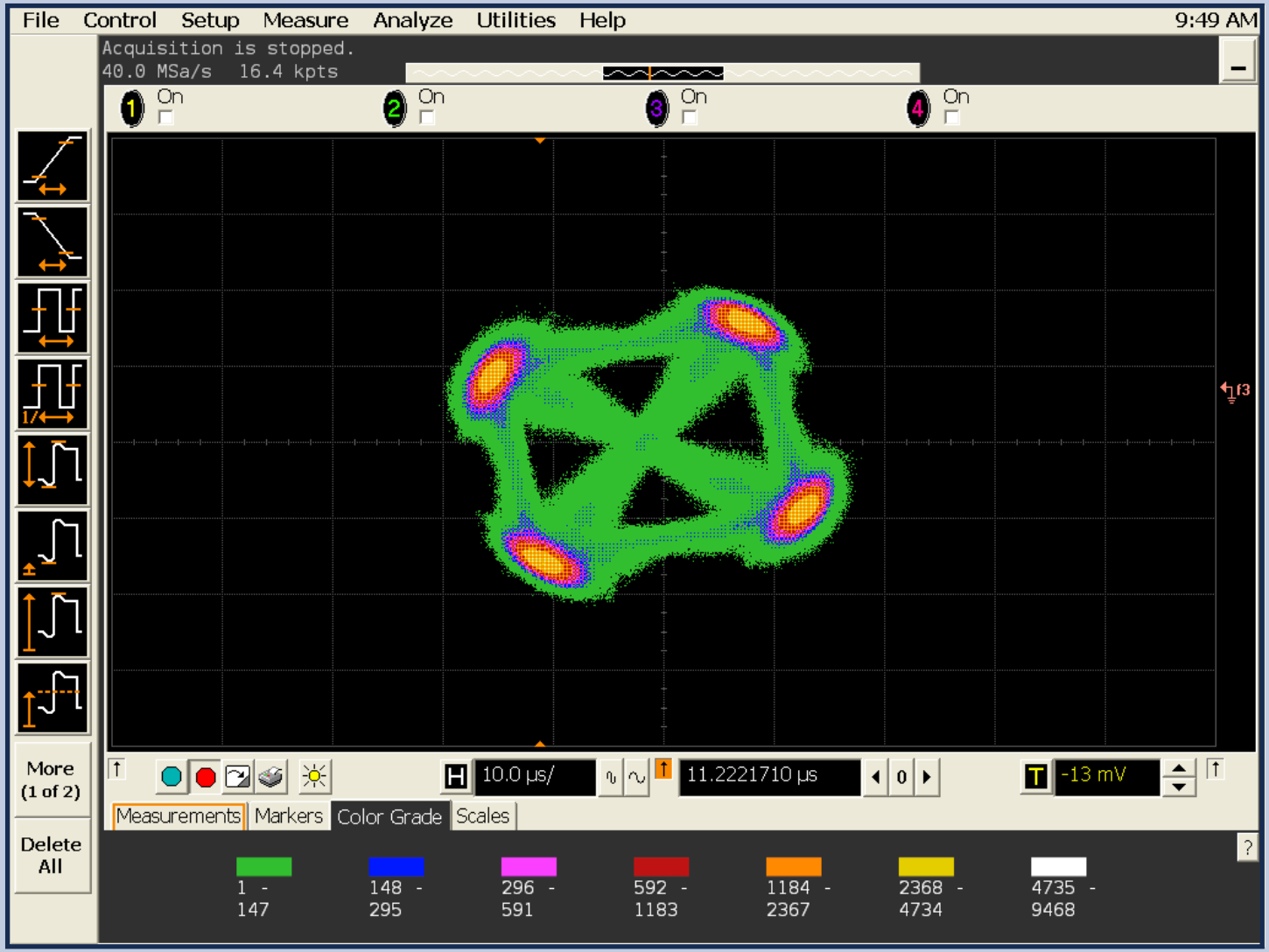
60 GHz test-bench for digital modulation: 2nd Rx with integrated antennas

