ASU MAT 591: Opportunities In Industry!

History of Radar

Speaker: John Schneider – Lockheed Martin

September 2, 2003

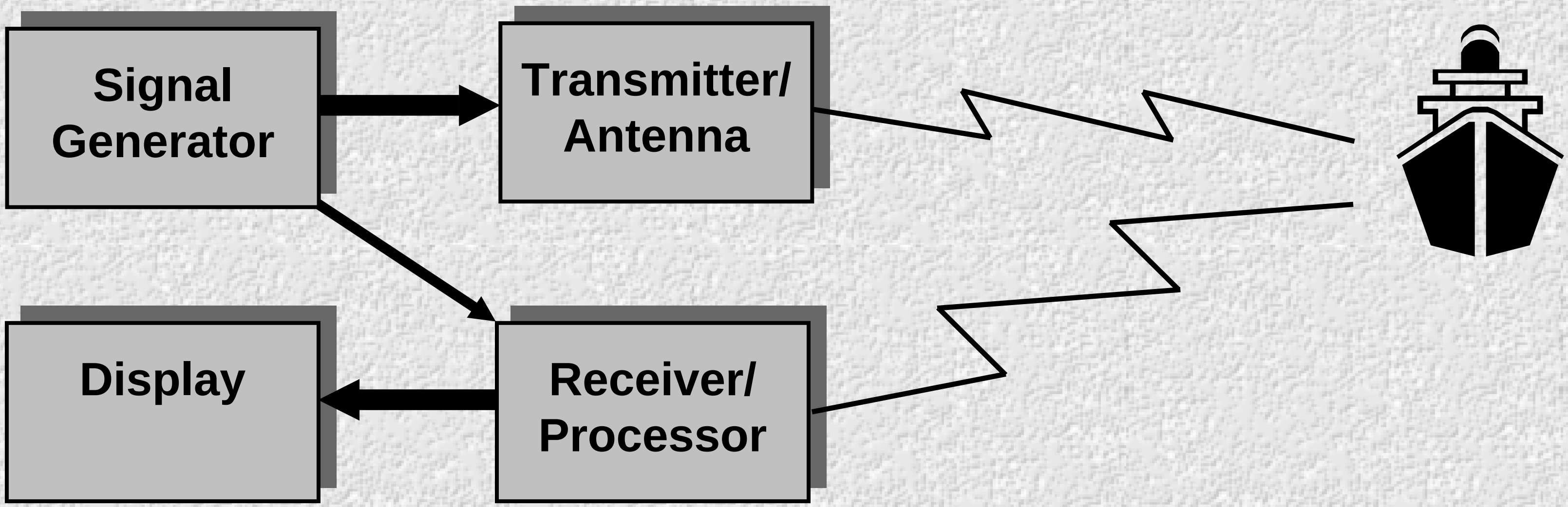
What is RADAR?

- An Internet acronym search yielded some of the following results:
  - ***RAD***ical ***AR***kansas
  - ***R***adio ***A***ssociation ***D***efending ***A***irwave ***R***ights
  - ***R***egional ***A***lcohol & ***D***rug ***A***wareness ***R***esource
  - ***R***eseau ***A***fro-Asiatique pour le ***D***eveloppement de l'***A***viculture ***R***urale
  - ***RA***dio ***D***etection ***A***nd *R*anging
- From Webster's Collegiate Dictionary, Tenth Edition

  "ra•dar \ˈrā där \ *n,often attrib* [*ra*dio *d*etection *a*nd *r*anging] (1941): a device or system consisting usu. of a synchronized radio transmitter and receiver that emits radio waves and processes their reflections for display and is used esp. for detecting and locating objects (as aircraft) or surface features (as of a planet)"

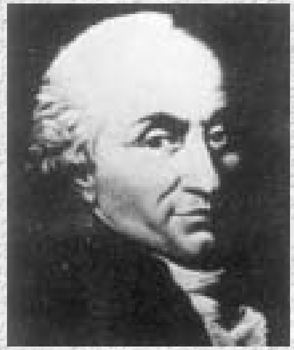
What is RADAR?

- In its simplest form....

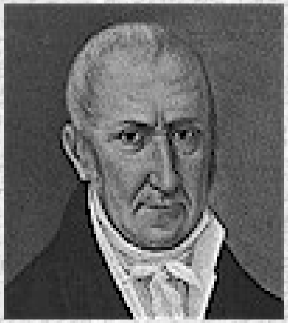


Development of Electromagnetic Theory

- Groundwork laid in the late 1700s and early 1800s:
  - Charles Augustin de Coulomb (b.1736-d.1806) writes a series of papers on the nature of electricity and magnetism, which included:
    - A theory of attraction and repulsion between bodies of the same and opposite electrical charge
    - Demonstration of an inverse square law for such forces
    - The proposition of attracting and repelling forces acting at a distance between electrical charges in a similar way as Newton's theory of gravitation acting at a distance between masses
  - Alessandro Volta (b.1745-d.1827) invents the "Voltaic Pile" in 1800, the first wet battery consisting of discs of copper and zinc separated by discs of paper or cardboards soaked in saltwater



Charles Coulomb



Alessandro Volta

Development of Electromagnetic Theory

- Groundwork laid in the late 1700s and early 1800s:
  - André Marie Ampère (b.1775-d.1836) creates a mathematical formulation for the science of electrodynamics and invents the means for measuring electrical current
  - Johann Karl Friedrich Gauss (b.1777-d.1855), contributes significantly to the studies of mathematics, astronomy, and magnetism:
    - Develops the concept of complex numbers and proves the fundamental theorem of algebra
    - Develops the method of least squares fitting
    - Develops the concept of the “bell curve”/normal distribution which is named after him
    - With Wilhelm Weber, discovers Kirchoff’s laws and builds the first telegraph device
    - Contributes to mathematical modeling of potential theory and magnetism, and invents practical devices for measurement of terrestrial magnetism and geodesy

André Ampère

Karl Gauss

Development of Electromagnetic Theory

- Modern Electromagnetic Theory begins with the formulations developed by James Maxwell:
  - James Clerk Maxwell (b.1831-d.1879), a mathematician and physicist, worked primarily in developing the mathematical models and underlying physical representations of electromagnetic fields. His contributions to science include:
    - Formulating the four equations which are the basis for all electromagnetic theory
    - Showing that these equations necessarily imply the existence of electromagnetic waves, traveling at the speed of light
    - Establishing the three color model of vision and creating the world's first color photo
    - Developing a theory of gases and showing that molecular movement was the root cause of heat and temperature

James Maxwell

Maxwell's Equations

- Equation 1 – A time-varying magnetic field produces an electric field

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

- Equation 2 – A static current and/or time-varying electric field produces a magnetic field

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

- Equation 3 – An electric charge is a source for electric fields

$$\nabla \bullet \mathbf{D} = \rho$$

- Equation 4 – Magnetic fields only exist in closed loops (no point source exists for them)

$$\nabla \bullet \mathbf{B} = 0$$

- Auxiliary equations:

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P}$$
$$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M})$$
$$\mathbf{J} = \sigma \mathbf{E}$$
$$\mathbf{J} = \rho \mathbf{v}$$

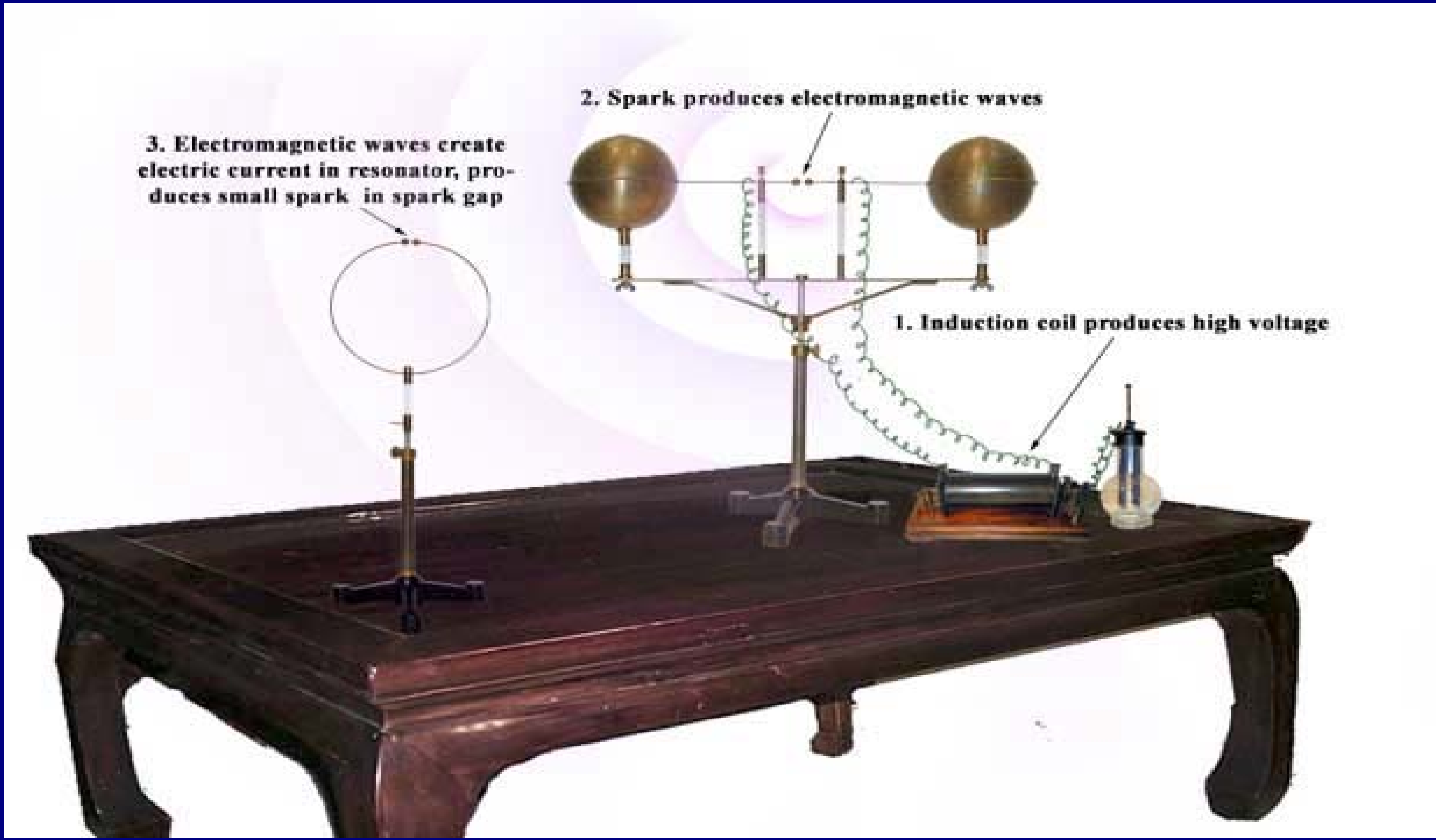
$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \qquad \lambda = \frac{c}{f}$$

