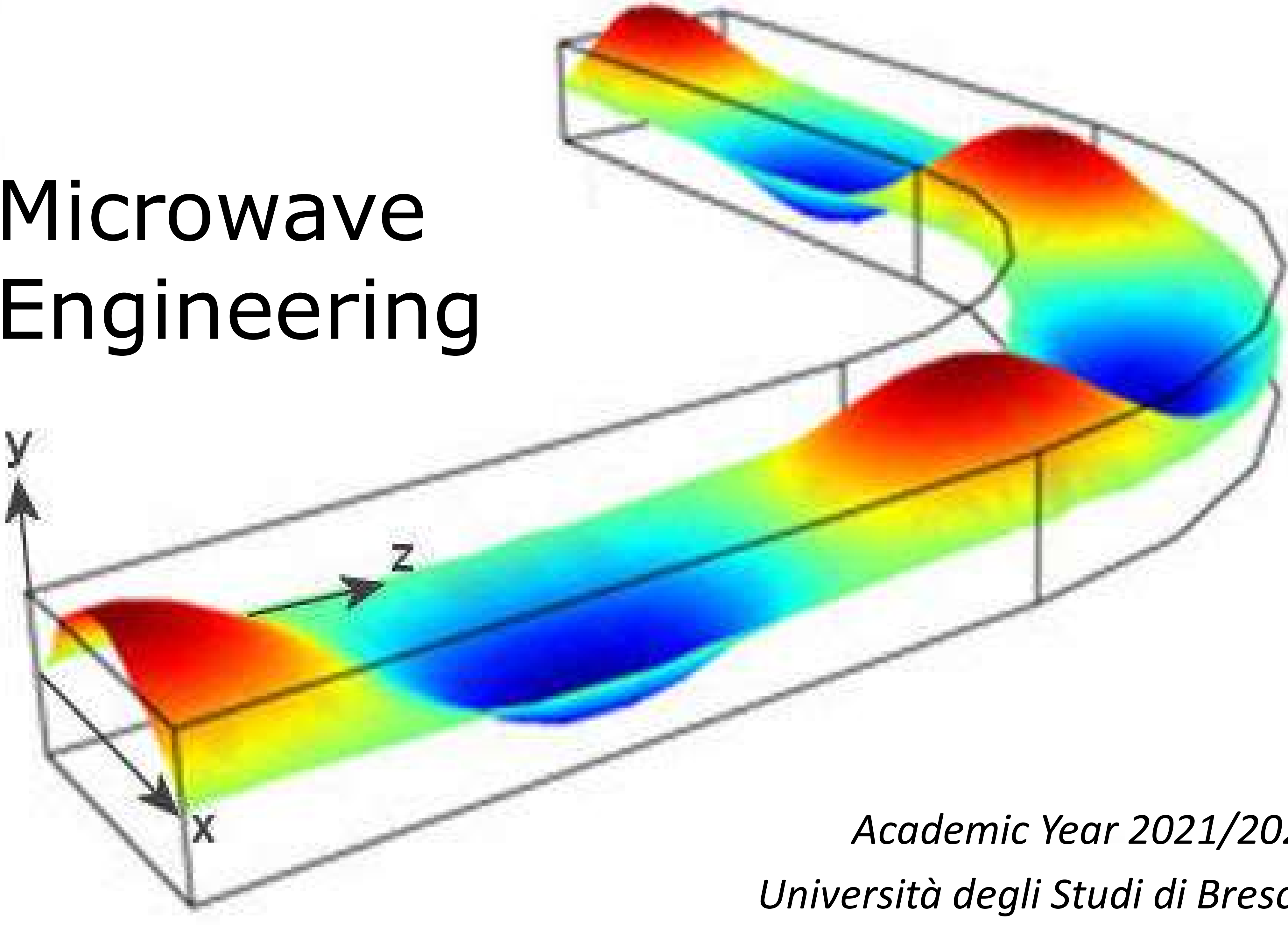
# Microwave Engineering



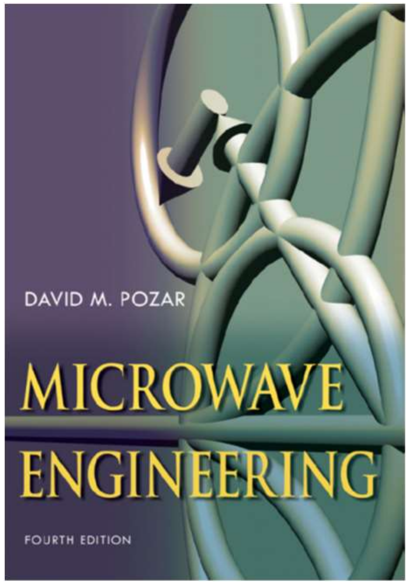

*Academic Year 2021/2022*

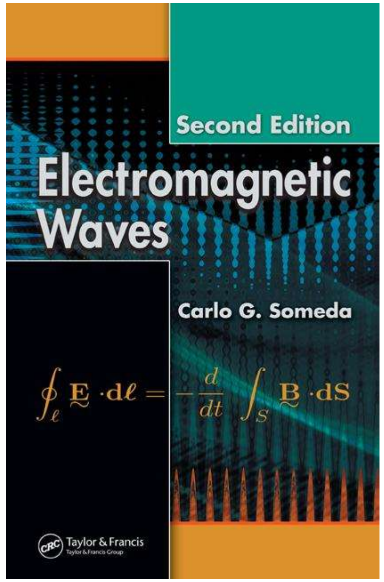
*Università degli Studi di Brescia*

# Course Material

## Primary sources

- David M. Pozar, *Microwave Engineering,* Wiley, 2012
- C. G. Someda, *Electromagnetic waves*, CRC Press, 2006
- Lecture notes and handouts



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# General Information

Lessons start – end: 21/2/2021 – 10/6/2021

Class Meets:

Tuesday 10.00-13.00 ROOM B1.7
Thursday 9.00-11.00 ROOM B2.9

Office hours: DII - Studio 25
please e-mail for appointment

Contact Information:

- Email: maria.vincenti@unibs.it
- Phone: 0303715924

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# Tentative Calendar

| FEBRUARY 2022 | | | | | | |
|---|---|---|---|---|---|---|
| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
| | 1 | 2 | 3 | 4 | 5 | 6 |
| 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 21 | 22 | 23 | 24 | 25 | 26 | 27 |

| MARCH 2022 | | | | | | |
|---|---|---|---|---|---|---|
| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
| 28 | 1 | 2 | 3 | 4 | 5 | 6 |
| 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 21 | 22 | 23 | 24 HW1 | 25 | 26 | 27 |
| 28 | 29 | 30 | 31 | | | |

| APRIL 2022 | | | | | | |
|---|---|---|---|---|---|---|
| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
| | | | | 1 | 2 | 3 |
| 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| 25 | 26 | 27 | 28 | 29 | 30 | |

| MAY/JUNE 2022 | | | | | | |
|---|---|---|---|---|---|---|
| Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
| | | | | | | 1 |
| 2 | 3 | 4 | 5 HW2 | 6 | 7 | 8 |
| 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 16 | 17 | 18 | 19 | 20 | 21 | 22 |
| 23 | 24 | 25 | 26 | 27 | 28 | 29 |
| 30 | 31 | 1 | 2 | 3 | 4 | 5 |
| 6 | 7 HW3 | 8 | 9 | 10 | 11 | 12 |

# Grading

Final Score is the sum of the homework evaluation and final test score:

- Homeworks (3 during the semester) – 3 pts max

IMPORTANT: homework points will be given ONLY if all homework assignments are completed on time. If only 1 or 2 assignments are completed NO points will be given toward the final score.

- Final Test – 30 pts max
    - two dates during summer session
    - one date in the make up session

# Syllabus

1. Introduction to Microwave Engineering and Wireless Communications
2. Electromagnetic Theory
3. Transmission Line Theory
4. Impedance Matching and Tuning
5. Microwave Waveguides
6. Microwave Network Analysis
7. Microwave Resonators
8. Power Dividers and Directional Couplers
9. Microwave Filters

# Introduction

# Who are the *microwaves*?

The term microwaves refers to signals whose frequency is between:

$$f = 300 \text{ MHz and } f = 300 \text{ GHz}$$

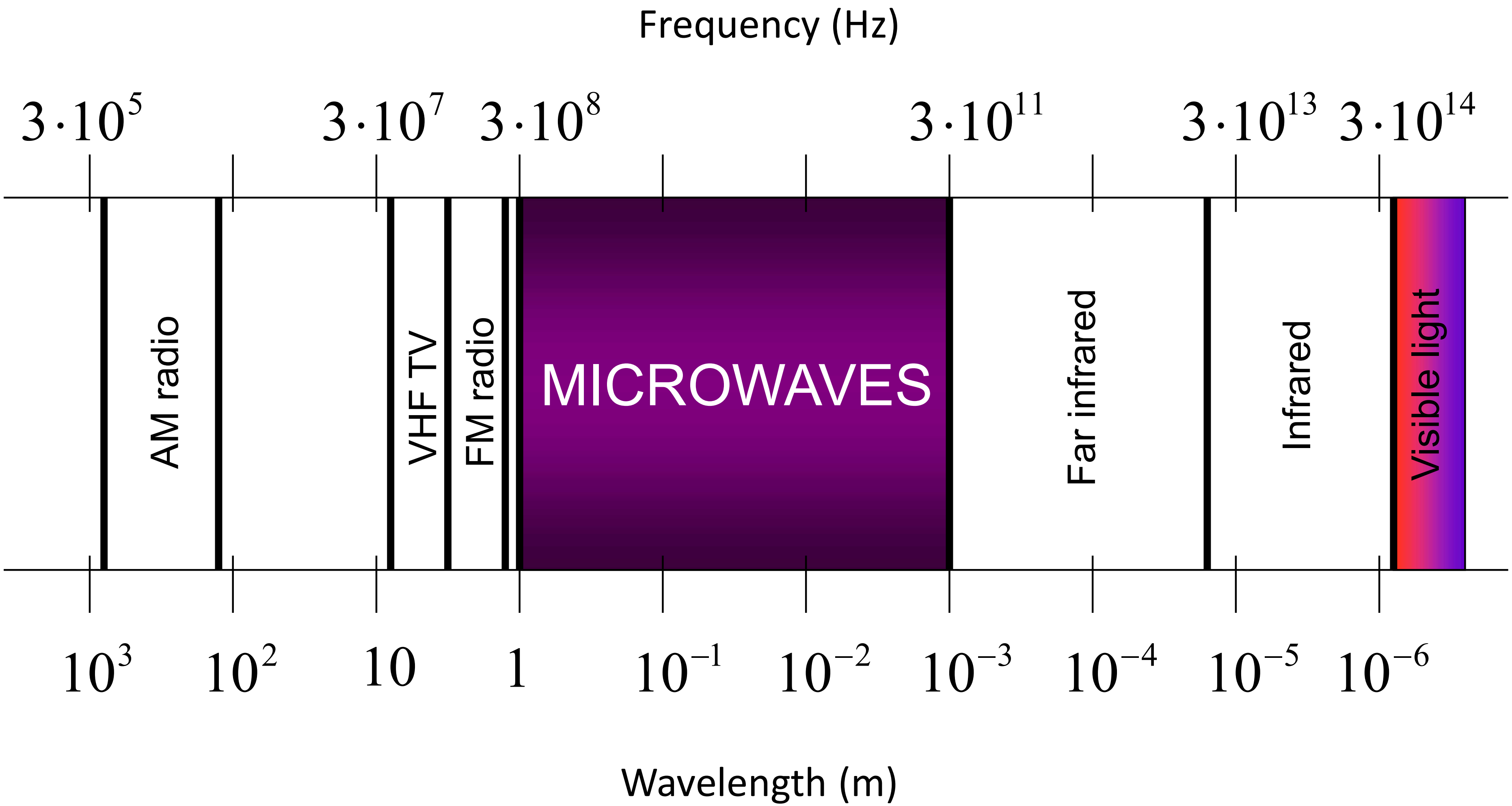
This means that the corresponding range of wavelengths ($\lambda = c/f$ ) of these signals is between:

$$\lambda = 1 \text{ m and } \lambda = 1 \text{ mm}$$

Circuit elements in a microwave system have sizes of the order of the operating wavelength, therefore ***standard circuit theory cannot be used blindly*** to solve microwave network problems!