Mm-wave Digital Modulation



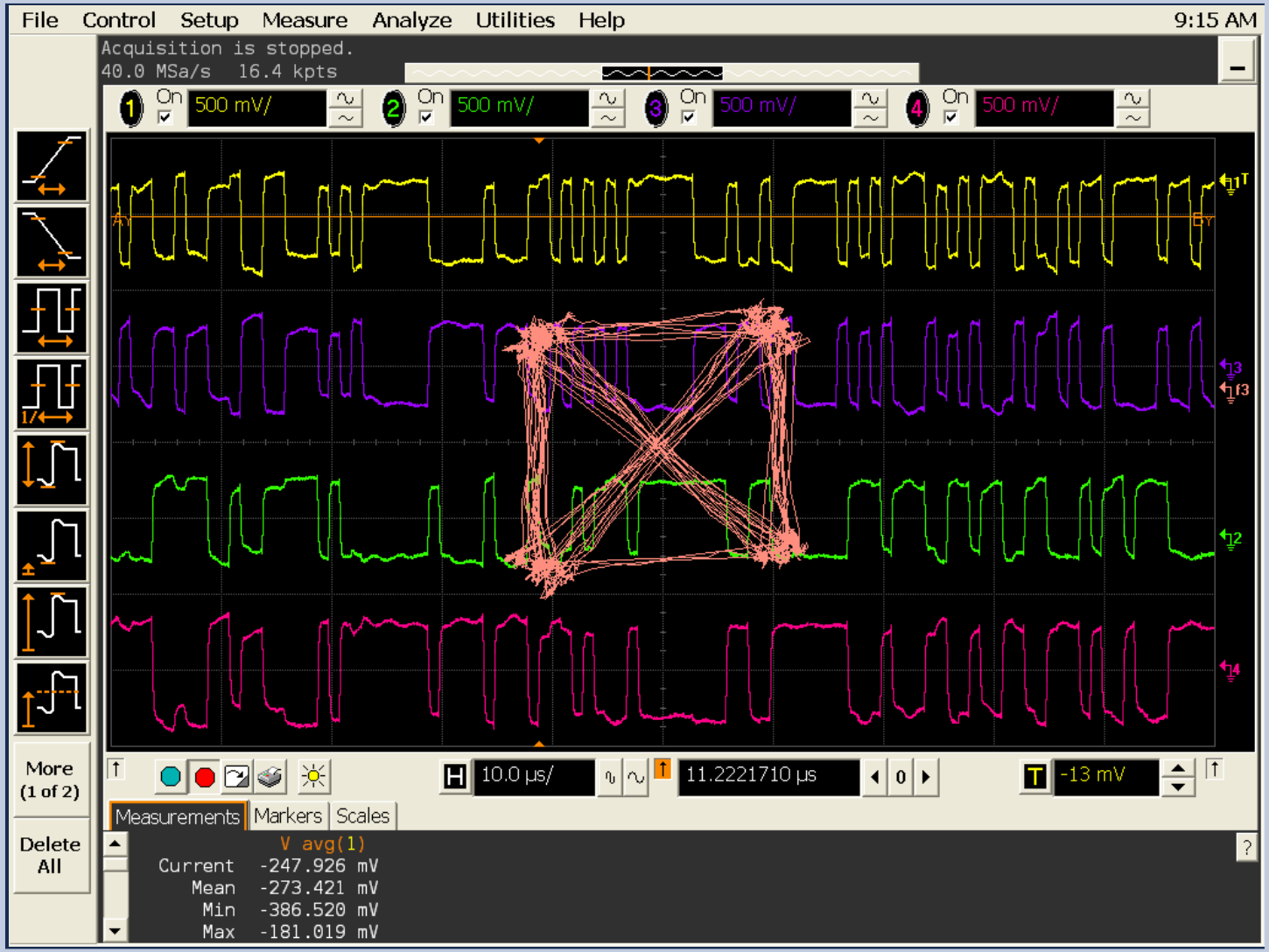
60 GHz test-bench for digital modulation: 1 MS/s BPSK