Experimental Demonstration of Radio Waves

- Heinrich Rudolf Hertz (b.1857-d.1894):
  - Proved that electricity can be transmitted by electromagnetic waves
  - With further experiments involving mirrors, prisms, and metal gratings, he showed that his electromagnetic waves to have analogous properties as light
  - Simplified and formalized Maxwell's equations into a more compact and symmetric form

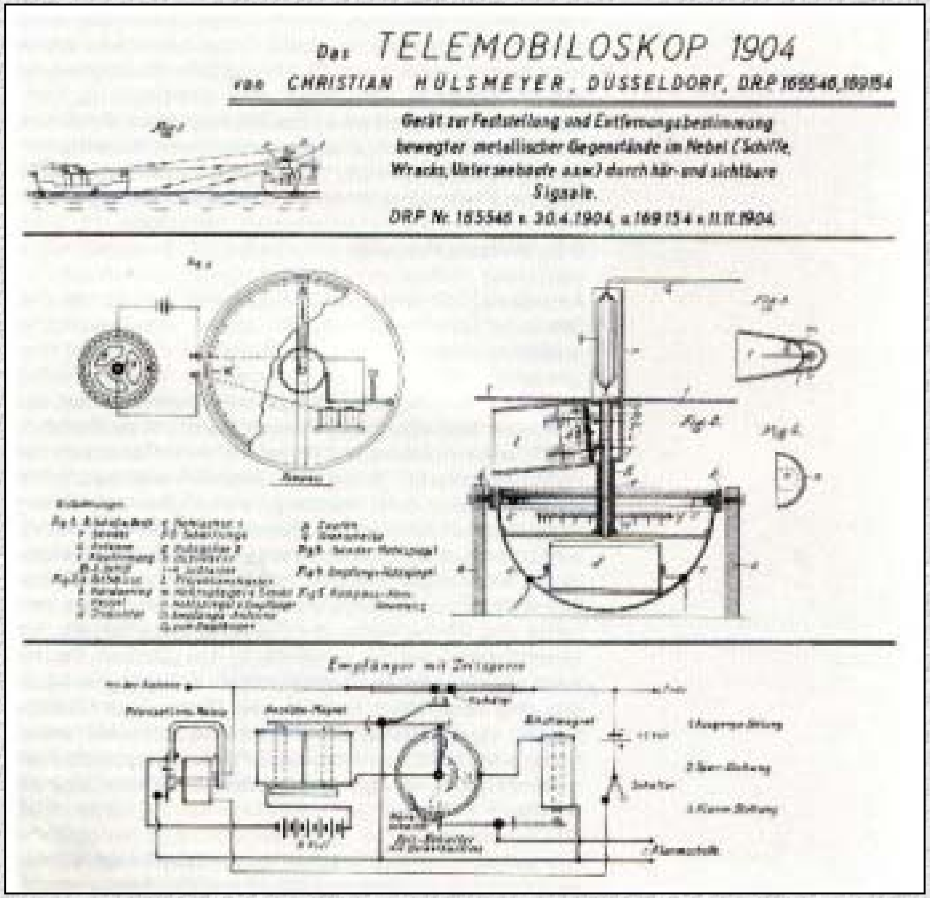
Heinrich Hertz

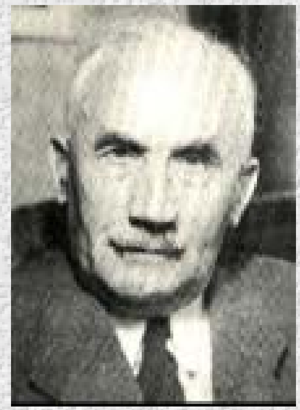
Hertz's Demonstration of Electromagnetic Waves



First Application of RADAR

- The first "practical" application of radio waves for RADAR was invented by Christian Huelsmeyer in 1904 for ship detection (Range = 3km)





Christian Huelsmeyer

Huelsmeyer's Telemobiloscope

TECH OPS Mountain Region

Technology Circa Early 1900s

- Transmitter/Antenna
  - Righi Oscillator set in the focal point of some reflecting material
  - Invented by Augustus Righi, a friend of the Marconi family
  - Induction coil connected to the oscillator would induce sparks across the narrow gaps

Technology Circa Early 1900s

- Receiver
  - Coherer detector developed in the late 1800s by Branly and Lodge
  - Nickel filings in partial vacuum glass tube, whose resistance dropped significantly when an RF signal was present

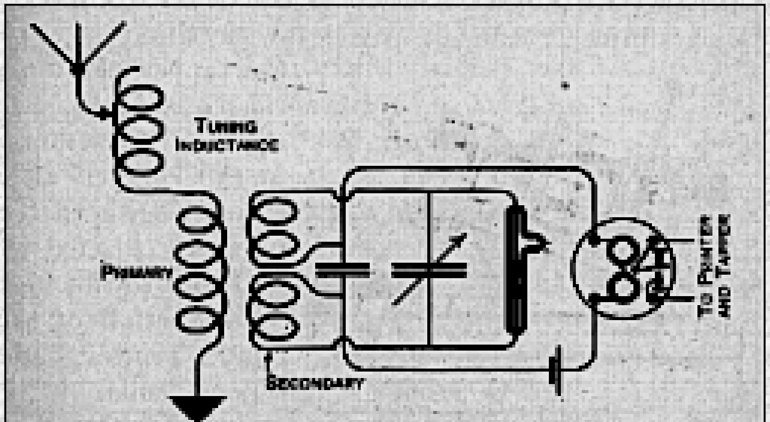
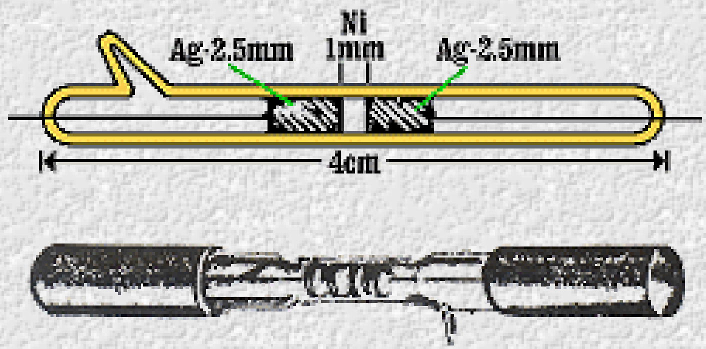


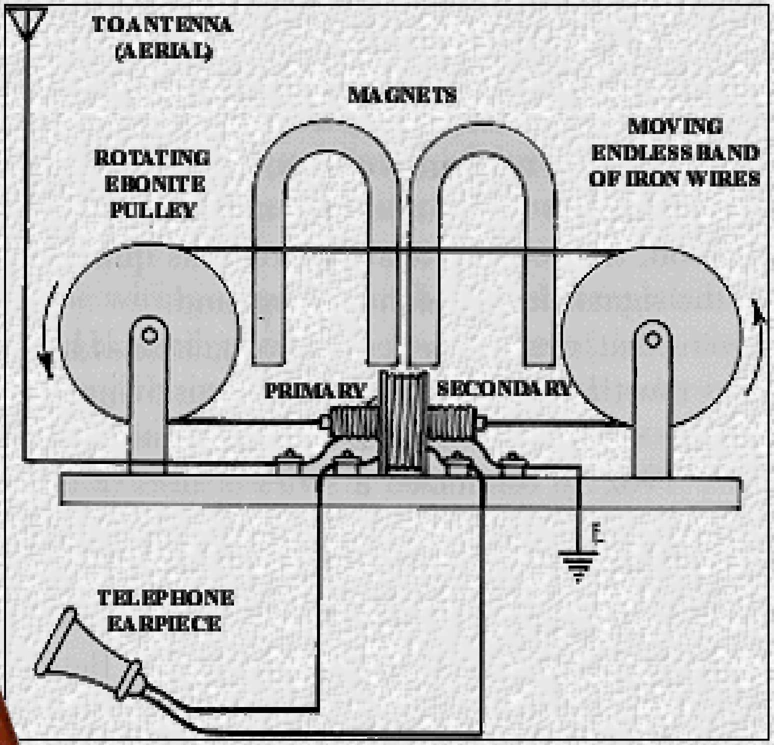
Fig. 42
Circuits of Marconi coherer receiver



Marconi Coheror

Technology Circa Early 1900s

- Receiver
  - Magnetic detector invented by Marconi in 1902
  - Much more sensitive than coheror



Technology Circa Early 1900s

- Limitations for Radar Usage:
  - Operating Frequencies were low (wavelengths too long)
    - Antenna Gain (Ga) is given by:

$$G_a = \frac{4\pi A_e}{\lambda^2}$$

longer wavelength means less antenna gain (shorter detection range)

    - Antenna Beamwidth (θa) is given by:

$$\theta_a = k\frac{\lambda}{L_a}$$

longer wavelength means wider beam (less angular resolution for position measurement)

  - Transmitters not powerful enough (limiting detection range)
  - Continuous Wave (CW) operation does not allow for easy range measurement
  - Receiver detectors not sensitive or reliable enough

Next Step - Developments in Radio Technology

- 1904 – Sir John Ambrose Fleming invents the vacuum tube and diode (based on the “Edison effect”)
- 1906 – Lee De Forest develops the triode, later making signal amplification with vacuum tubes practical
- 1912 – Edwin Armstrong devises the first practical amplitude modulation (AM) radio receiver
- 1918 – Edwin Armstrong invents the super-heterodyne receiver
- 1934 – Edwin Armstrong discovers a practical frequency modulation (FM) method and demonstrates it the following year

First Meteorological Use of RADAR

- The first application of RADAR to meteorology was by Sir Robert Watson-Watt (b.1892-d.1973):
  - Used radio signals generated by lightning strikes to detect/locate thunderstorms (so that they may be avoided by RAF aircraft)
  - Location difficulties led to the development of rotating directional antennas
  - Pioneered the idea/use of oscilloscopes as a 2D display device

Robert Watson-Watt

Watson-Watt apparatus for studying waveforms of atmospherics

RADAR and World War II

- RADAR development continued at a faster pace during the 1930s in the build-up towards World War II
  - England's Air Ministry pushed for development to counter its vulnerability to the German Luftwaffe
  - Germany's Navy was pushing radar development to counter the superior English naval forces

RADAR and World War II

- Some popularized myths concerning British/German radar prior to World War II:
  - The British invented radar and scientist Sir Robert Watson-Watt was the man responsible for its invention
  - The Germans had no little or no pre-war radar capabilities and did not grasp its importance
- Realities:
  - Huelsmeyer had developed and patented the first radar device in 1904
  - In 1934, Dr. Rudolph Kuhnold (head of German Navy signals research) “rediscovers” radar
  - Germany actually had more sophisticated technology leading up to WWII