In the microwave regime, we can sometimes reduce the complexity of a field theory solution in terms of a simpler circuit theory, but other times we will have to solve the full electromagnetic problem by means of Maxwell's equations.

# Where are the *microwaves*?



| Frequency Bands | Designation | Typical service |
|---|---|---|
| 3-30 kHz | VLF<br>Very Low Frequency | Navigation |
| 30-300 kHz | LF<br>Low Frequency | Radio beacons |
| 300-3000 kHz | MF<br>Medium Frequency | AM transmission |
| 3-30 MHz | HF<br>High Frequency | Citizen’s band |
| 30-300 MHz | **VHF**<br>Very High Frequency | FM transmission<br>Television |
| 300-3000 MHz | **UHF**<br>Ultra High Frequency | Television<br>Satellite communications<br>Wi-Fi<br>Radar |
| 3-30 GHz | **SHF**<br>Super High Frequency | Satellite communications<br>Radar |
| 30-300 GHz | **EHF**<br>Extreme High Frequency | Radar |

# Band Designations

- AM Broadcast Band 535-1605 kHz
- FM Broadcast Band 88-108 MHz
- Television (VHF) 54-88 MHz
- Television (UHF) 174-890 MHz
- Mobile Communications: GSM 880-915 MHz, 925-960 MHz
  UMTS 1885-2025 MHz, 2110-2200 MHz
  US Cellular 824-849 MHz, 869-894 MHz
- GPS (Global Positioning System) 1575.42 MHz and 1227.60 MHz
- Bluetooth 2.4 GHz
- WLAN (Wireless Local Area Network) 902-928 MHz
  2.4-2.484 GHz, 5.725-5.850 GHz
- US DBS (Direct Broadcast Satellite) 11.7-12.5 GHz
- Radar (Air Traffic Control) 1-2 GHz
- Short range Radar: 2-4 GHz, 27-40 GHz
- Radar for weather forecast 4-8 GHz
- US UWB Radio (Ultra Wide Band) 3.1-10.6 GHz
- US ISM (Industrial, Scientific and Medical Bands) 902-928 MHz
  2.400-2.484 GHz, 5.725-5.850 GHz

Microwaves

# Band Designations

IEEE, ITU designation in the 1-140 GHz frequency range

| Frequency Band (GHz) | Wavelength (cm) | Designation |
|---|---|---|
| 1-2 | 15-30 | L |
| 2-4 | 7.5-15 | S |
| 4-8 | 3.75-7.5 | C |
| 8-12.4 | 2.4-3.75 | X |
| 12.4-18 | 1.67-2.4 | Ku |
| 18-26.5 | 1.13-1.67 | K |
| 26.5-40 | 0.75-1.13 | Ka |
| 40-140 | 0.21-0.75 | U, V, E, W, F |

# History

# History of MW Engineering

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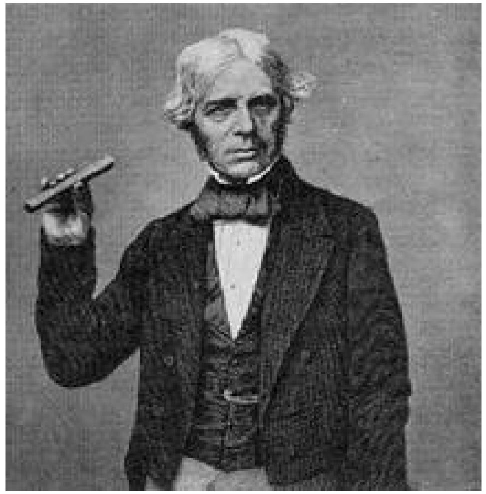
**Johann Carl Friedrich Gauss** was born in 1777 in Braunschweig, Germany, and is regarded by many as the most prominent mathematician ever. His name is used every day in discussions of probability theory (Gaussian distribution). He also was a major contributor to physical sciences, inventing the heliotrope (for measuring long distances using sunlight) and developing accurate methods for measuring terrestrial magnetism.
He helped install a telegraph system in Europe. **Maxwell's equations include two that are derived from Gauss** (magnetic and electric induction).

**Michael Faraday**, born in 1791, is credited as the discoverer of magneto-electric induction, the law of electrochemical decomposition, the magnetization of light, and diamagnetism, among many other contributions to chemistry and physics. Faraday's name is immortalized in the **Farad, the unit of capacitance**.



# History of MW Engineering

At the same time Faraday was working on EM theory, Princeton Professor **Joseph Henry** was also playing with large electromagnets, developing one that lifted 750 lbs., partly because he was the first person to consider source and load impedance matching to maximize power transfer. In his own words, one of Henry's experiments "illustrates most strikingly the **reciprocal action of the two principles of electricity and magnetism**".

In 1873, **James Clerk Maxwell** laid the foundations of modern electromagnetic theory in his work, "A Treatise on Electricity and Magnetism" in Scotland, which he wrote as a retired college professor. Born in 1831 **Maxwell theorized that, if combined, electrical and magnetic energy would be able to travel through space in a wave**.

$$\nabla \cdot \boldsymbol{D} = \rho_f$$

$$\nabla \cdot \boldsymbol{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \boldsymbol{B}}{\partial t} - \boldsymbol{M}$$

$$\nabla \times \boldsymbol{H} = \frac{\partial \boldsymbol{D}}{\partial t} + \boldsymbol{J}_f$$

# History of MW Engineering

Several years after Maxwell's famous treatise, **German Heinrich Hertz** (1857-1894) **conducted experiments that proved Maxwell's theories were correct**. Hertz began testing these theories by using a high-voltage spark discharge to excite a half-wave dipole antenna. The receiving antenna consisted of an adjustable loop of wire with another spark gap. When both transmit and receive antennas were adjusted for the same resonant frequency, Hertz was able to demonstrate propagation of electromagnetic waves.

In another experiment, Hertz used a coaxial line to show that electromagnetic waves propagated with a finite velocity, and he discovered basic transmission line effects such as the existence of nodes in a standing wave pattern a quarter wavelength from an open circuit and a half wavelength from a short circuit.

He then went on to develop cylindrical parabolic reflectors for directional antennas, as well as a number of other radio frequency (RF) and microwave devices and techniques.

**Hertz was honored for his work by naming the unit of frequency after him**.

Library of Congress

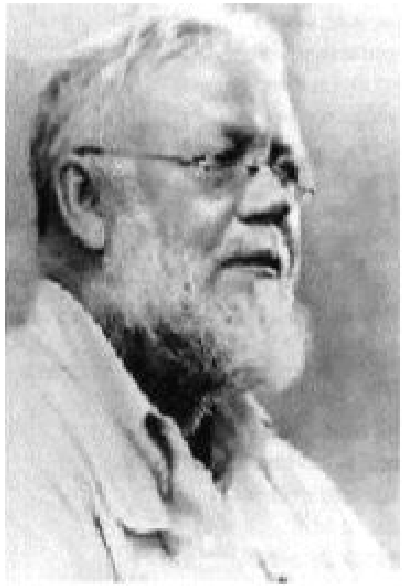
# History of MW Engineering

In 1894, 20 year old **Guglielmo Marconi** began experiments in Italy sending a **wireless signal using Morse code**, at first for short distances, and ultimately thousands of miles. He had limited education and no formal training as engineer or scientist, just an idea that wireless communications would one day render the telegraph obsolete.
His high-tech startup of the '90s, The Wireless Telegraph & Signal Company (a U.K. company) was soon renamed Marconi's Wireless Telegraph Company. This business began by installing company-owned and operated wireless communications onto ships to communicate with huge antenna installations on key coastlines, while the founder pursued ground communications across the Atlantic.

**Marconi received the Nobel physics prize of 1909** for his work, shared with German Ferdinand Braun.
Marconi was the first experimenter to notice that transmission during daylight hours was more prone to noise than at night, which was later explained by Heaviside as due to the ionosphere.
Although **Marconi was the singular force behind long distance wireless communications**, he admitted he didn't really know how it all worked. Some years later the scientific community discovered that Marconi's idea that longer wavelengths would travel farther around the globe was incorrect, and Marconi's amazing 300,000 watt steam-powered spark gap transmitters, building-sized capacitor banks and multi-mile antenna elements were unnecessary at higher frequencies (short waves).

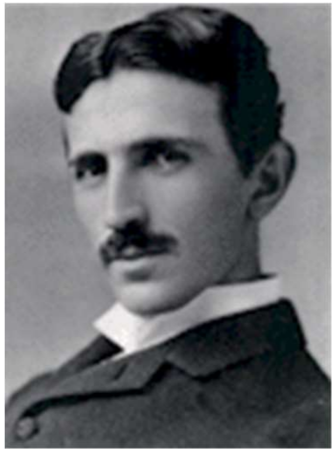
# History of MW Engineering

**Reginald Aubrey Fessenden**, born in Canada in 1866, was a **huge pioneer of wireless**. He was **the first inventor to demonstrate transmission of voice** in December 1900 (Marconi always transmitted Morse Code), and his first transmission involved a weather report! He was the first to think in terms of continuous wave (CW) transmissions instead of the pulsed spark-gap transmitters of the day. He also developed the theory of heterodyne detection and coined that word (demonstrating and patenting the first mixer), but didn't have a practical, stable source to reap its full benefits in a radio receiver.



Born in the UK, **Oliver Heaviside**'s **research in transmission-line theory** was first applied to telegraphs, including the transatlantic cable, but microwave engineers use his concepts to this day. A mathematician, he rewrote Maxwell's equations into their simple, vector-calculus form. He predicted the E-layer of the ionosphere, which allows propagation of electromagnetic waves around the curvature of the earth.

# History of MW Engineering



Although Marconi was awarded the Nobel prize in 1909 for his "wireless telegraphy" work , the **U.S. Supreme Court revoked Marconi's patents since Serbian-American genius Nikola Tesla had taken out a patent for radio communications as early as 1897**. Tesla's life has taken on legendary status, having obtained more than 700 U.S. patents. Some of his other inventions include a unique steam turbine, liquefaction of nitrogen, and the awesome Tesla coils from which he coaxed 10,000,000 volts to light up the Colorado sky.

**Walter Schottky**'s name is embedded in solid-state physics (Schottky effect, Schottky barrier, Schottky contact, Schottky diode). Born in 1878 in Germany, he was a contemporary of Einstein and Max Planck. His work included superheterodyne receivers, noise theory, and radio tube work such as invention of the tetrode, but his most important contribution to microwaves is his **investigation of metal-semiconductor rectifying junctions** (published in 1938), which is the basis for the gate contact of all MESFETs. He died in 1976.

# History of MW Engineering

**Harry Nyquist** was born in Sweden in 1889, and emigrated to the U.S. when he was 18 years old. Nyquist's 1928 paper *Certain topics in Telegraph Transmission Theory* nails down a **fundamental law of telecommunications**: the highest frequency that can be accurately sampled is one half the sampling frequency (the *Nyquist Frequency*). His other most notable contribution to electronics is the Nyquist Stability Theorem (1932), which determines when a feedback amplifier will and won't be stable. He also contributed to noise theory, the fax machine, and television, earning 138 patents and several major awards. Nyquist died in 1976.

While still in high school, **Edwin Howard Armstrong** erected a 125 foot radio mast at his parents' house in Yonkers, New York, to receive the weak radio signals of the day. While still in college in 1912, he invented a feedback circuit based on Lee de Forest's three-terminal audio tube that provided the first usable electrical amplifier, and submitted a patent for the regenerative receiver in 1913. Armstrong won the triple crown of electrical engineering, soon **inventing the superheterodyne receiver**, then **inventing frequency-modulation (FM) broadcasting**. He cashed in on his patents, in spite of a corporate war between AT&T and RCA over who really invented the feedback amplifier.