Mm-wave Digital Modulation



60 GHz test-bench for digital modulation: 1 MS/s QPSK

Mm-wave Digital Modulation



I+

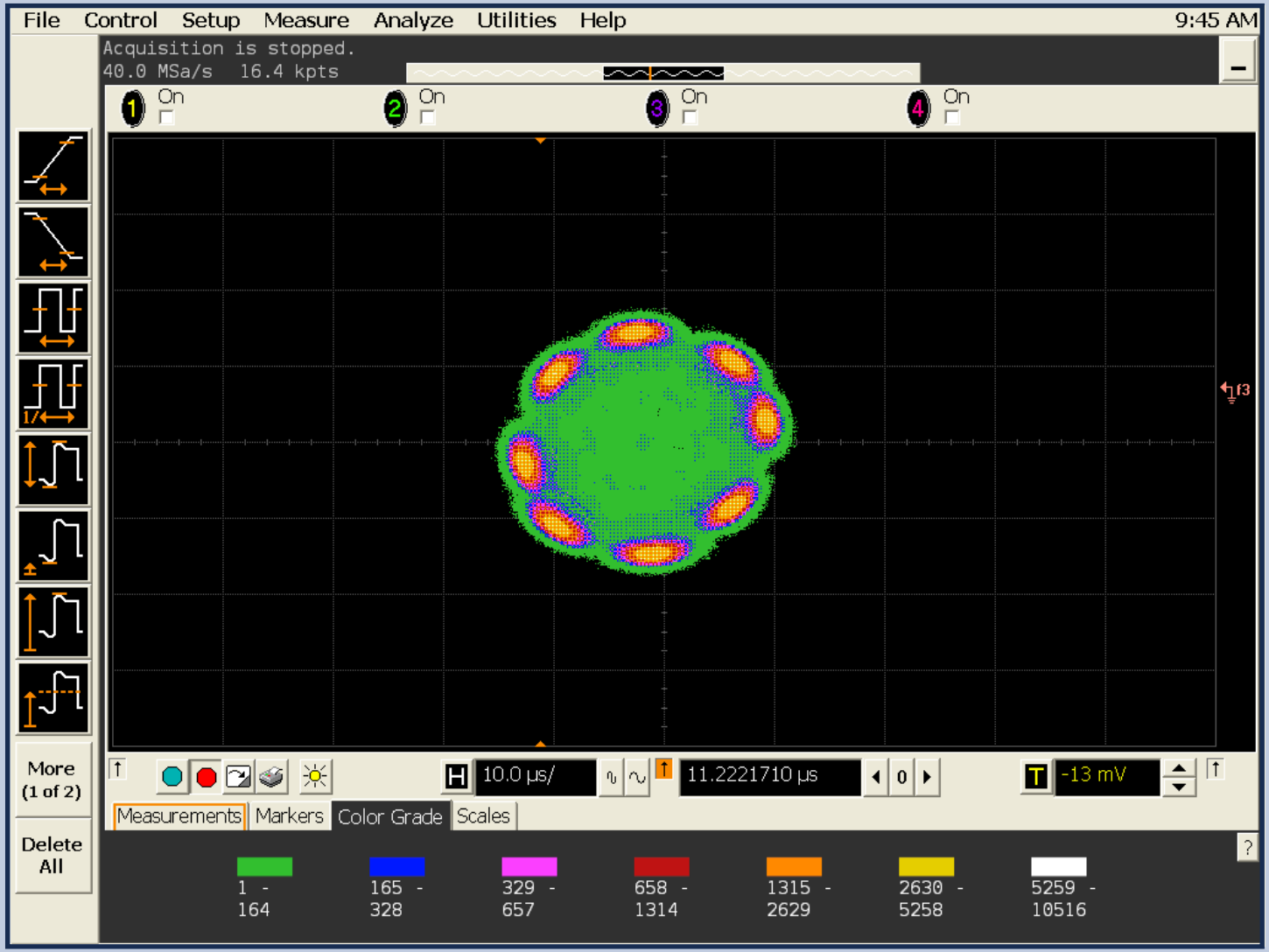
I-

Q+

Q-

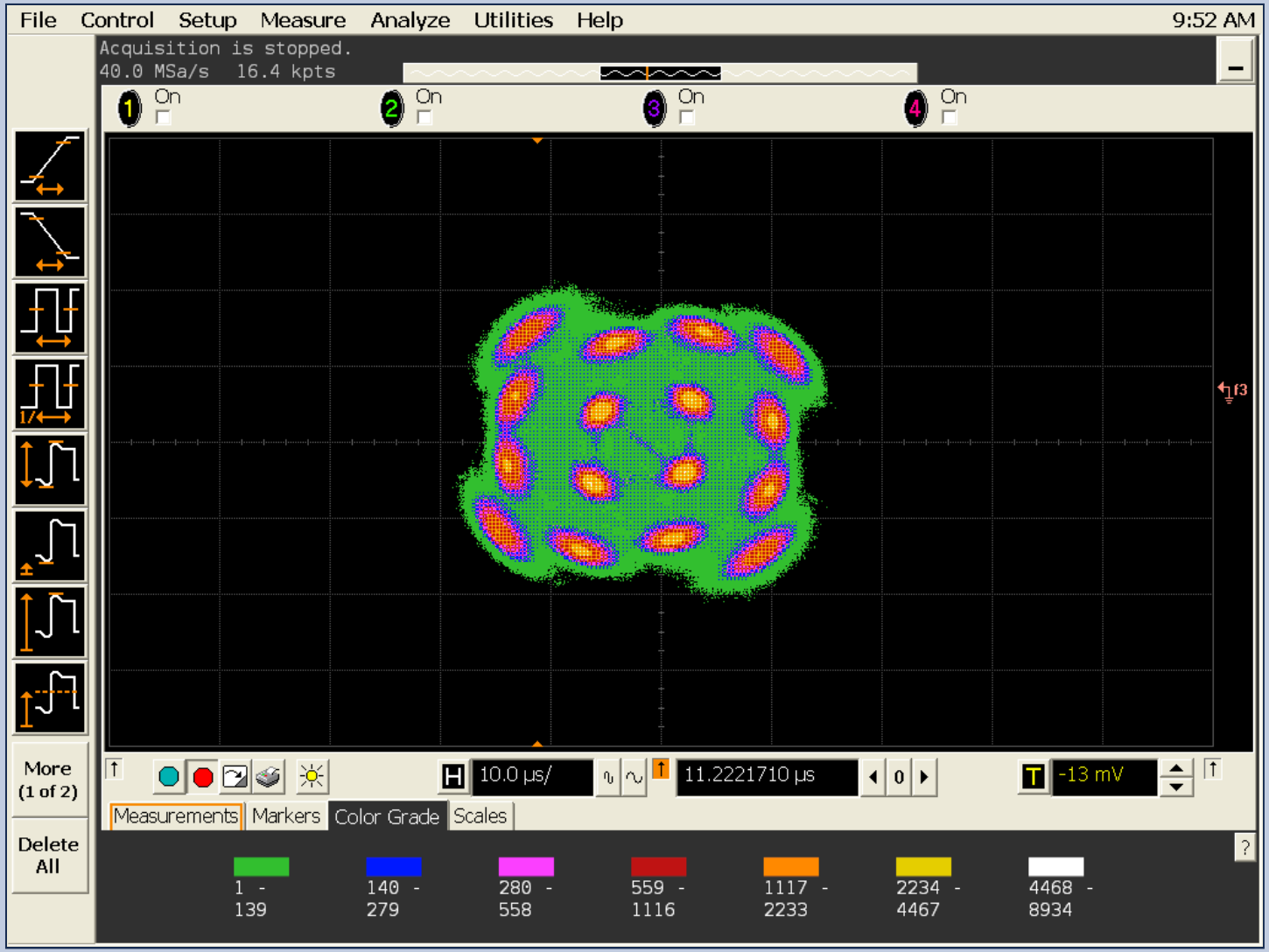
60 GHz test-bench for digital modulation: 1 MS/s QPSK