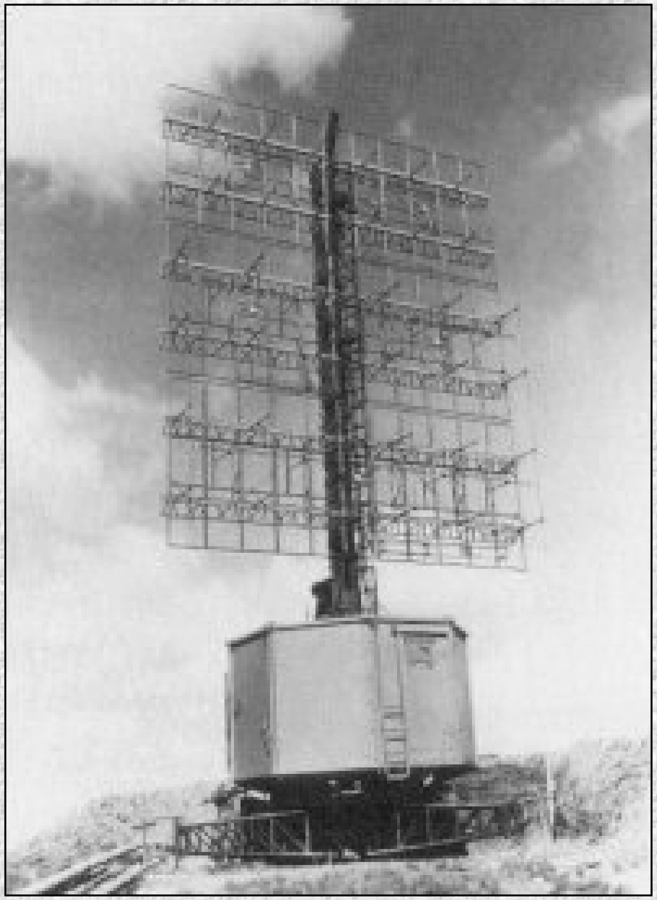
German RADAR

- Hans Hollmann was the leading technical expert of the time on radar technology:
  - Consultant for both the GEMA and Telefunken corporations—leading manufacturers of radar in the late 1930s
  - Holder of 300 patents (76 in US) on all key components of radar systems (oscillators, transmitters, receivers, cathode ray tube displays, etc.)

Hans Eric Hollmann

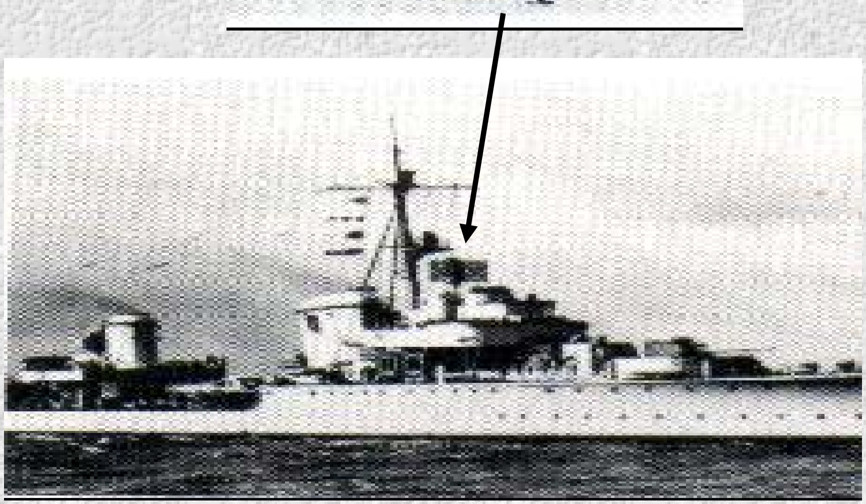
German RADAR - Freya

- "Freya" was the first radar produced in quantity for the German Navy:
  - Land-based aircraft detection radar
  - Operated at 120 to 130 MHz
  - Pulsed radar with pulse width of 3 microseconds at a PRF of 500 Hz
  - Peak Power output of 15 to 20 kW
  - Max range of 100 nmi
  - Over 1000 built throughout the war
  - Installed along Germany's northern coast



German RADAR - Seetakt

- Adapted from “Freya” radar for ship-board use as a ranging device for gunnery:
  - Operated at 375 MHz
  - Pulse width of 3 microseconds and PRF of 500 Hz
  - Peak Power output of 8 kW
  - Max range of 9 nmi
  - Range accuracy of 70 meters
  - Azimuth accuracy of 3 degrees
  - Over 200 built



German RADAR - Wurzburg

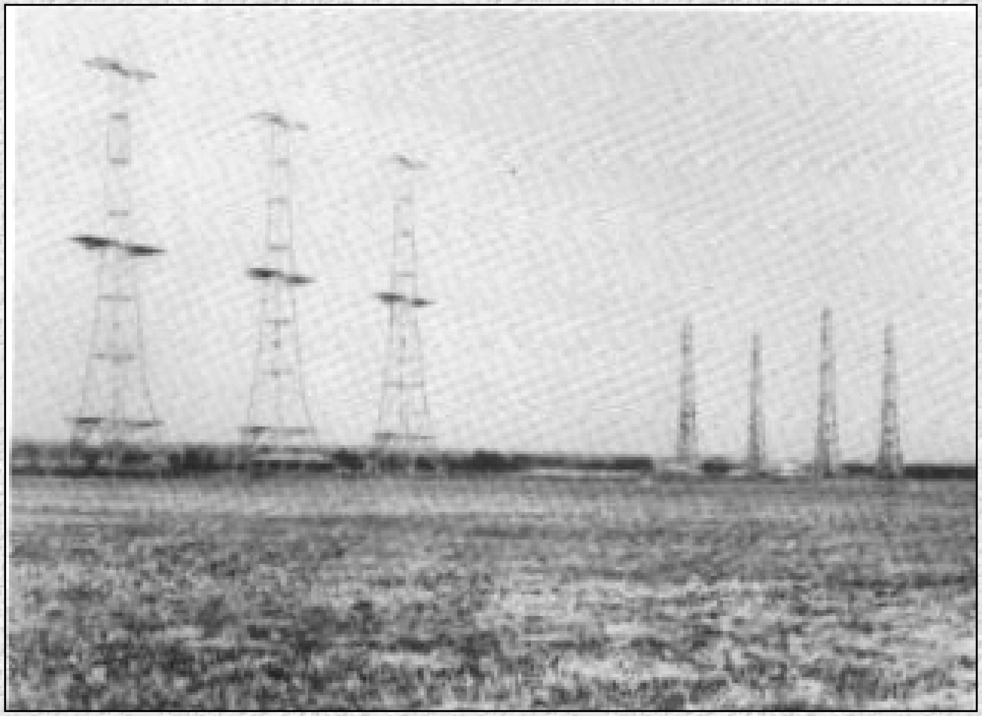
- Telefunken produced a very high accuracy anti-aircraft gun targeting radar, the "Wurzburg":
  - Operated at 560 MHz (very high frequency for its time)
  - Operating range out to 25 miles
  - Range accuracy of 100 meters
  - Bearing accuracy of 0.2 degrees

British Pre-War RADAR – Killing Sheep

- British investigations into radar began with the question of whether a "death ray" could be produced which could incapacitate or destroy attacking aircraft
- The British Air Ministry had offered a prize of £1000 to the first person who could devise a "death ray" to kill a sheep from 100 yards
- Air Ministry turned to Sir Robert Watson-Watt to investigate whether a "death ray" was practical; his conclusion was that a "death ray" could not be fabricated with the technology of the time (it would require Megawatts of power), but that radio waves could be used for aircraft/ship detection and location
- 1935 – Robert Watson-Watt demonstrates radar for Air Ministry using a BBC transmitter; later that year, an English team of scientists demonstrates detection and three-dimensional locating of aircraft at 100 km range, using a 100 KW transmitter (pulsed) operating in the 5 to 10 MHz frequency range

British Pre-War RADAR – CHAIN HOME

- CHAIN HOME was a network of “floodlight” radars positioned along the coast of England



One of the CHAIN HOME radar installations, with transmit towers at left and receive towers at right

British Pre-War RADAR – CHAIN HOME

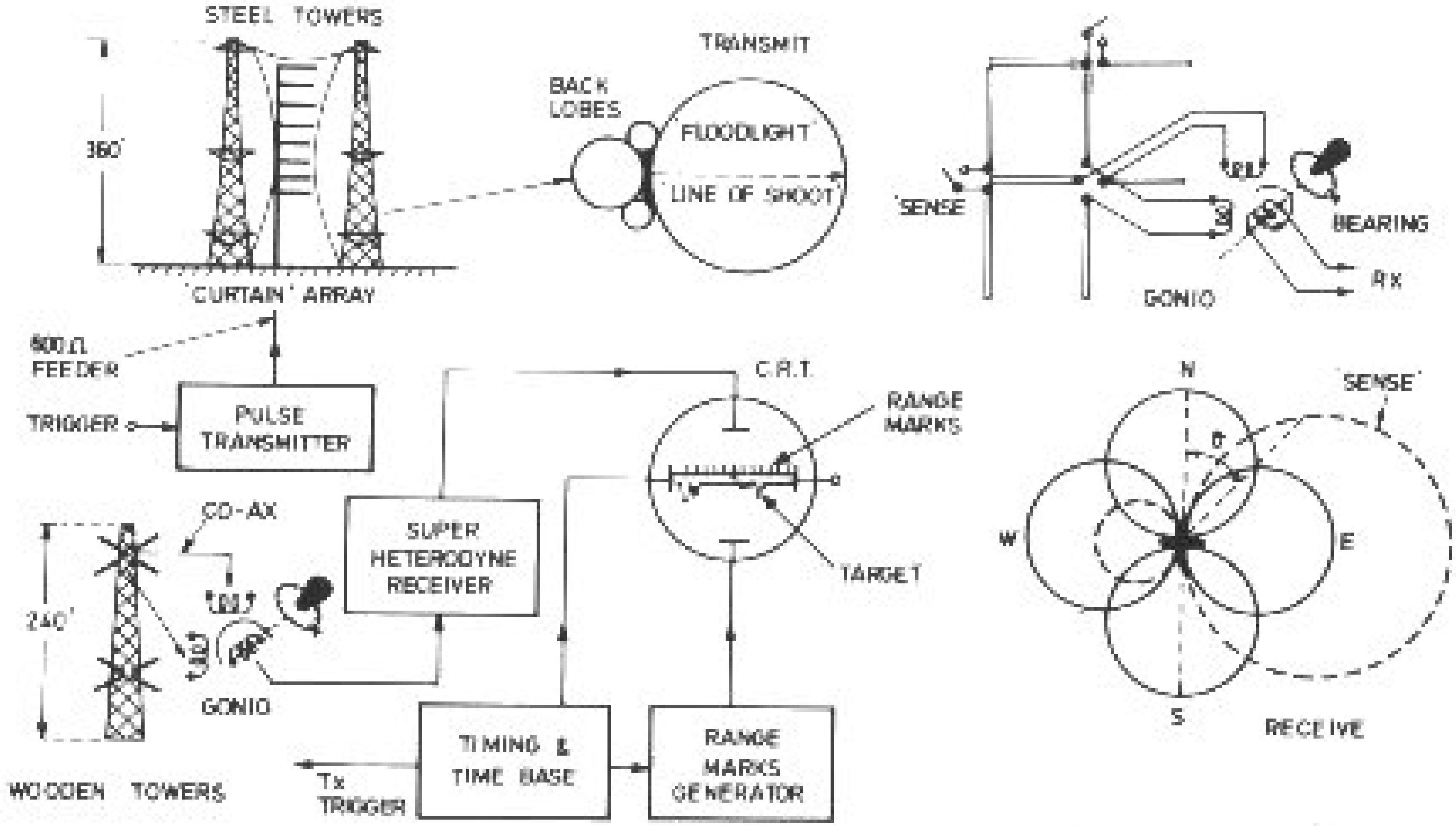


Fig. 1. Principles of CH (Chain Home) R.D.F. system

British Pre-War RADAR – CHAIN HOME

- CHAIN HOME Specifications:
  - Frequency: 20 to 30 MHz
  - Power: 350 KW (later 750)
  - PRF: 25 and 12.5 Hz
  - Pulse: 20 us
  - Range: ~ 200 nmi
  - There were 18 CHAIN HOME sites, time synchronized so that one system within the network would not interfere with another; the pulse timing was synchronized to the national 50 Hz power grid