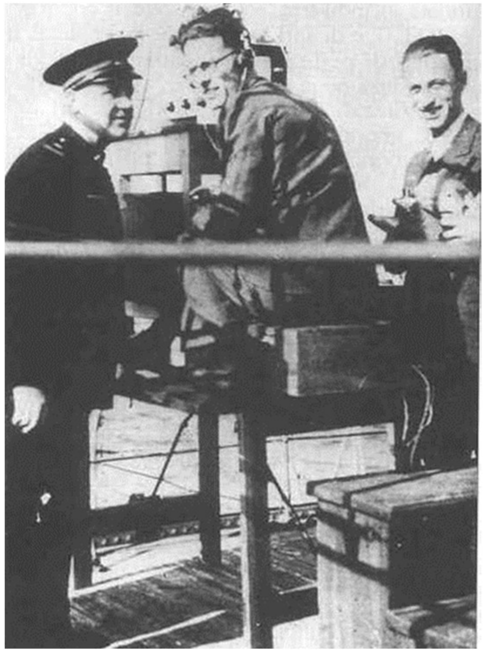
# History of MW Engineering

**Shintaro Uda** (1896-1976) **invents and patents a high-gain antenna** in 1926, while attending Tohoku Imperial University, in Sendai, Japan. His faculty adviser was Hidetsugu Yagi. The Yagi-Uda concept uses reflector and director elements to drive a "live" dipole. Yagi published an English translation describing the work in 1928, from that time on his name was associated with the invention of his pupil.

**Albert Wallace Hull** was born in the US in 1880. He earned a Ph.D. in physics at Yale, then worked at General Electric's research lab. He was a noted vacuum tube inventor. One of his tubes used magnetic control; it was called the **magnetron**. Hull's magnetron only operated at kHz frequencies, but it cranked out 15,000 watts of power and could be used as both an amplifier or an oscillator. By WW II, the magnetron became an important component of many radar systems. Today, **all commercial microwave ovens use mass-produced magnetrons**.

# History of MW Engineering

In 1932, Sir **Robert A. Watson-Watt** came up the idea of RDF, Radio Direction Finding. He wrote a paper (with A.F. Wilkins) describing this **new technique of Radio Detection and Ranging giving it the code name of "radar" in 1935**. It was proved that the theory would work, but with a range of only eight miles using the state-of-the-art devices of the day. By the autumn of 1938 radar systems were in place along the south coast of Britain. Watson-Watt became scientific advisor to the British Air Ministry in 1940 and in 1941 went to the United States to set up radar systems there. He died in 1973.



**Nello Carrara** was born in Florence in 1900. He wrote his doctoral thesis on X-ray diffraction in 1921. At the age of 24, he became a professor at the Italian Naval Academy, where he taught hundreds of Italian Marina Militare officers and academic researchers until 1954. While there he was involved with the development of radar, **helping to create the first Italian RDT (Radio Detector Rangefinder)**, the continuous wave EC1 in 1936. Carrara founded the Electromagnetic Wave Research Institute in Florence in 1946. As a researcher, he published over 100 works. In his paper on "The Detection of Microwaves" in 1932, **he coined the common term "microwave"**.

# History of MW Engineering

Also at Bell Labs in the 1930s, **Dr. George Clark Southworth** (1890-1972) discovered that radio waves could be transmitted efficiently through a hollow, water-filled copper pipe. He and his team at Bell found that **electromagnetic energy traveling through an enclosed structure moved in distinct patterns that we all know as "modes"**, and that the optimum diameter for a waveguide pipe was slightly greater than one-half wavelength. They also experimented successfully with square, rectangular and oval waveguides.

At the same time, **W. L. Barrow** had been studying antennas and reflectors of various shapes, which led him to experiment with hollow tubes. His successful **propagation of waves through a tube 18 inches in diameter** was published in May 1936. Today, the most common shape for waveguides is rectangular, with dimensions about one half wavelength by one quarter wavelength at the center frequency.

# History of MW Engineering

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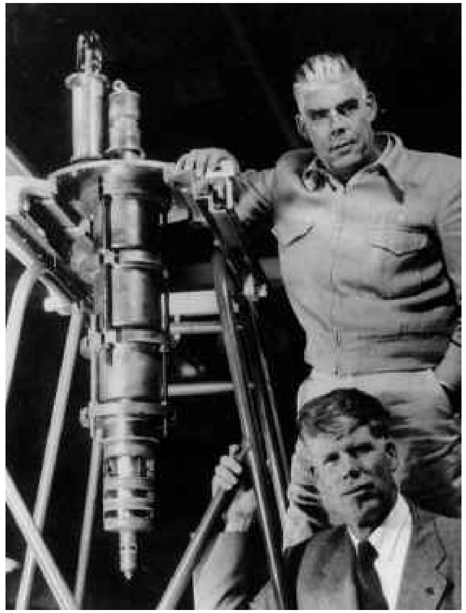
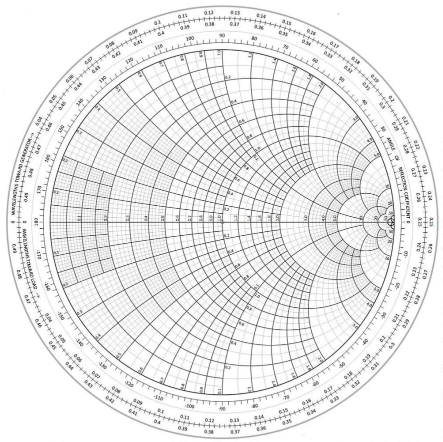
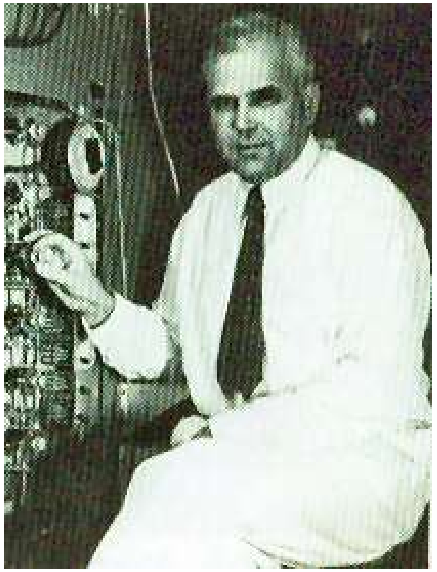


In 1937, **Sigurd and Russell Varian** demonstrated the **first klystron tube**, later used in American radar systems during WWII. In 1949 they founded Varian Associates, one of the very first technology-based companies in what would soon become silicon valley. Variations of their klystron tube provide millimeter-wave power today.

At Bell Labs, **Phillip Hagar Smith**, born in Lexington Massachusetts, developed a circular chart form in 1939 that shows the entire universe of complex impedances in one convenient circle. **The Smith chart** remains in wide use today. Les Besser recalls that Philip Smith submitted an article on his development to the IRE, which was rejected.



# History of MW Engineering



In 1942, **Harald T. Friis**, working in Bell Labs, developed the theory of "noise figure" that allows engineers to **calculate the signal-to-noise ratio at the output of a complex receiver chain**, and thus has a powerful equation named after him. Harald was born in Denmark, in 1893. He graduated 1916 in Electrical Engineering from the Polytechnic Institute. In 1919 he received a fellowship which enabled him to come to the United States where he studied radio engineering at Columbia University.

One of Raytheon's engineers, **Percy Spencer**, took home one of the super-secret magnetrons, and figured out a new manufacturing process that cut manufacturing time to a mere fraction of what it was AND improved the power efficiency. Within a month, Raytheon was making thousands of magnetrons a day for the war effort. Just after the war, Percy Spencer **was still working with magnetrons when he noticed that a chocolate bar in his pocket melted when he walked in front of the magnetron**. After a bunch of experiments, he found that popcorn popped and eggs exploded! Percy Spencer had invented the **microwave oven**.

# History of MW Engineering

**Edward Mills Purcell** (1912-1997) and **Harold Irving Ewen** (born 1922) **gave birth to the field of radio astronomy** in 1952 when they were the first to detect the elusive 21 cm (1420 MHz) hydrogen line. This feat allowed for the first time a mapping of the spiral structure of our Milky Way galaxy, including the relative velocities of the "arms", determined by Doppler shift. Purcell was previously a Nobel prize winner for discovering Nuclear Magnetic Resonance and he worked on the development of radar at the MIT Rad Lab during WWII.

**Claude Shannon** (1916-2001) established the **Nyquist-Shannon sampling theorem** which establishes the sampling rate for an analog signal of a given bandwidth, and the Shannon-Hartley Theorem, which tell you how much information you can deliver over a channel of given bandwidth in the presence of noise.

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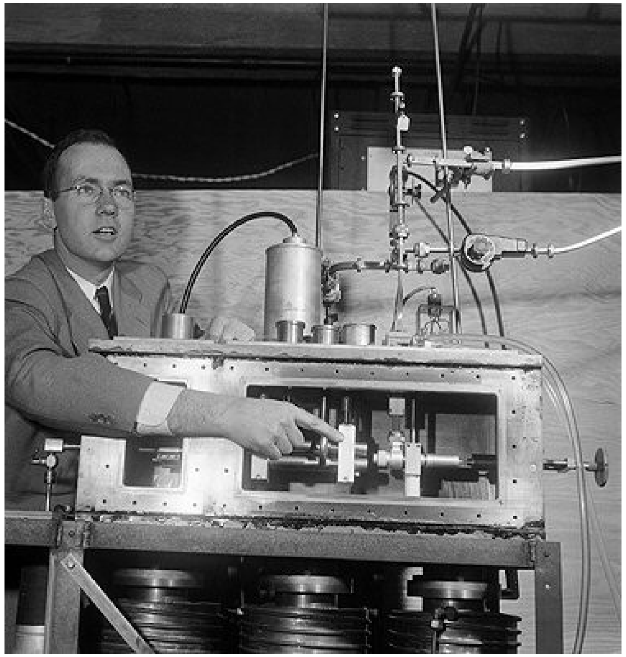
# History of MW Engineering

**Seymour B. Cohn** (1920-2015) earned his PhD in applied science at Harvard in 1948. During the war he was employed as a scientist/observer on the Mediterranean front. During his long career he worked at Sperry, Stanford Research and later Rantec. Cohn published dozens of papers in the IEEE, on a **diverse set of topics including stripline, isolators, waveguide to coax transitions, power dividers, ridged waveguide, filter theory**, and much, much more. His writings are in depth, easy to understand, and above all still relevant today. He was also a major contributor to the book Microwave Filters, Impedance-Matching Networks, and Coupling Structures by Matthaei, Young and Jones.

**Charles Hard Townes** was born in 1915; He earned his Ph.D. at Cal Tech in 1939. He worked at Bell Labs during the war, and later joined Columbia University. His post-war work in spectroscopy provided insight into interactions between molecules and electromagnetic radiation. In 1951 Charles Townes was sitting on a park bench when a new idea came to him that resulted in **microwave amplification by stimulation of emission of radiation** (the **maser**). By 1954, he and his students had completed the first maser using ammonia gas. An awesome derivative of the maser is the atomic clock, demonstrated by 1955.



# History of MW Engineering

In 1960 **Ernest J. Wilkinson** Jr.'s published in IRE Transactions on Microwave Theory and Techniques a paper entitled simply "**An N-way Hybrid Power Divider**". Mr. Wilkinson's demonstration of the technique consisted of a circular 8-way coaxial divider with center frequency of about 500 MHz. For this development he was awarded U. S. patent number 3,091,743. Ernest J. Wilkinson, Jr. passed away in 2012.

E. J. WILKINSON

**J. B Gunn** (1928-2008) was known to his associates & friends as J. B. Gunn, or Ian Gunn. He is recognized for **inventing the negative-resistance Gunn "diode"** in 1963; the effect he proved had been predicted by the theoretical work of Watkins and Hillsum. Gunn diodes have been used to build cheap oscillators up to 100 GHz. Next time you get a speeding ticket measured by radar, remember to thank Mr. Gunn for his contribution!