Mm-wave Digital Modulation



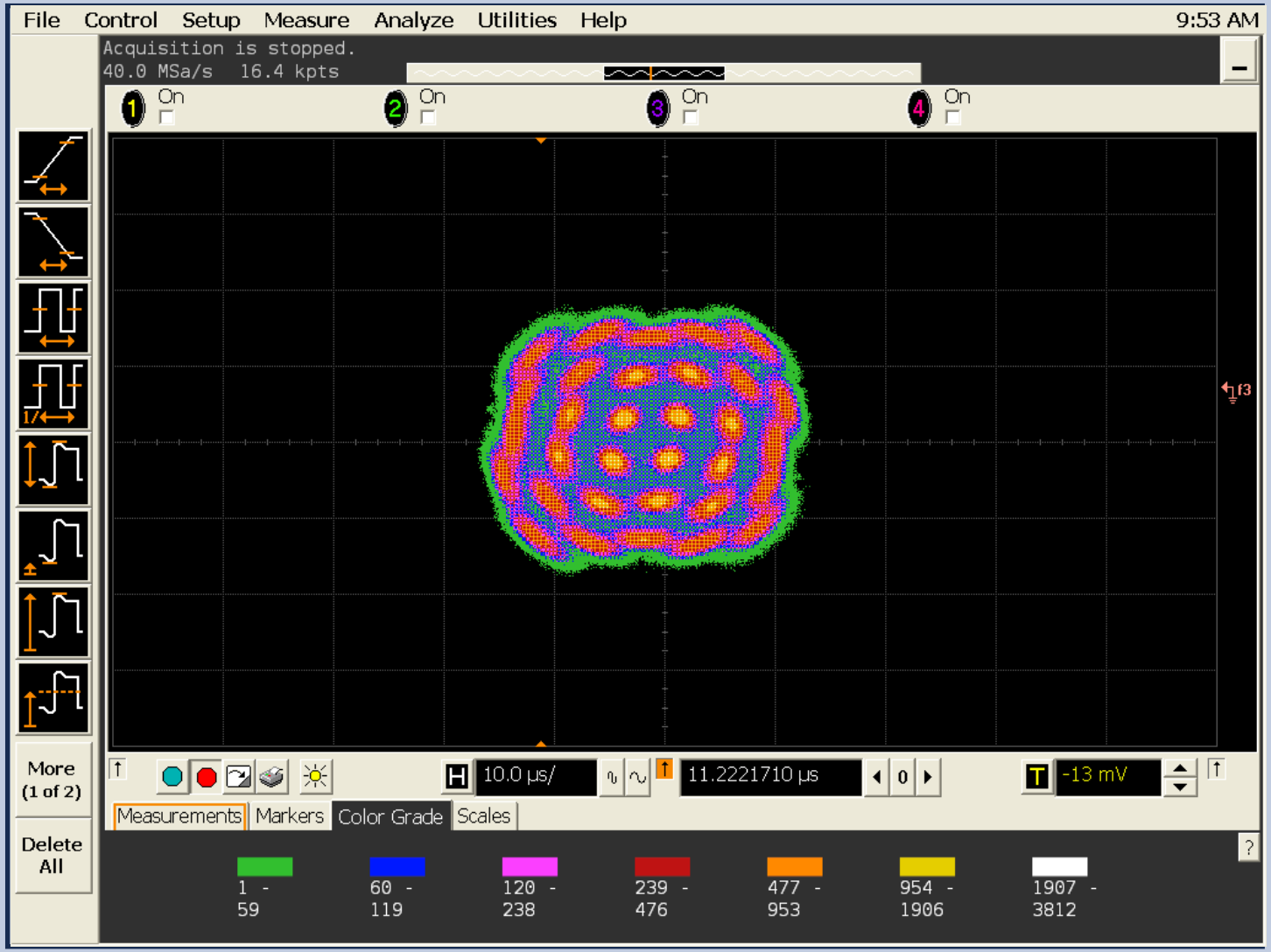
60 GHz test-bench for digital modulation: 1 MS/s 8PSK

Mm-wave Numerical Modulations



60 GHz test-bench for digital modulation: 1 MS/s 16QAM

Mm-wave Numerical Modulations



60 GHz test-bench for digital modulation: 1 MS/s 32QAM

130 Years of Radio History: Modulation Techniques

1. *Wireless Telegraphy (Spark and CW)*
2. *Amplitude Modulation (AM)*
3. *Single Side-band (SSB) Modulation*
4. *Frequency Modulation (FM)*
5. *Digital Modulation (ASK, FSK, PSK, QAM)*

The evolution of the radio in 130 years

INRS Institut national de la recherche scientifique

IEEE

Société québécoise des collectionneurs de radios anciens • Quebec Society for Vintage Radio Collectors



1896 – Marconi Wireless Telegraphy



1910's – Crystal Radios



1920's – TRF Radios



1930's – Superheterodyne Radios



1950's – Transistor Radios



1960's – 1970's – Miniature Transistor Radios



1960's – today: CB Radios



1900's – today: Amateur Radio Transceivers



Today's Internet and Satellite Radio

[150 Years of radio & telephone history, the most famous & unique exhibition! - YouTube]

Thank you for your attention !

Questions ?