Comparing British and German Systems

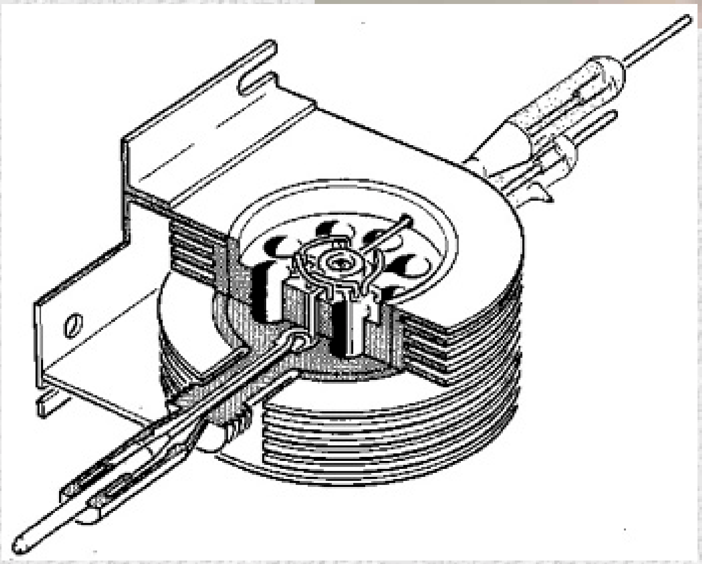
- Britain
  - Had only one system in operation prior to WWII, CHAIN HOME
  - Had a sophisticated, coordinated plan for use of the system
  - Had highly trained staffing and communications
  - Had backup systems in place, anti-jamming, redundancy, etc.
  - Technologically inferior, but superior as an end-to-end system
  - RADAR was integrated into the overall battle strategy
- Germany
  - Had several systems in operation
  - Technologically superior (rotating high gain antennas, higher frequency of operation, superior range/bearing measurements)
  - Multiple-use systems – detection, anti-aircraft gun targeting, bomb targeting, etc.
  - Not employed in a coordinated strategy

World War II Advancements

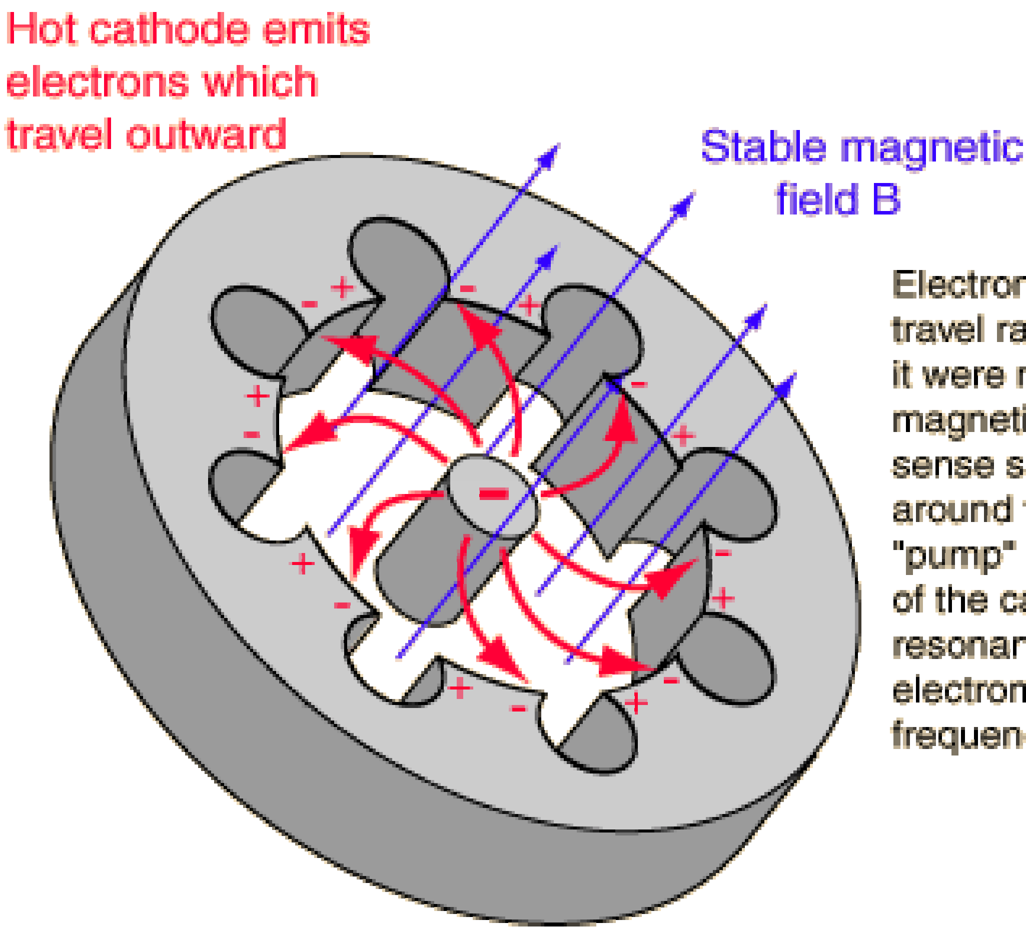
- Pre-War British program was to set up CHAIN HOME, but this provided nothing in terms of capabilities for anti-aircraft gun targeting, bomb targeting, etc.
- The British and American radar programs were using low frequency radars (the prevailing technology at that time), which severely limited their usefulness
- Britain was pushing very hard to generate microwave frequency radar components
  - Clarendon Laboratory of Oxford directed to develop microwave receivers
  - University of Birmingham directed to develop microwave transmitters

World War II Advancements

- The most significant advancement was achieved at the University of Birmingham by John Randall and Henry Boot, the “cavity magnetron”

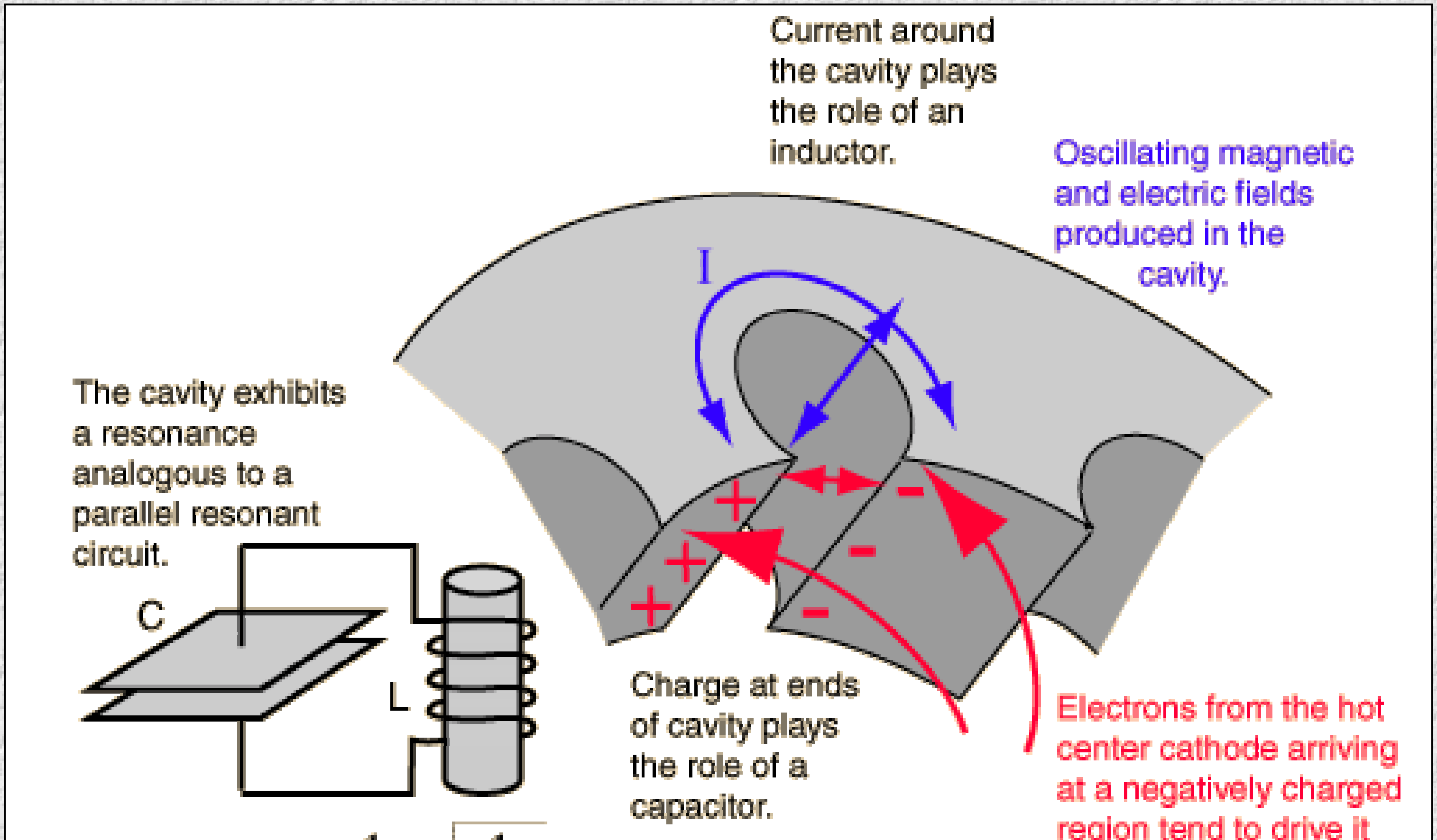


Cavity Magnetron Operation



Electrons from a hot filament would travel radially to the outside ring if it were not for the magnetic field. The magnetic force deflects them in the sense shown and they tend to sweep around the circle. In so doing, they "pump" the natural resonant frequency of the cavities. The currents around the resonant cavities cause them to radiate electromagnetic energy at that resonant frequency.