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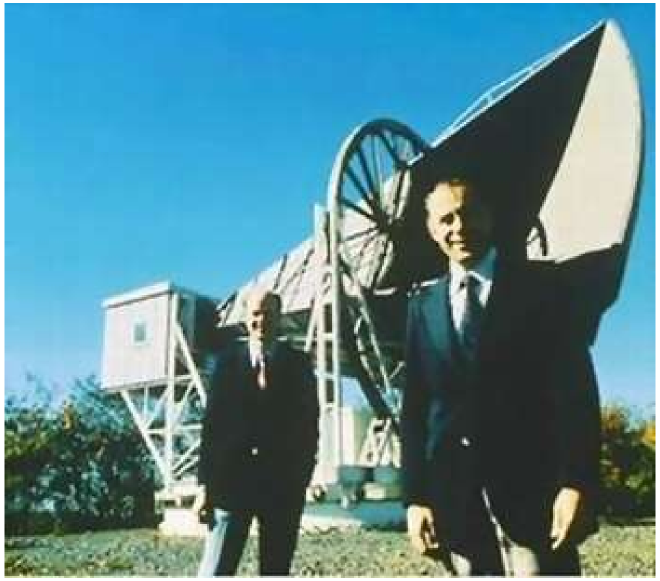
# History of MW Engineering



In 1964 Bell Labs researchers **Arno Allan Penzias** (1933) and **Robert Woodrow Wilson** (1936) **detected the cosmic microwave background of the Big Bang**. This discovery proved that it is 15 billion years old; Penzias' family fled Germany in the 1930s, and he earned his doctorate at Columbia University in New York, while Wilson did his graduate work at Cal Tech. Penzias and Wilson shared the 1978 Nobel prize in Physics with a third researcher who did unrelated work.

In 1964, **George Matthaei, Leo Young, and Edward McLung Thompson Jones published a 4.5 lbs. (2 kg) book called Microwave Filters**, **Impedance-Matching Networks, and Coupling Structures**. Most often referred to as simply "Matthaei, Young and Jones", the book is also known as the "Black Bible" because its original cover was black. The best filter designers still refer to this masterpiece, five decades later. These three researchers worked together at Stanford Research Institute in Menlo Park, California, when the book was written. Seymour Cohn was also a major contributor to this effort. Dr. Leo Young was born in Austria. Matthaei and Jones were both born in the USA.

# History of MW Engineering

Dr. **Kaneyuki Kurokawa** was born in Japan in 1928. While on leave of absence from from his position at University of Tokyo, he worked during the early 1960s at Bell Labs in New Jersey. His March 1965 IEEE paper entitled Power Waves and the Scattering Matrix, makes Kurokawa the first to popularize the **concept of S-parameters**.

**Robert Eugene Munson** is regarded as the **father of practical microwave patch antennas**. Ubiquitous today, the patch antenna was first theorized by G. A. Deschamps in 1953, but it was not put to use for many years (by Munson), first on a datalink for Sidewinder missile, then on Sprint missile's semi-active seeker.

# History of MW Engineering

While working at Philips Research Laboratories in the UK, **Peter J. Gibson** invented a unique antenna that is sometimes called a tapered notch, sometimes called a flared notch radiator, but most often called the "**Vivaldi antenna**". Peter published his results at the Ninth European Microwave Conference (IEEE) in 1979 in a paper entitled The Vivaldi Aerial. In the abstract he describes it as "a new member of the class of aperiodic continuously scaled antenna structures, as such, it has theoretically unlimited instantaneous bandwidth." Peter Gibson died in 2010.

**Eric W. Strid and K. Reed Gleason** were Tektronix employees when they began fooling around with methods of RF probing circuits. By 1983 they'd **invented the RF probe** and started a new company, Cascade Microtech, which now employs almost 300 people and does close to $100M in business each year. This single innovation changed the industry forever, helping **pave the way for cheap wireless products** that we can't live without today. Before 1983, MMIC devices could not be delivered to assembly as known-good parts, the true electrical performance of these tiny microwave circuits was impossible to measure at the wafer level.

# Systems & Applications

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# MW Systems & Applications

## What are the advantages of using higher frequencies (shorter wavelengths) for practical applications?

**1. Antenna gain is proportional to the electrical size of the antenna.**

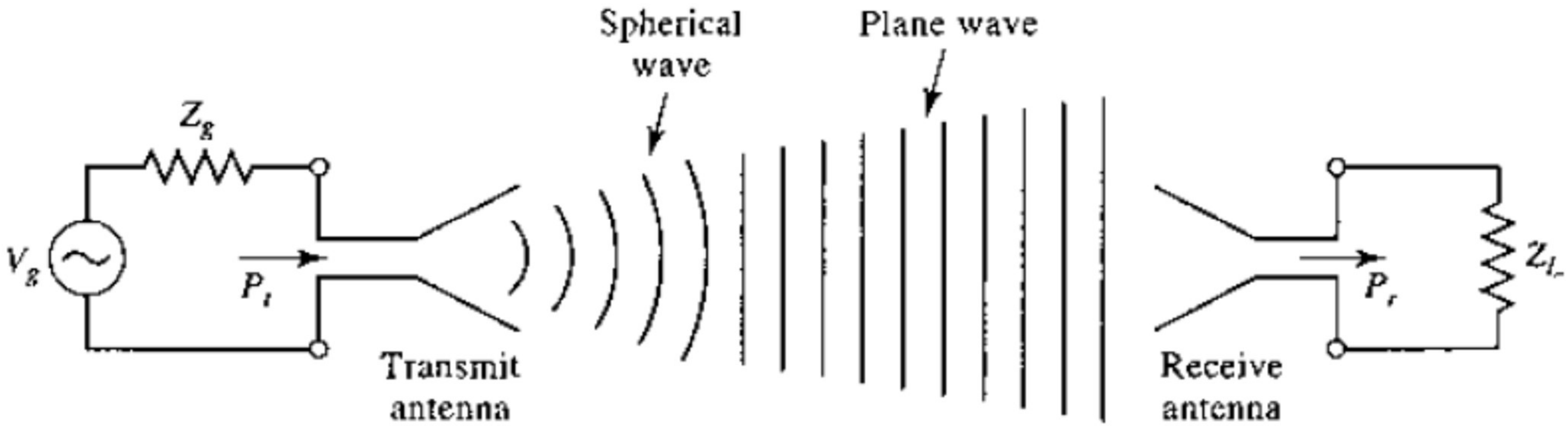
At higher frequencies, more antenna gain can be obtained for a given physical antenna size, and this has important consequences when implementing microwave systems.


$$\boxed{A_{eff} = G\frac{\lambda^2}{4\pi}}$$

# MW Systems & Applications

Antennas are the basic elements of a MW system. From a system point of view the most important characteristics of an antenna are:

1. Radiation pattern;
2. Directivity;
3. Gain;
4. Efficiency;
5. Noise Characteristics.



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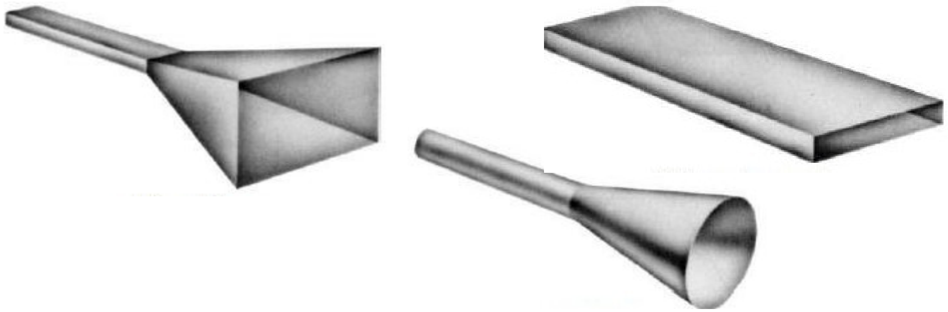
# MW Systems & Applications

## Types of antennas:

### Wire antennas

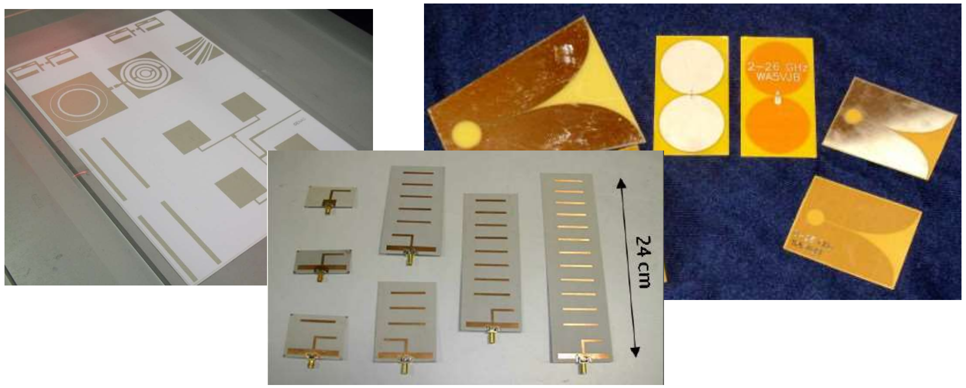
Low gain, HF to UHF, lightweight, low-cost