Cavity Magnetron Operation



$$f_{resonance} \approx \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

The Cavity Magnetron Improvement

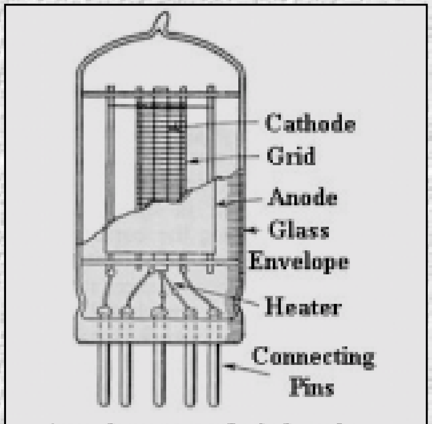
- By mid-1940, Britain had succeeded in improving on the prototype cavity magnetron, producing a relatively small, light-weight transmitter which could generate RF pulses at 3 GHz, with an output power of 15 KW
- Factor of 10 improvement in operating frequency over German radar
  - Since antenna gain is inversely proportional to wavelength squared, an antenna of the same size could now produce beams 100 times more powerful
  - Since antenna beamwidth is inversely proportional to wavelength, a 3 GHz radar is 10 times as accurate in each dimension (azimuth and elevation) in determining target bearing

Receiver Technology

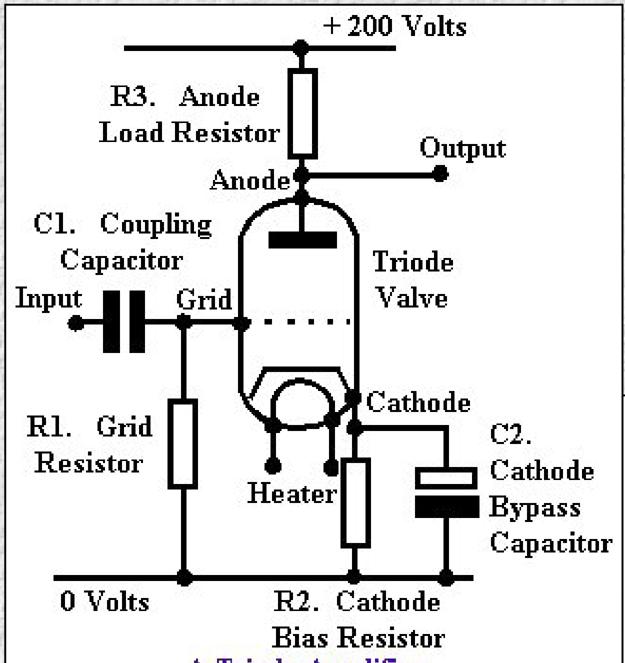
- Modern radio and radar receiver operation principles were developed in the 1920s and 1930s
  - Vacuum tube (thermionic valve) oscillators, amplifiers, and detectors
  - Superhet (supersonic heterodyne) receiver
- Developed to overcome sensitivity/reliability problems in radio communications
- Radar receivers use these same techniques, but operate at higher frequencies

Triode Vacuum Tube

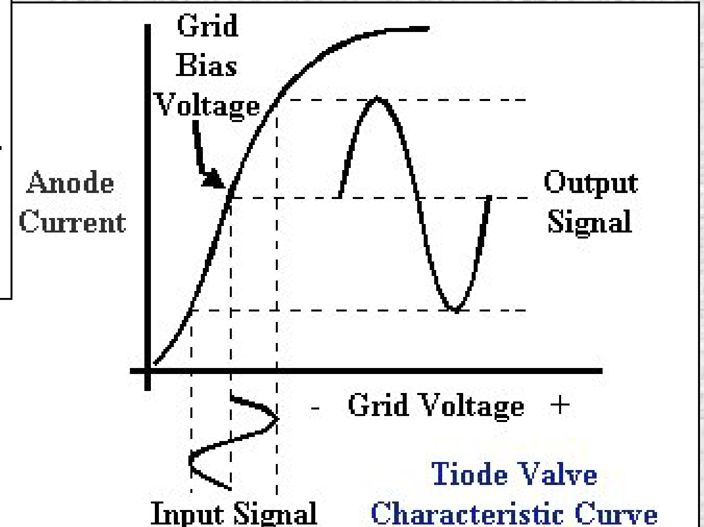
- Triode, invented by Lee De Forest in 1906



A modern type of triode valve



A Triode Amplifier



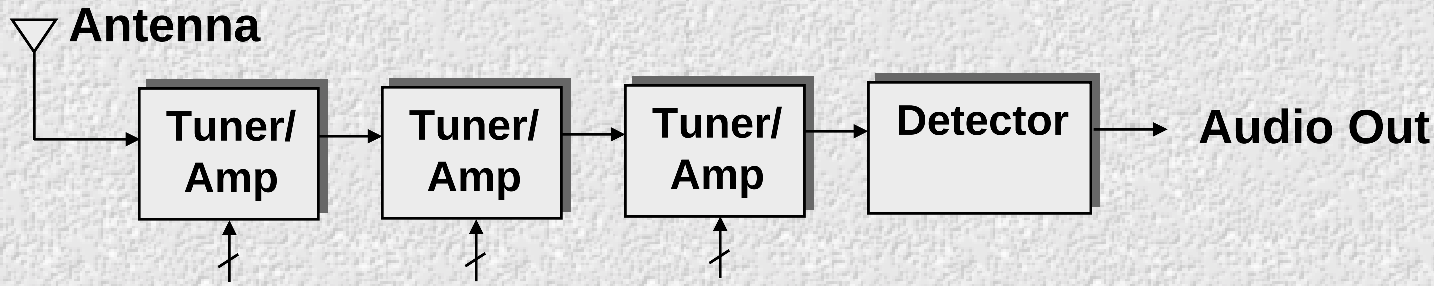
Tiode Valve
Characteristic Curve

Vacuum Tube Advancements

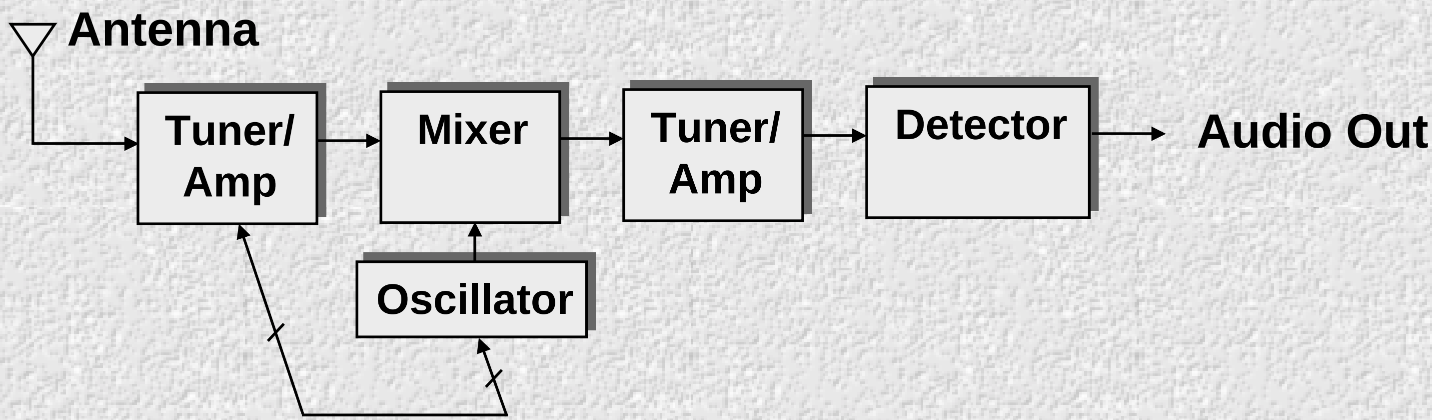
- Over the years following the diode and triode vacuum tube inventions, several improvements were made to the design and more applications for it were devised:
  - Focus during World War I years was modifying the design for mass manufacturability
    - Newer materials to enhance performance (particularly in the filament)
    - Better methods for inducing and holding a vacuum in the tube
    - Repeatability in materials, manufacturing tolerances, testing, etc.
  - Multi-grid tube variations were invented (tetrode, pentode, hexode, heptode, octodes, etc.)
  - Special purpose tubes (low/high power, multi-use, fast warm-up, etc.)

Superhet Receiver

- Older Style Tuned Radio Frequency (TRF) Receiver

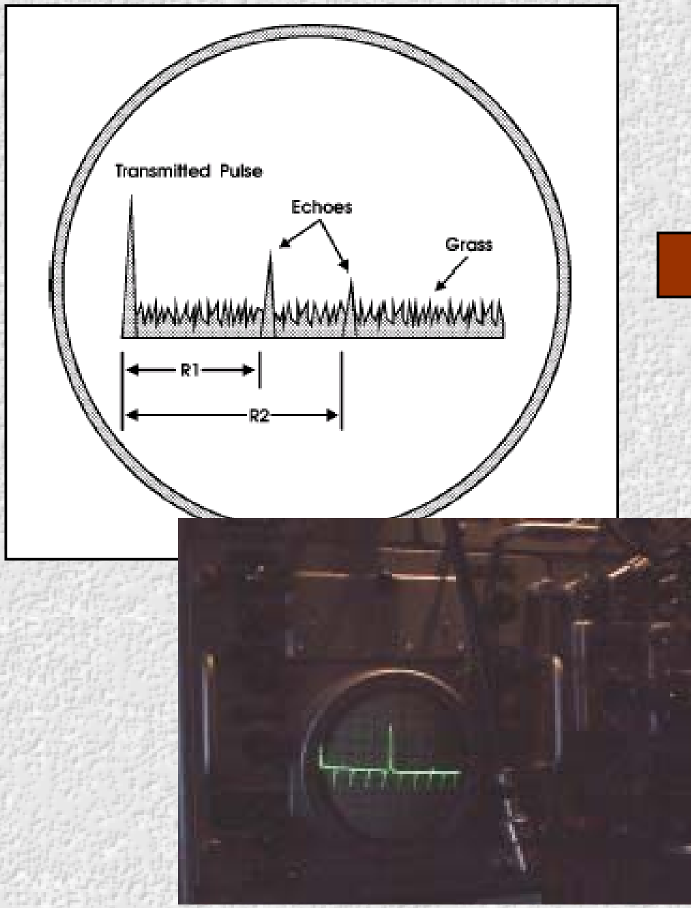


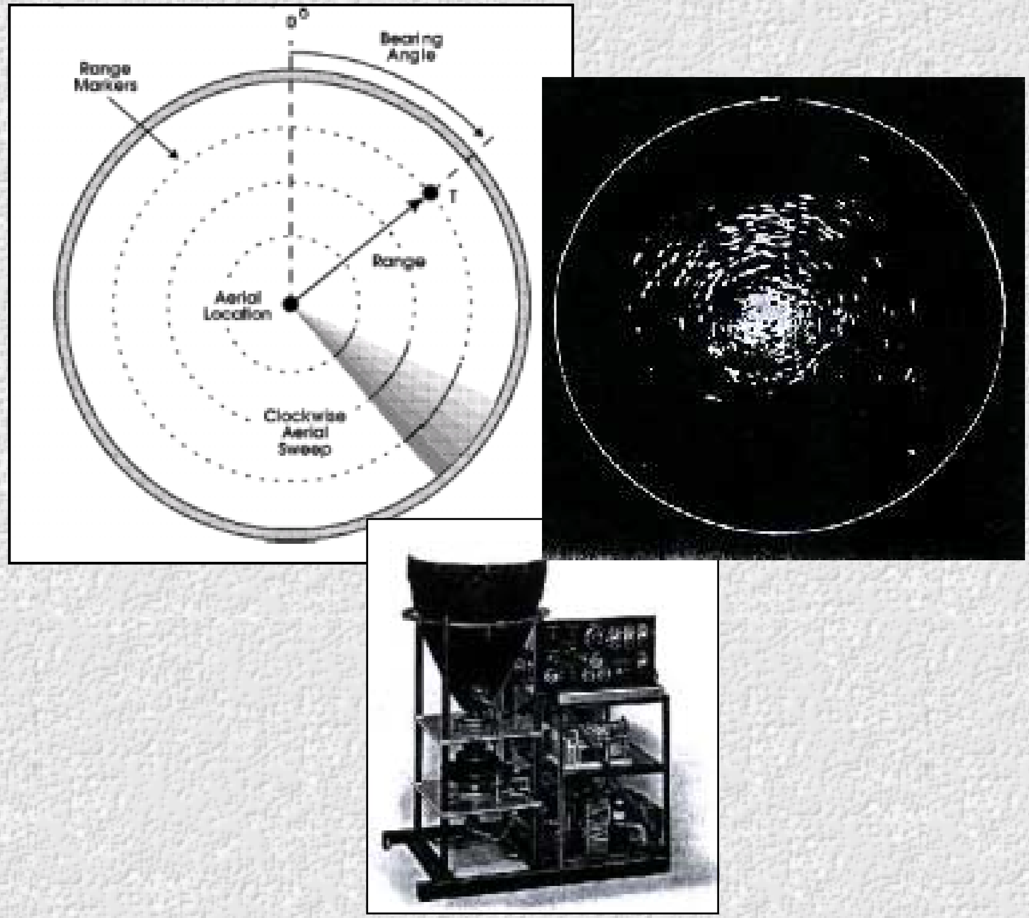
- Superhet Receiver



PPI Display

- The PPI Display provided a more useful picture of the radar field of view





American Involvement in World War II

- Some British and American politicians recognized early on that the U.S. would likely get pulled into the war
- Sir Henry Tizard, a leader in development of the British CHAIN HOME and other radar programs, led a team of experts to meet with various American scientists and leaders
- The British shared a great number of technical secrets with the Americans, including the cavity magnetron
  - The U.S. quickly set up a new laboratory at MIT, the "Radiation Laboratory"
  - The Naval Research Laboratory and other groups also were recipients of the new technology
- By 1941, both Britain and the U.S. had begun to produce S-band (3 GHz) and later X-band (10 GHz) components and systems

Status Quo at End of WWII

- Radar had evolved from prototypes built in the mid-1930s to an explosion of different systems/applications by mid-1940s
- Microwave signal generation had become practical and advances in all areas (antennas, transmitters, receivers, displays, etc.) led to wide-spread use in communications and radar applications

Civilian Use of RADAR

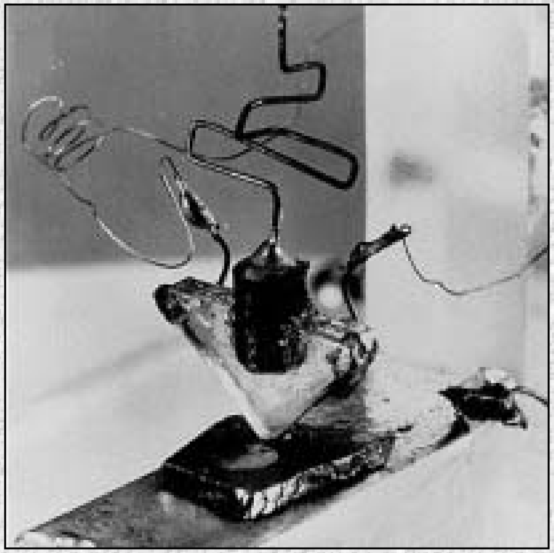
- Following World WAR II, there was a lull in development of new technology for radar use
- Surplus military radars were put into service for civilian use, primarily as weather and air traffic control radars; later, radars were built specifically for those purposes
  - 1945 – First military radar (AN/APQ-13) is converted from ground mapping/bombing radar on B-29 bombers to storm warning radar; 30 systems installed on military bases
  - 1950 – US Civil Aeronautics Administration (pre-cursor of the FAA) begins deployment of ASR-1 Airport Surveillance radars
  - 1954 – AN/APQ-13 is replaced by the AN/CPS-9, the first radar designed specifically for meteorological use
  - 1959 – WSR-57 weather surveillance radar is commissioned at the Miami hurricane forecast center

Semiconductor Development

- Following WWII, Bell Laboratories had a program focused on development of semiconductor devices to replace vacuum tubes in communications/electronics
- In 1947, the first transistor was invented by Dr. John Bardeen, Dr. Walter Brattain, and Dr. William Shockley
- In 1951, the first junction transistor is invented

Semiconductors affected radar development in two ways:

- **Solid state devices could now be developed and utilized in transmitters, receivers, amplifiers, etc.**
- **Development of computers, integrated circuits, etc. provided automated computer control, processing, etc.**

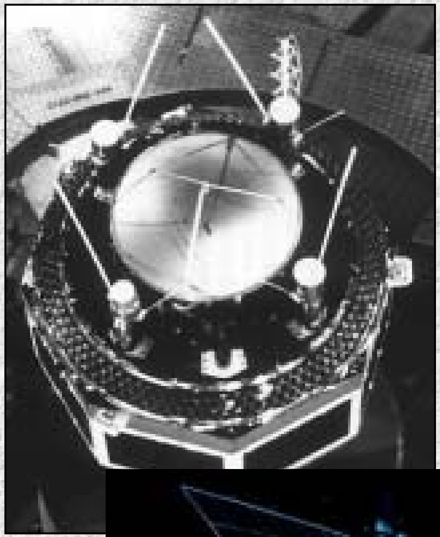


Modern RADAR Applications

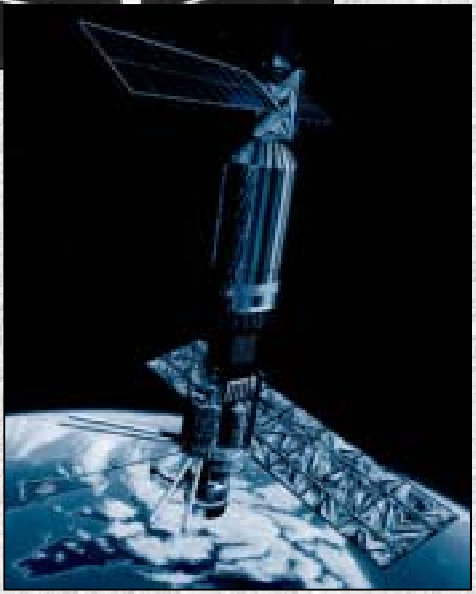
- Following the development of semiconductor devices and digital computers, there was another mini-revolution in capabilities and applications of radar systems
  - Satellite radar for altitude mapping and surveillance
  - Pulse compression techniques for higher range resolution
  - Higher frequency, higher power, wider bandwidth components
  - Phased Array/Active Antennas
  - Advanced Doppler radar applications
    - Advanced meteorological measurements
    - Advanced Moving Target Indicators (MTI)
    - Synthetic Aperture Radar (SAR)

Satellite RADAR

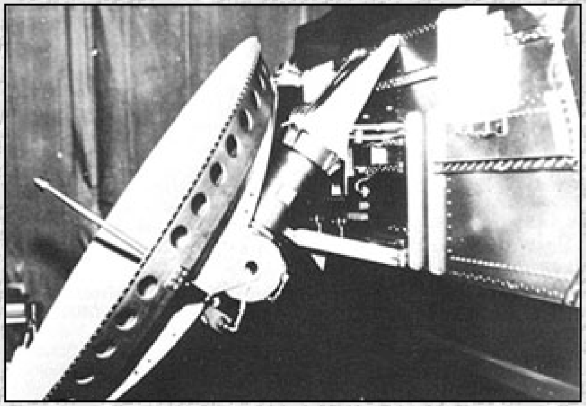
- Early satellite radar focused on altitude mapping:
  - 1973 - Skylab S193 radar altimeter (1st in space); altitude/range resolution is 15 meters
  - 1974 - GEOS-3 launched, 1.9m resolution
  - 1978 - SEASAT launched, 0.5m resolution
  - 1985 - GEOSAT launched; 0.5m resolution
  - 1991 - ERS-1 launched; 0.5m resolution
  - 1995 - ERS-2 launched; 0.5m resolution