### Aperture antennas



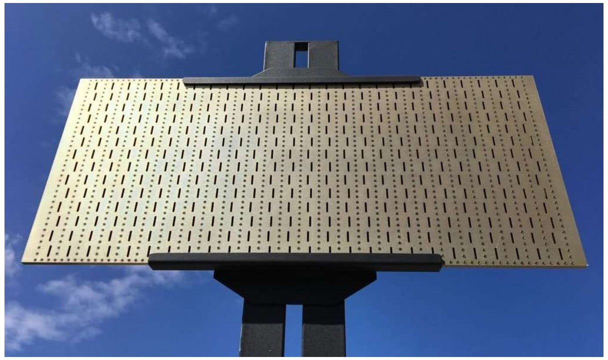
Used at MWs, moderate to high gains

### Printed antennas



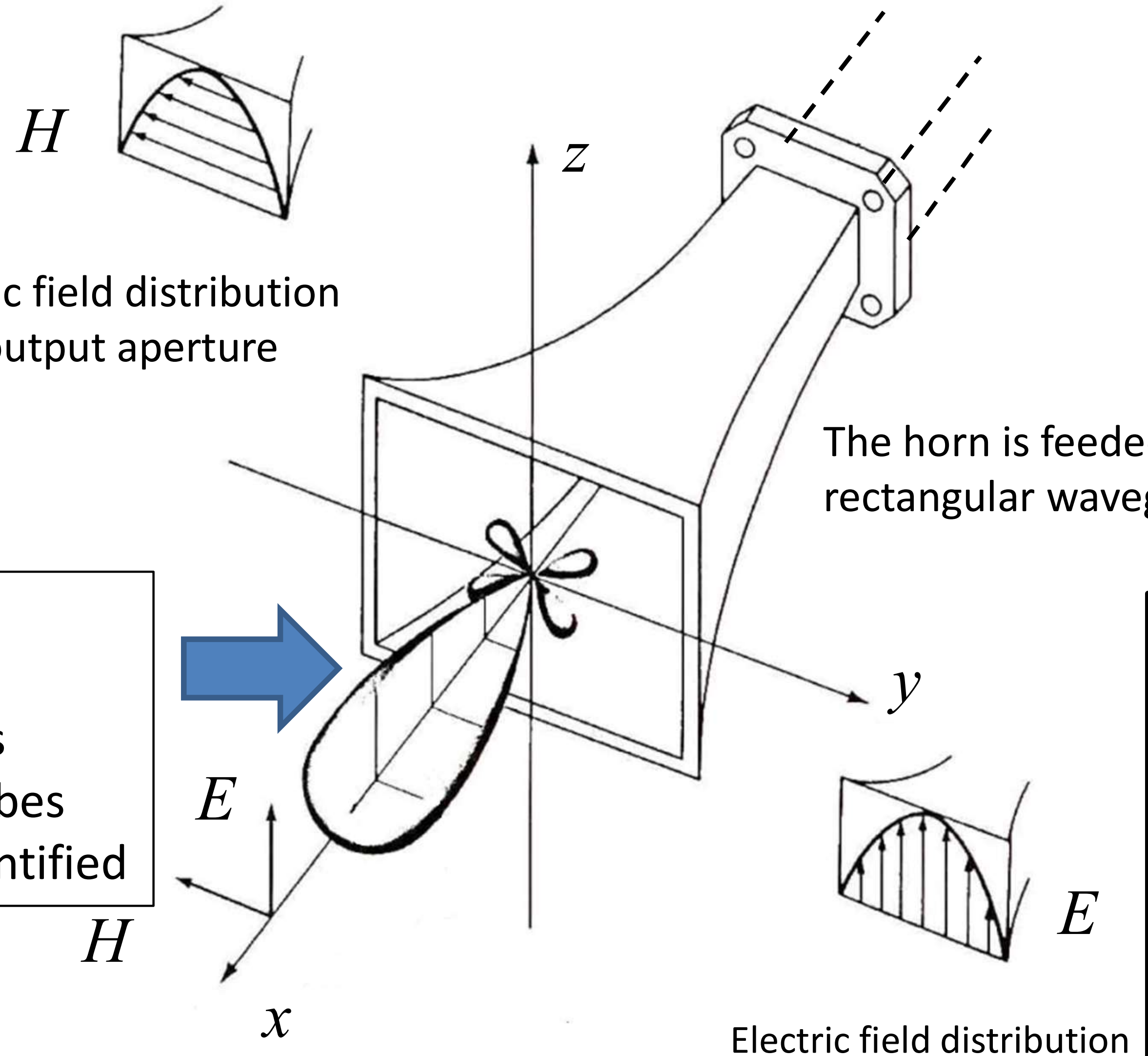

Integrated, used at MWs, high gain designs

### Array antennas



High gain, high directivity and beam forming

# Example: Horn Antenna




Magnetic field distribution on the output aperture

The horn is feeded by means of a single mode rectangular waveguide

Radiation Pattern
main lobes and sidelobes can be identified

Electric field distribution on the output aperture

**Directivity**

It is a measure of the focusing ability of an antenna. It is the ratio of the max radiation intensity in the main beam to the average radiation intensity over all space.

## Antenna Gain and Efficiency

As for all electrical components, *resistive losses* impact the ratio between the input power and the delivered power, therefore defining what is called ***radiation efficiency*** (other type of losses are not included since they can be compensated)*:*

$$\eta_{rad} = \frac{P_{rad}}{P_{in}}$$

On the other hand, ***antenna directivity*** depends only on the shape of the radiation pattern and it is not affected by losses.
We can define the ***antenna gain*** as the *product of the directivity and radiation efficiency*:

$$G = \eta_{rad} D$$

# MW Systems & Applications

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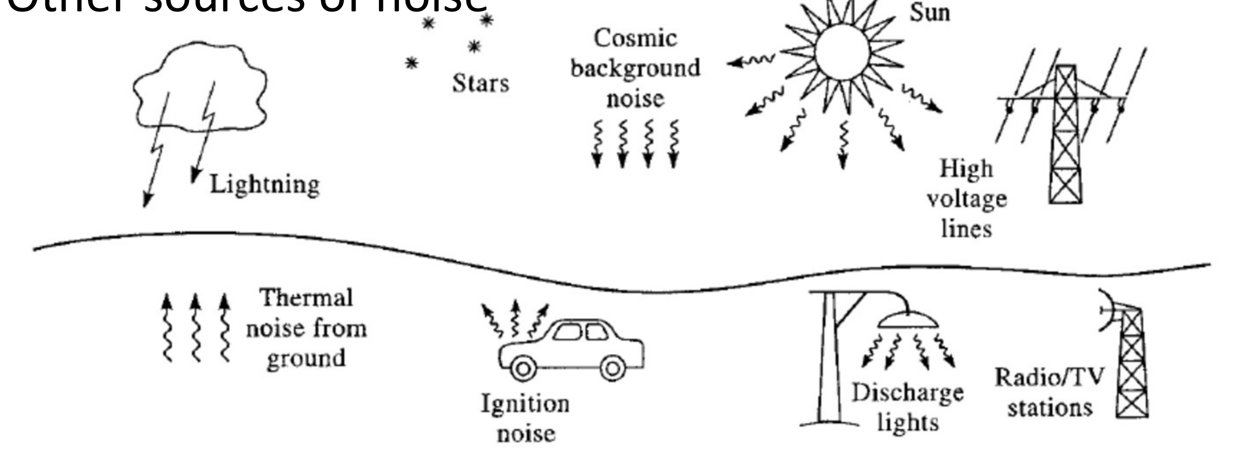
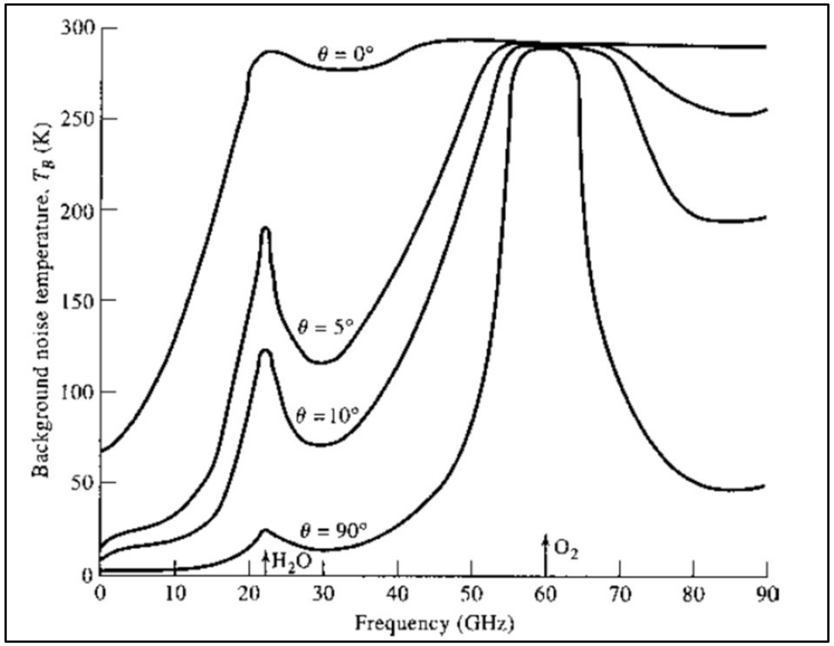
## Antenna Noise

Noise can come from:

- *Lossy components in the receiver and active devices;* ← can be controlled
- *External environment;* ← Has to be evaluated, can exceed thermal noise, Increases going from the zenith to the horizon
- *Thermal noise of the antenna.* ← Has to be evaluated

Other sources of noise



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# MW Systems & Applications

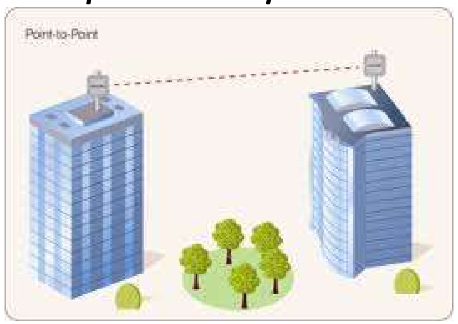
**2. Bandwidth for wireless communication systems increases with frequency.**

RF and microwave signals offer wider bandwidth and the advantage of being able to penetrate fog, dust and even buildings and vehicles with some attenuation.
Wireless systems in use today are:

- Broadcast radio and TV
- Direct Broadcast Satellite (DBS) television service
- Wireless local area networks (WLANs)
- Paging systems
- Global Positioning Satellite (GPS)
- Radio Frequency Identification systems (RFID)

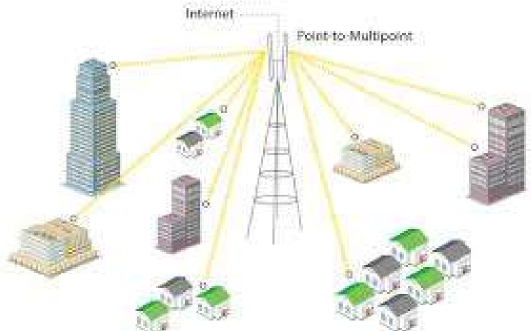
Either terrestrial or satellite

*point to point*



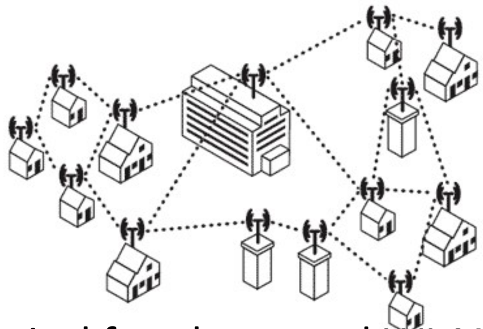

Single transmitter/single receiver
High gain antennas

*point to multipoint*




Radio and TV broadcast
Transmitter uses a broad beam

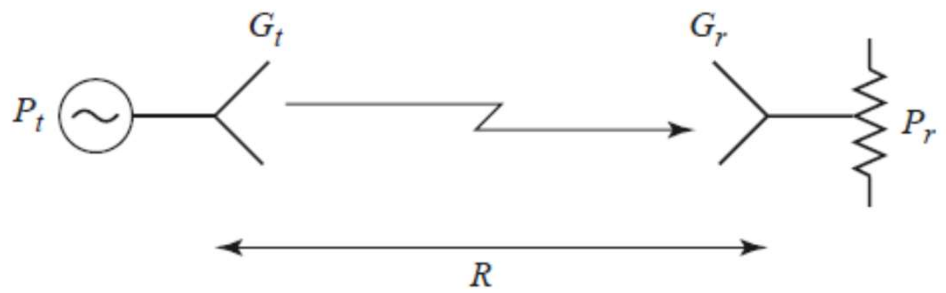
*multipoint to multipoint*



Typical for phone and WLANs
Rely on a grid of base stations

# MW Systems & Applications

General radio system




The maximum possible received power in a radio link is given by the Friis formula:

$$P_r = \frac{G_r G_t \lambda^2}{(4\pi R)^2} P_t \; [W]$$

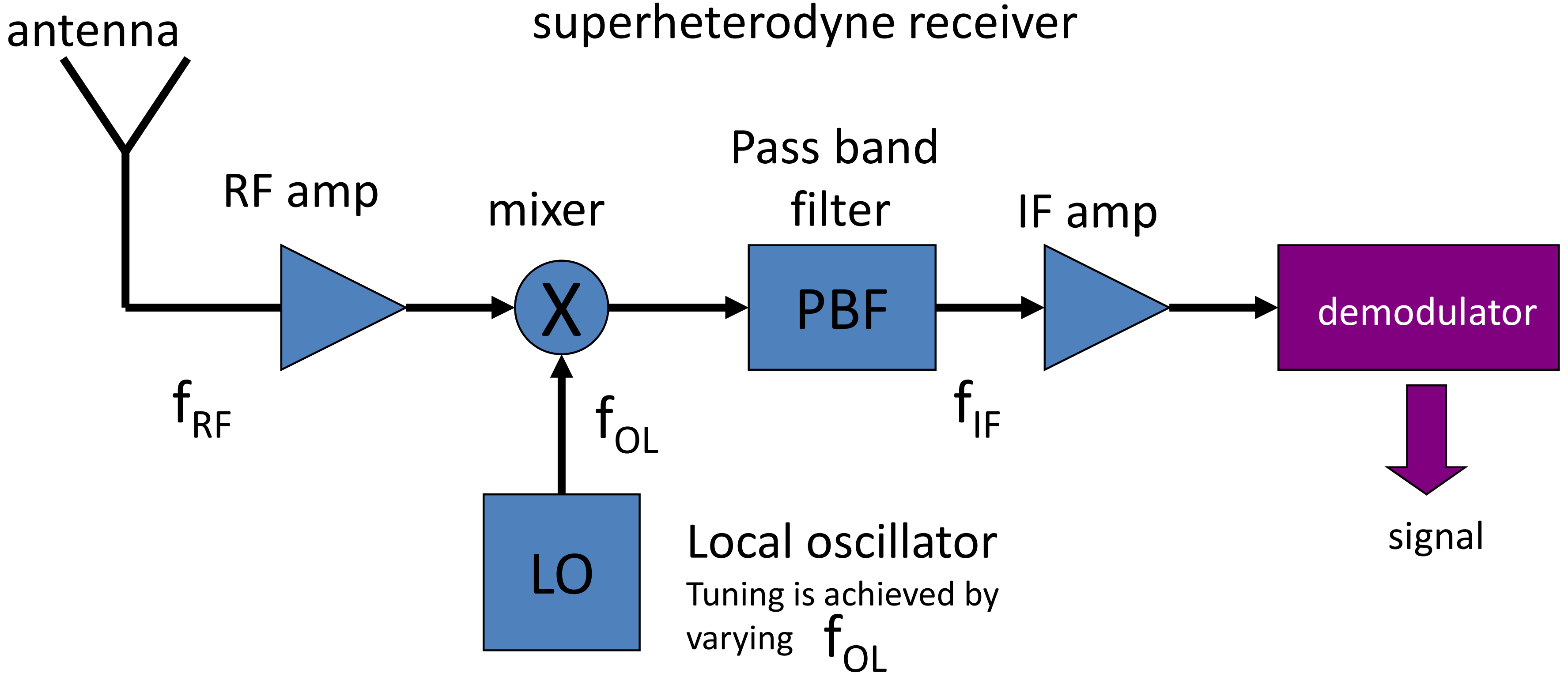
NOTE 1: the attenuation in a wireless system decays with the square power while in a wired system decreases exponentially.

NOTE 2: The Friis formula assumes perfect impedance matching. Otherwise, it should be multiplied by the impedance mismatch factor.

NOTE 3: Friis formula assumes perfect polarization matching.

# MW Systems & Applications

Radio Receiver Example:
superheterodyne receiver




Critical requirements of a radio receiver:

- *High gain* (100dB)
- *Selectivity*
- *Down-conversion* from RF to IF and baseband
- *Detection* of analog/digital information
- *Isolation* from transmitter to avoid saturation

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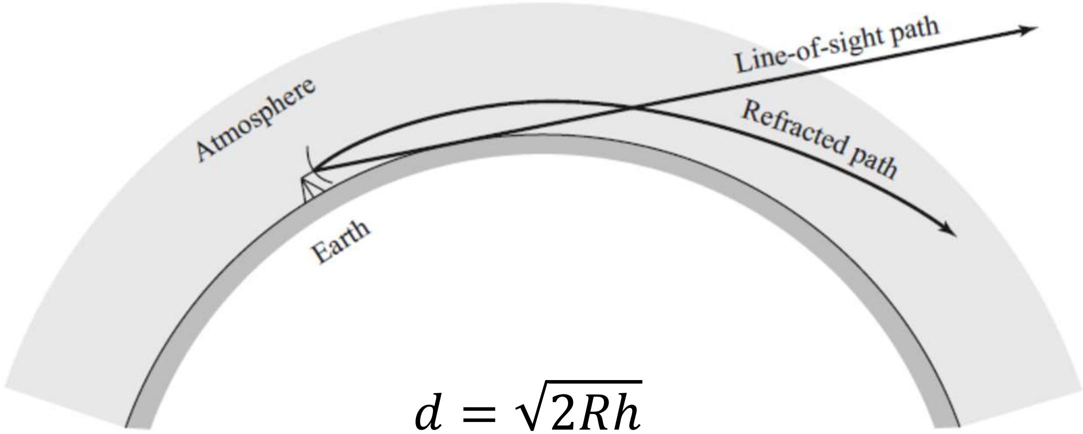
# MW Applications

**3. Microwave signals travel by line of sight and are not bent by the ionosphere as are lower frequency signals.**

Satellite and terrestrial communication links with very high capacities are therefore possible, with frequency reuse at minimally distant locations.

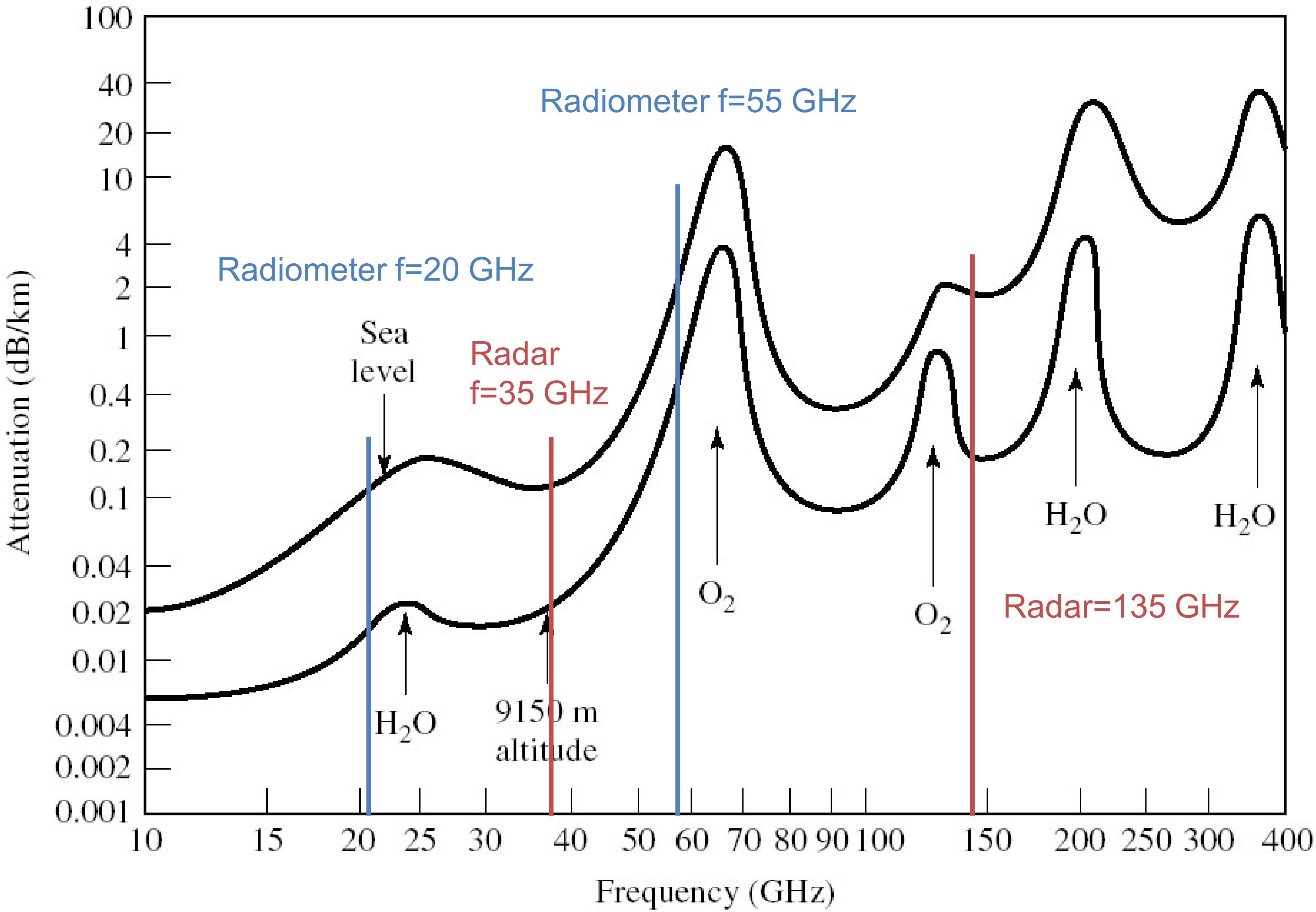



$$d = \sqrt{2Rh}$$

Effects of **refraction** can be accounted for by using an effective Earth radius *kR*, where k > 1. A value commonly used is k = 4/3, but this value changes with weather conditions.
Another atmospheric effect is **attenuation**, caused primarily by the absorption of microwave energy by water vapor or molecular oxygen.

# MW Applications

## Attenuation level in the atmosphere




Below 10 GHz the attenuation can be considered negligible

# MW Applications

## Additional issues in MW propagation

### Ground effects

The presence of the ground on RF and microwave propagation is *reflection* from Earth's surface (land or sea).
Another ground effect is *diffraction*, whereby a radio wave scatters energy in the vicinity of the line-of-sight boundary at the horizon, thus giving a range slightly beyond the horizon. This effect is usually very small at microwave frequencies. Of course, when obstacles such as hills, mountains, or buildings are in the path of propagation, diffraction effects can be stronger.

### Plasma effects

The ionosphere consists of spherical layers of atmosphere with particles that have been ionized by solar radiation, and thus forms a plasma region; depending on density and frequency, a wave might be reflected, absorbed, or transmitted by the plasma medium. Wave propagation in a plasma is allowed only above the plasma frequency. Anisotropy in the plasma can be induced by magnetic fields, i.e. Earth's magnetic field.

# MW Applications

**4. The effective reflection area (radar cross section) of a radar target is usually proportional to the target's electrical size.**

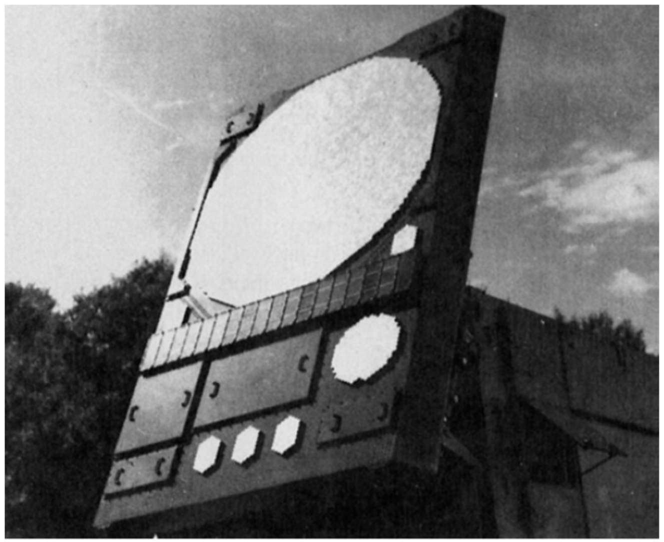
This fact, coupled with the frequency characteristics of antenna gain, generally makes microwave frequencies preferred for radar systems.