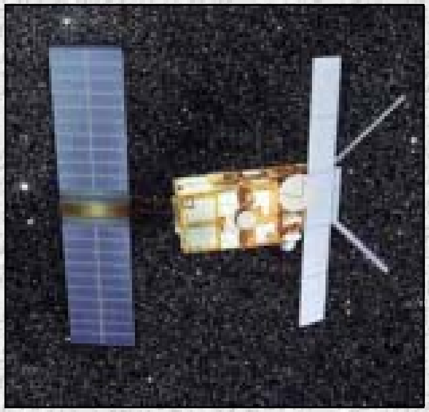
GEOS-3



SEASAT Artist Concept

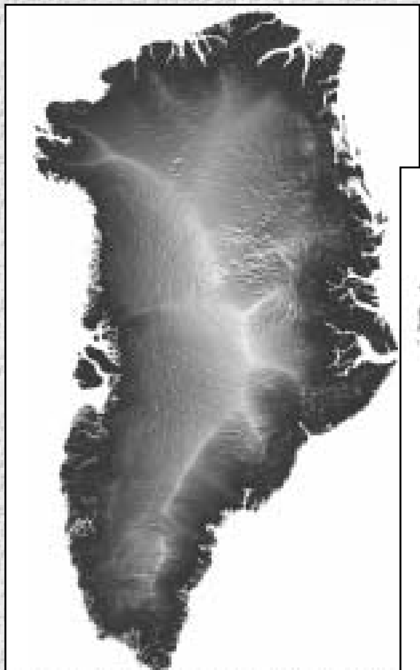


Skylab S193

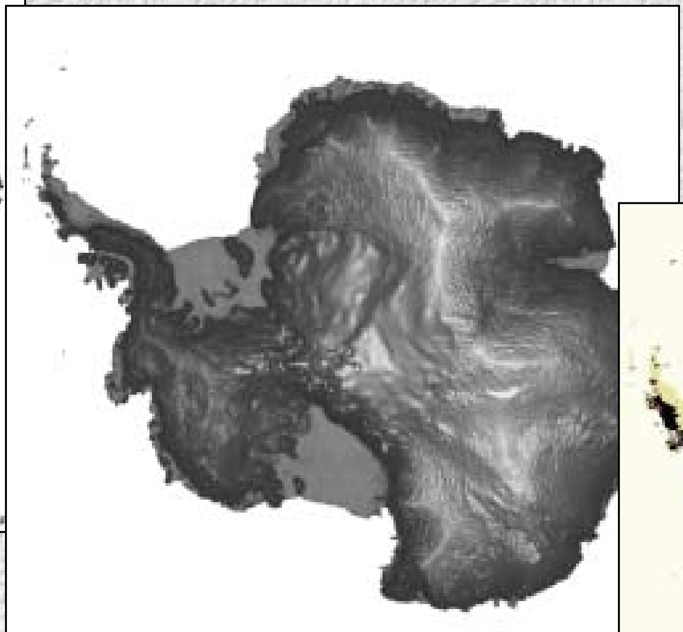


ERS Artist Concept

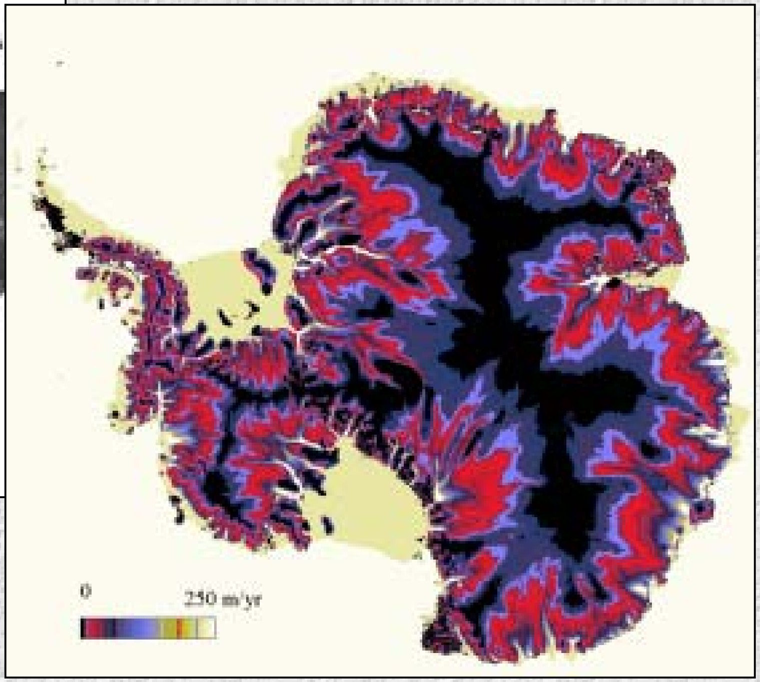
Satellite RADAR – Altitude Mapping



1 km DEM of Greenland derived from ERS-1 geodetic phase da



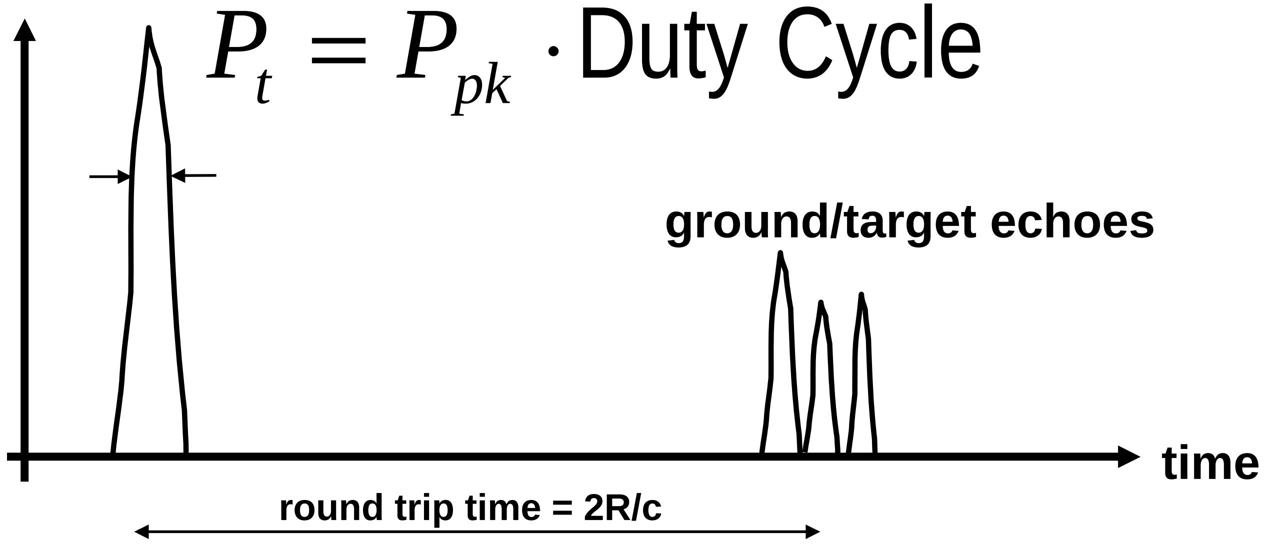
5 km DEM of Antarctica derived from ERS-1 geodetic phase data



Pulse Compression Techniques

- Invented in the late 40s as a means to provide higher range resolution while maintaining good signal to noise performance of a radar system
- Older Style, Non-Pulse Compression System

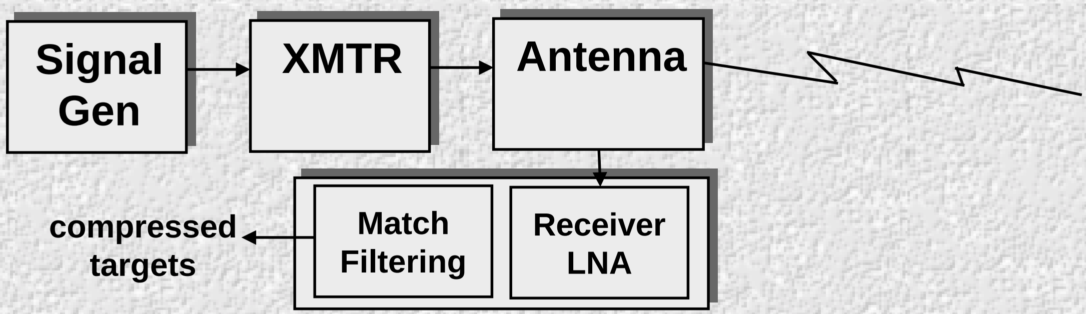
$$P_t = P_{pk} \cdot \text{Duty Cycle}$$

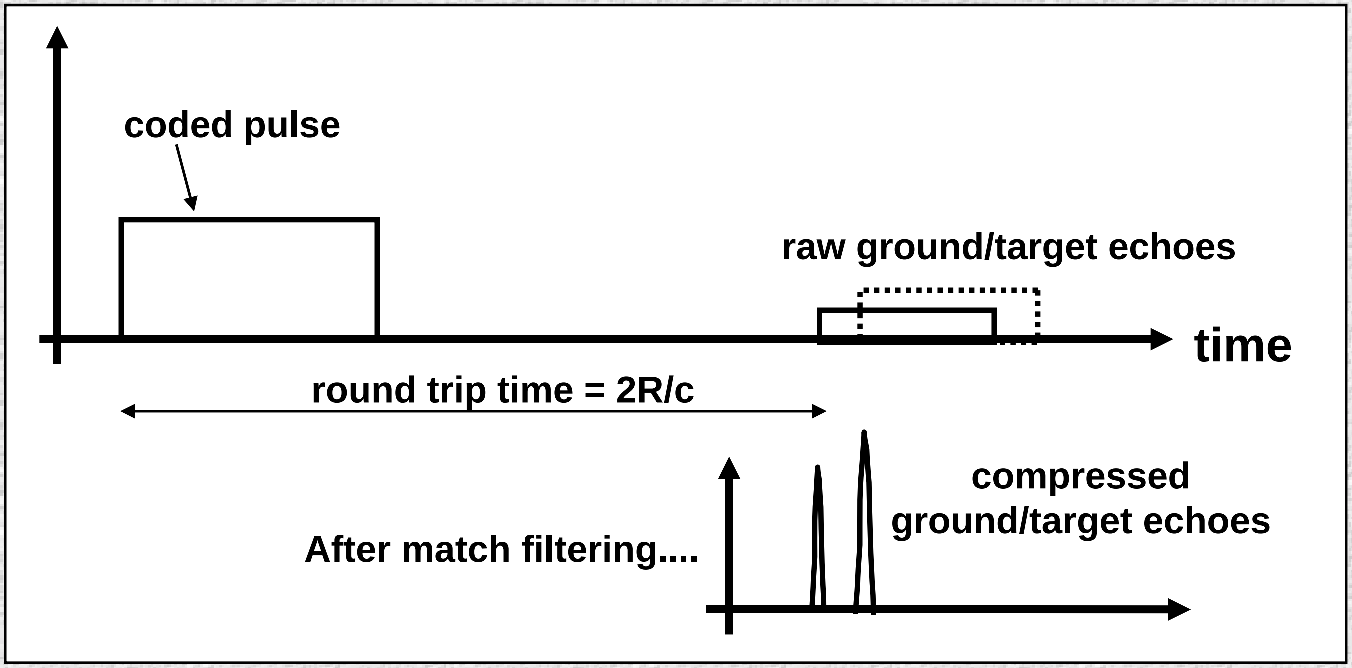


  – Higher resolution means less average power transmitted (lower signal return strength and shorter range of operation)

Pulse Compression Techniques

- Pulse Compression System





Pulse Compression Techniques

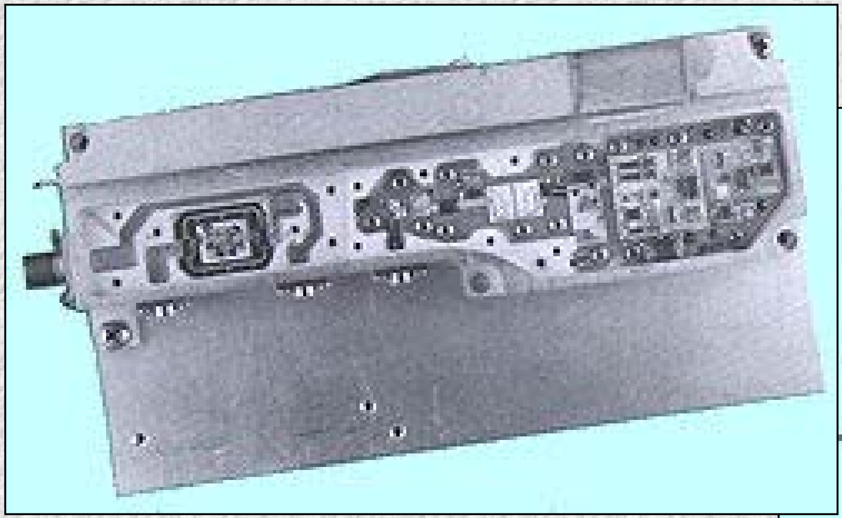
- In a pulse compression system, the resolution of the radar is given by the bandwidth of the transmitted pulse, not by its pulse width