RADAR (short for *radio detection and ranging*) is one of the most prevalent applications of microwave technology. Allows to precisely determine:

- Position of the target (narrow beam antenna is used)
- Distance of the target (calculated from the time passed to receive the reflected signal)
- Velocity of the target (calculated from Doppler shift of the returned signal)

RADAR APPLICATIONS:

- Civilian (airport control, marine navigation, weather radar, aircraft landing, alarm, speed measurements, altimetry)
- Military (air and marine navigation, missile guidance, fire control, reconnaissance)
- Scientific (astronomy, mapping and imaging, remote sensing, precision distance measurements)



# MW Applications

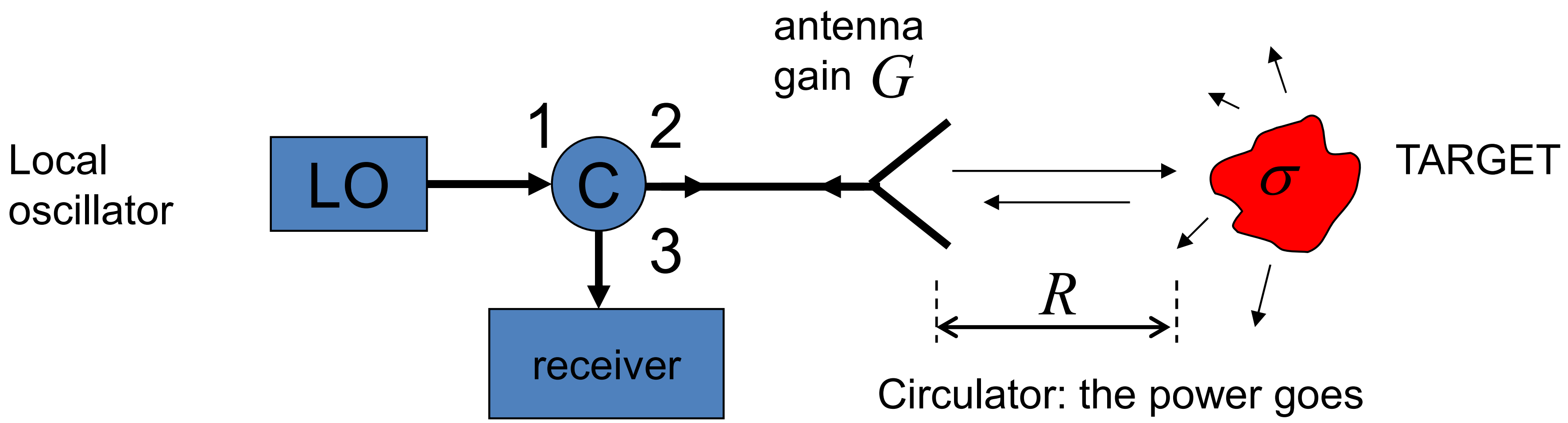
RADAR operation summary:

The source (the transmitter) sends a signal which is partially reflected by the target located in the far field region; the reflected signal is sensed by a receiver.

We can thus measure the distance of the target by computing the time of flight. For big enough antenna directivities (small enough angular aperture of the main lobe) also the angular position of the target can be measured accurately.

In *monostatic radars* the same antenna is used to transmit and to receive.

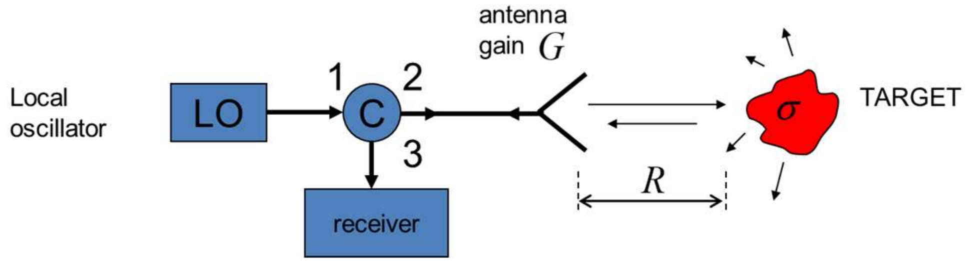
In *bistatic radars* two different antennas are used to transmit and to receive.




Circulator: the power goes
from port 1 to port 2
from port 2 to port 3
ports 1 and 3 are perfectly isolated

# MW Applications

RADAR operation summary:




$P_T$ Transmitted power

$P_S$ Back scattered power

Intensity at the target location $S_T = G \dfrac{P_T}{4\pi R^2}$

**Radar cross section** $\sigma = \dfrac{P_S}{S_T}$

Scattered field at the receiving antenna $S_R = G\sigma \dfrac{P_T}{\left(4\pi R^2\right)^2}$

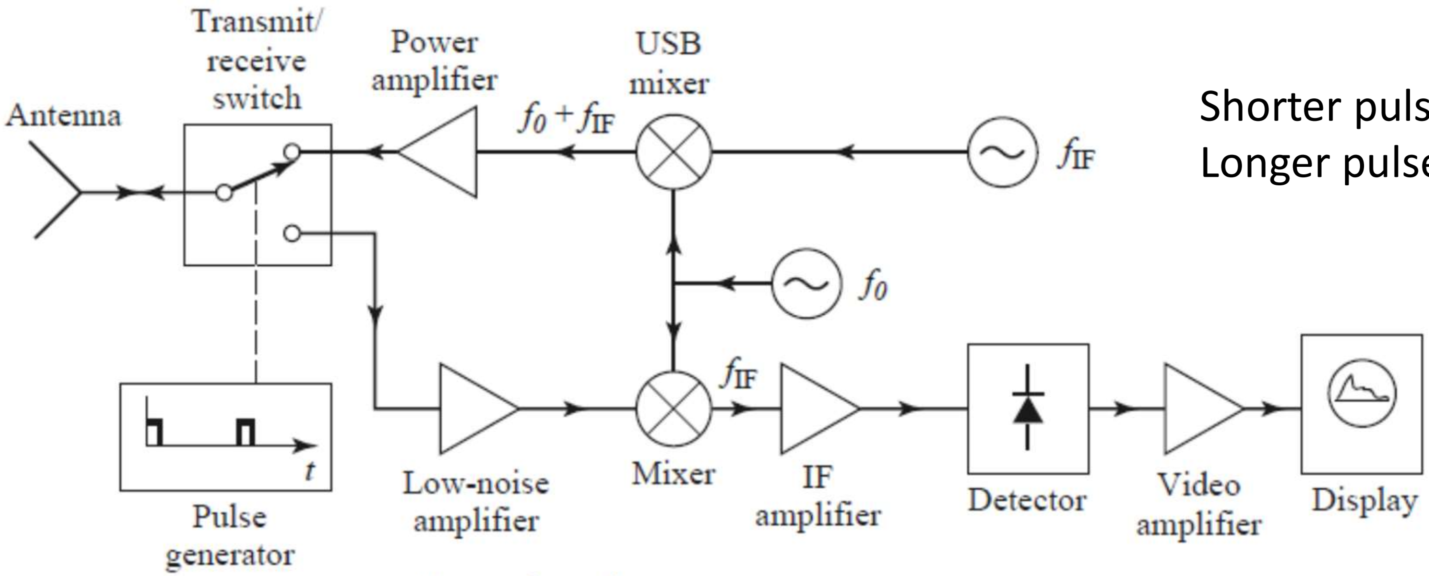
The target is equivalent to a transmitting antenna radiating backward.
The power received by the monostatic radar is thus:

$$P_R = A_{eff} S_R = G\frac{\lambda^2}{4\pi}\left(G\sigma \frac{P_T}{4\pi R^2}\frac{1}{4\pi R^2}\right) = \boxed{\frac{G^2\lambda^2\sigma}{(4\pi)^3 R^4} P_T = P_R}$$

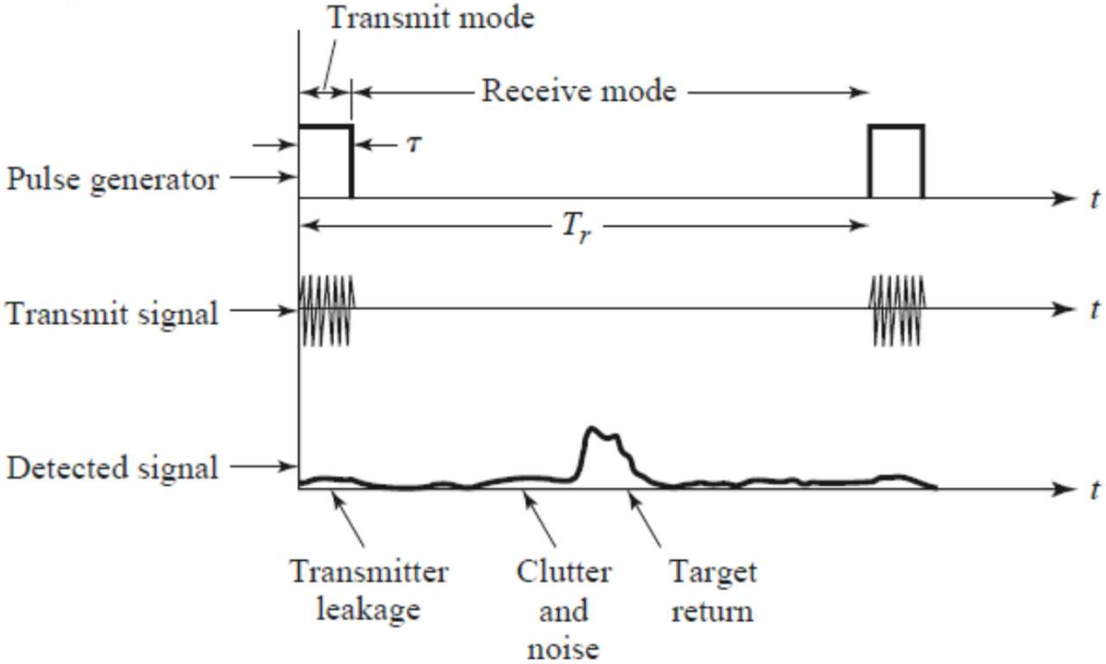
**Radar equation**

# MW Applications

**PULSED RADAR**
used to reduce noise level




Shorter pulses - better range resolution
Longer pulses – better signal-to-noise ratio




Frequency repetition rate

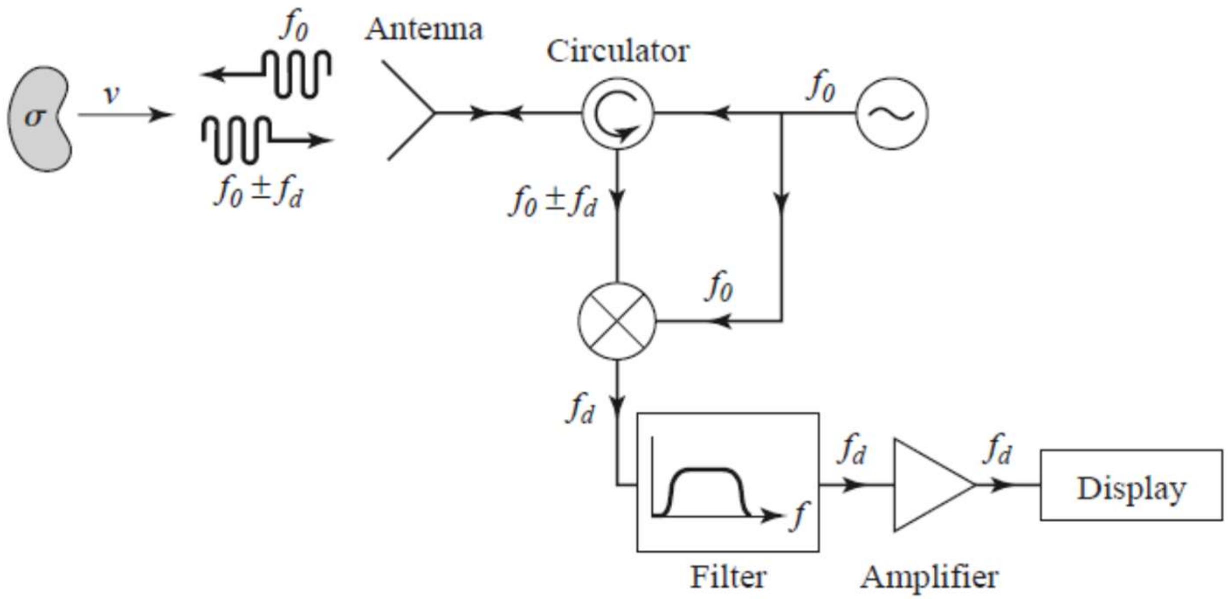
$$f_R = 1/T_R \approx 0.1-100\ kHz$$

**Position of the target** $R \approx \dfrac{\Delta t\, c}{2}$

# MW Applications

**DOPPLER RADAR (and PULSED DOPPLER RADAR)**

used to calculate target velocity




The phase of the reflected signal is: $\varphi = 2\pi f_0 t - \dfrac{2\pi 2R}{\lambda_0}$

If the target is moving away with velocity $v$, then $\varphi = 2\pi f_0 t - \dfrac{4\pi(R + vt)}{\lambda_0}$

The frequency of the received signal shifts <u>(Doppler shift)</u> is: $f_0 \pm f_d = \dfrac{1}{2\pi}\dfrac{\partial\varphi}{\partial t} = f_0 \pm \dfrac{2v}{c} f_0$

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# MW Applications

## RADAR CROSS-SECTION (RCS)

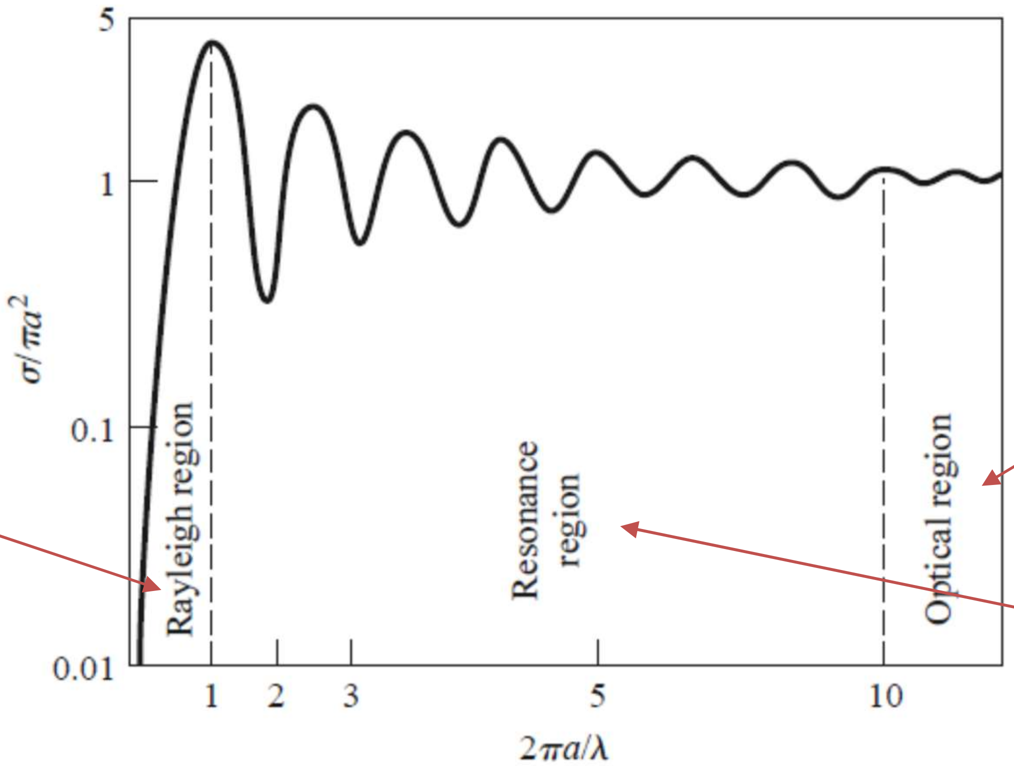
Any radar target is characterized by a RCS that depends on:

- the nature and shape of the object;
- Frequency and polarization of the incident wave;
- Incident and reflected angles.

As a simple example let us consider the cross section of a metal sphere of radius *a*:

$$\boxed{\sigma = \frac{P_S}{S_T}}$$

$$\sigma \propto \left(\frac{a}{\lambda}\right)^4$$




$$\sigma \approx \pi a^2$$

The oscillatory behaviour is due to the phase difference among different reflected components

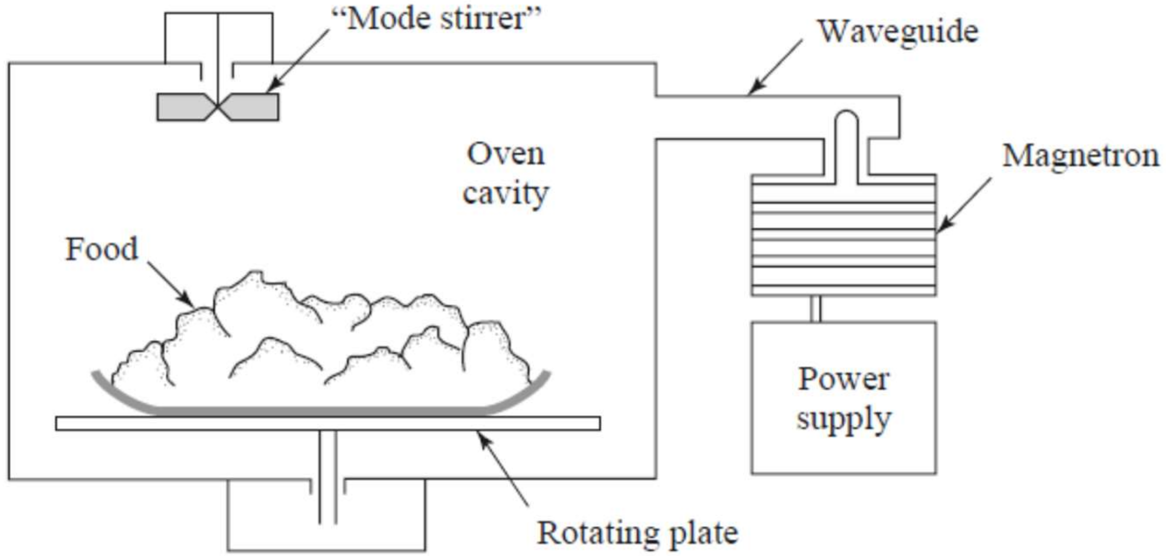
# MW Applications

**5. Various molecular, atomic, and nuclear resonances occur at microwave frequencies.**

## Microwave Heating

In microwave heating, the inside of the material is heated first. The process through which this occurs primarily involves the conduction losses in food materials.

NOTE: The loss tangents of many foods decrease with increasing temperature, so that microwave heating is to some extent self regulating. The result is that microwave cooking generally gives faster, and more uniform heating of food as compared with conventional cooking.



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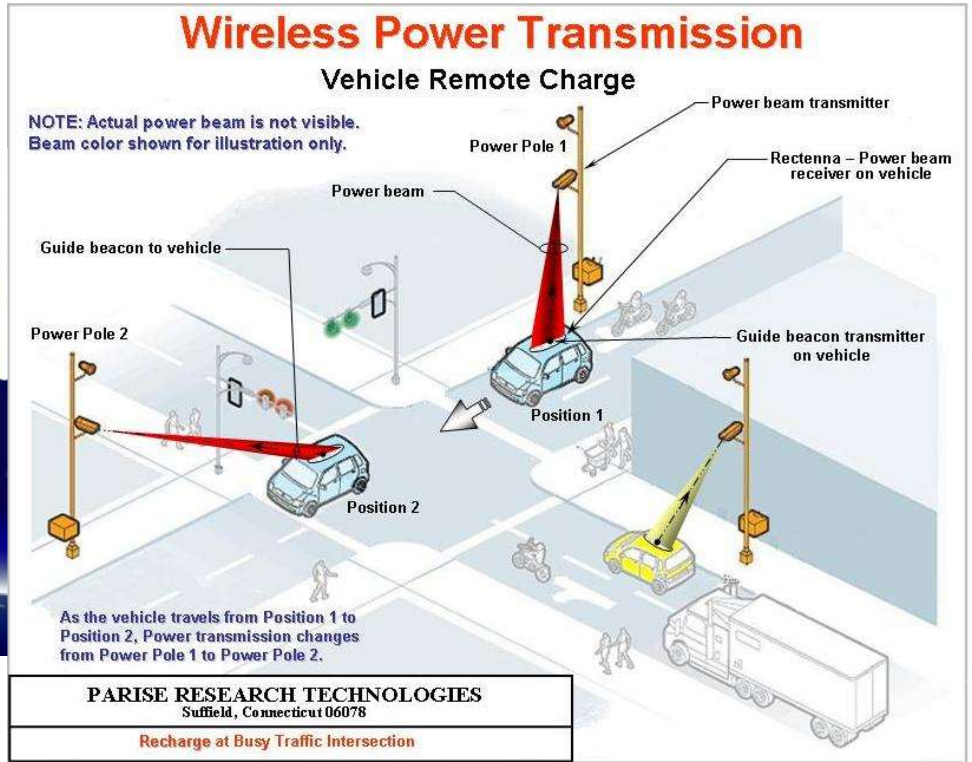
# MW Applications

## Wireless power transfer

Electrical power can be transmitted without wires by a well-focused microwave beam.

Examples:

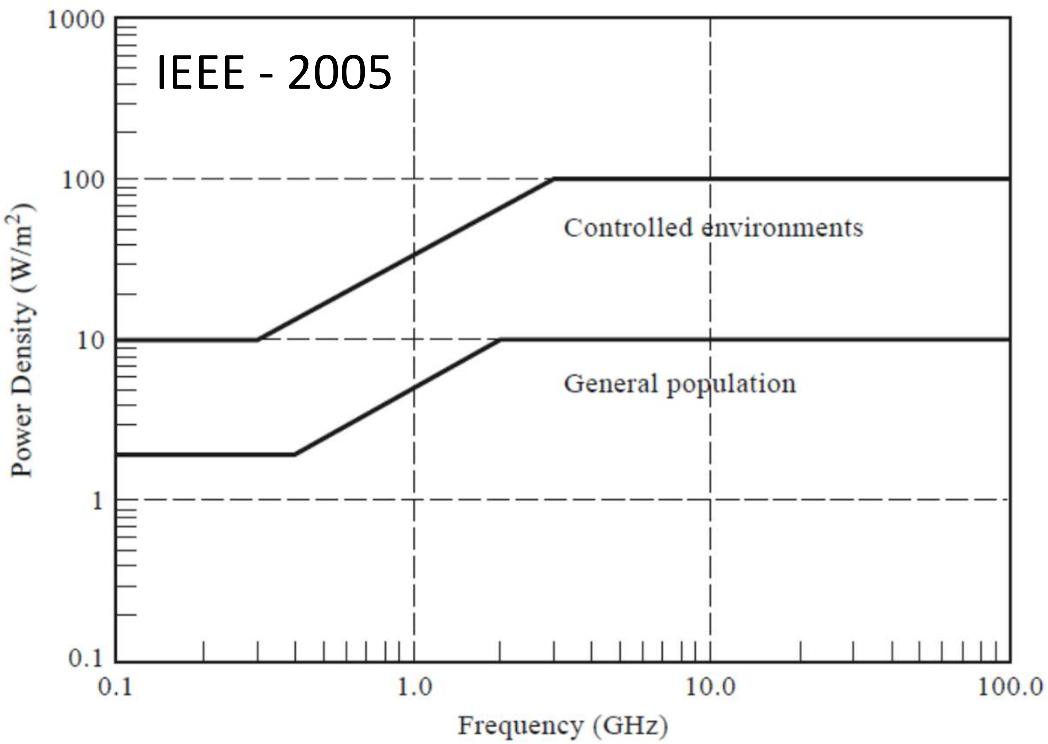
- solar satellite power station: electricity is generated in space by a large orbiting array of solar cells and transmitted to a receiving station on Earth by a microwave beam.
- transmission of electrical power from Earth to a vehicle such as a small drone helicopter or airplane;
- wireless transmission of power to RFID tags;



# MW Applications

## Biological Effects and Safety

The body absorbs RF and microwave energy and converts it to heat; as in the case of a microwave oven, this heating occurs within the body and may not be felt at low levels.
Such heating is most dangerous in the brain, the eye, the genitals, and the stomach. Excessive radiation can lead to cataracts, sterility, or cancer.
In the RF-microwave frequency range of 100 MHz to 100 GHz, exposure limits are specified for the power density (W/m$^2$) as a function of frequency:




At higher frequencies most of the power absorption occurs near the skin surface, so the safe limits can be higher.
At frequencies below 100 MHz electric and magnetic fields interact with the body differently than higher frequency electromagnetic fields, and so separate limits are given for field components at these lower frequencies.