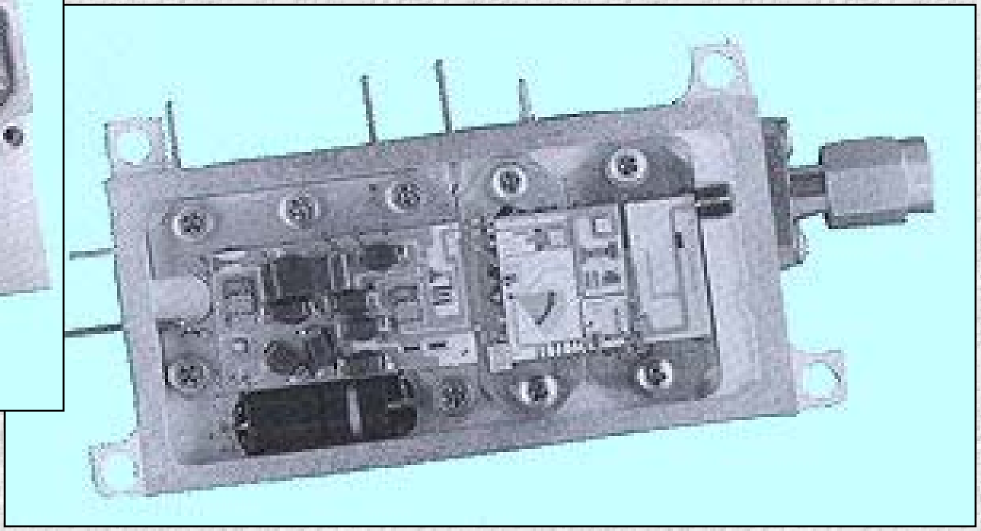
$$\text{Range Resolution} \approx \frac{c}{2 \cdot BW_t}$$

- This allows very high resolution to be obtained with very long pulses (higher average transmit power/longer operating range)
- Popular pulse compression techniques:
  - Binary phase coding of the pulse
  - Linear FM modulation of the pulse (“chirp” radar)
  - Stepped frequency waveform

Modern Microwave Components

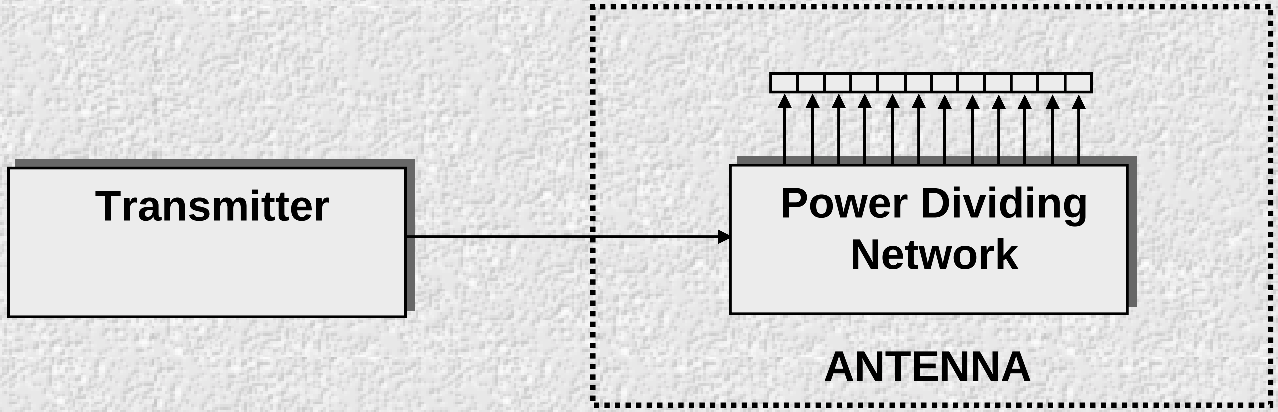
- New materials, new techniques for building microwave components, transmission line improvements, monolithic microwave integrated circuits (MMICs), etc. have provided improvements in terms of sensitivity, bandwidth, power, etc. in all areas



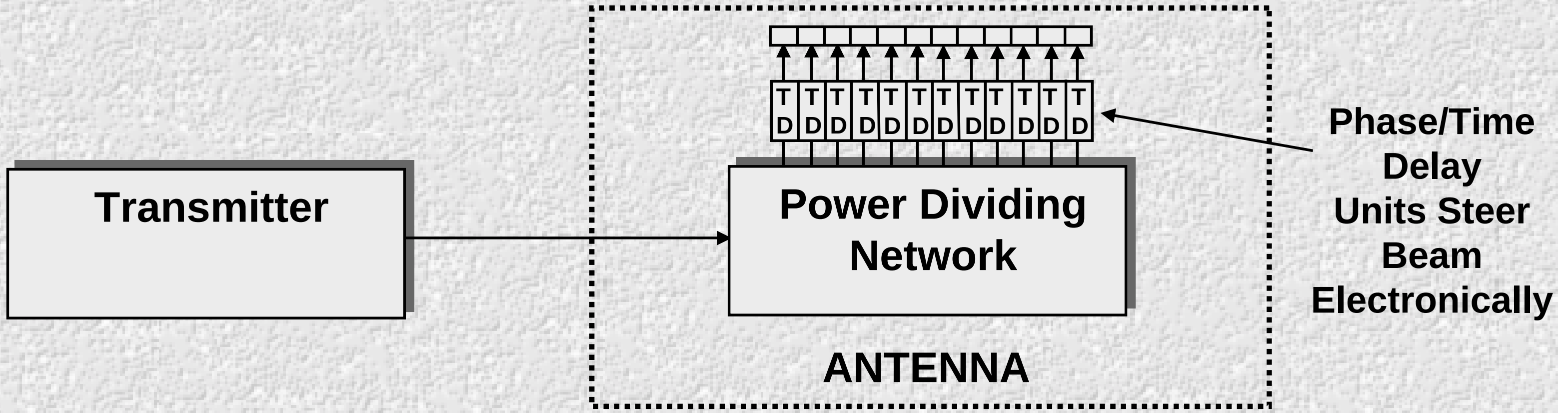


Phased Array/Active Antennas

- Typical Flat Plate Antenna Array

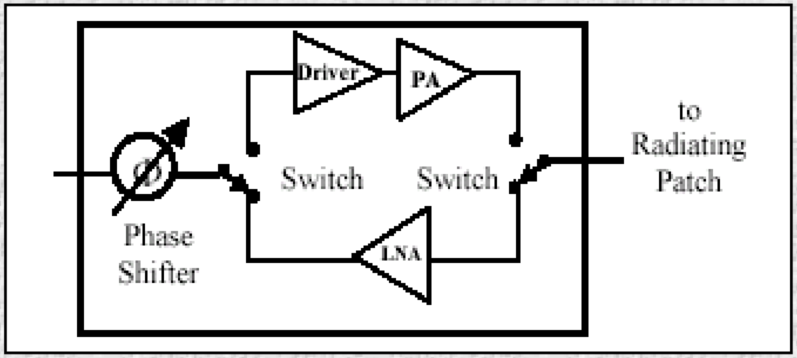


- Electronically Steerable Array (ESA)

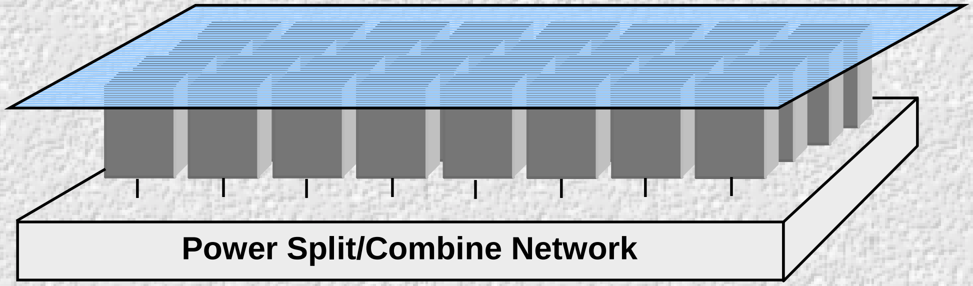


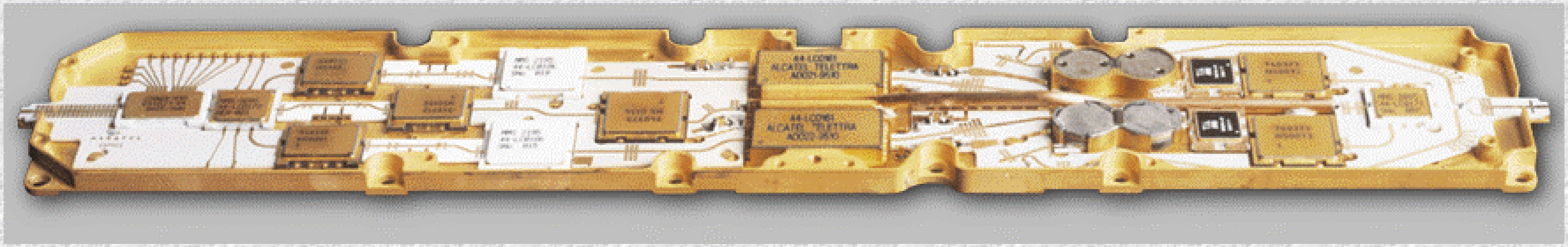
Phased Array/Active Antennas

- Active Antenna
  - Build-up of Transmit/Receive (T/R) modules which integrate a low-power (~ 1 Watt) solid state transmitter, a low-noise amplifier receiver, and a time-delay and/or phase shifter



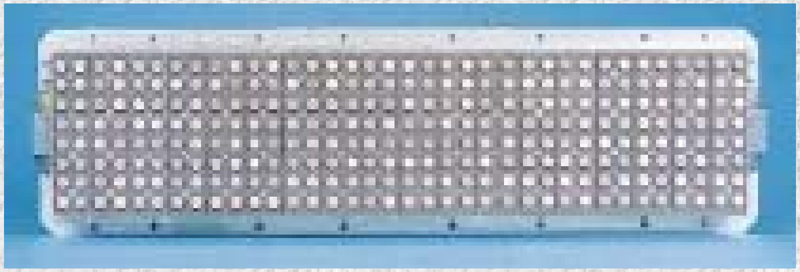
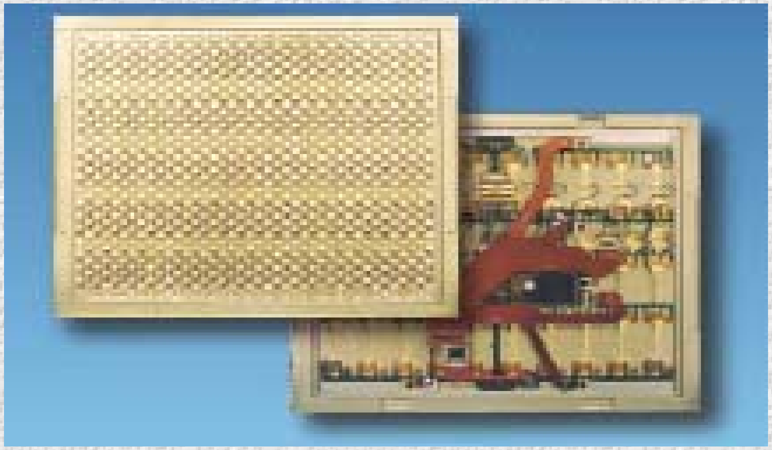
T/R Module Block Diagram





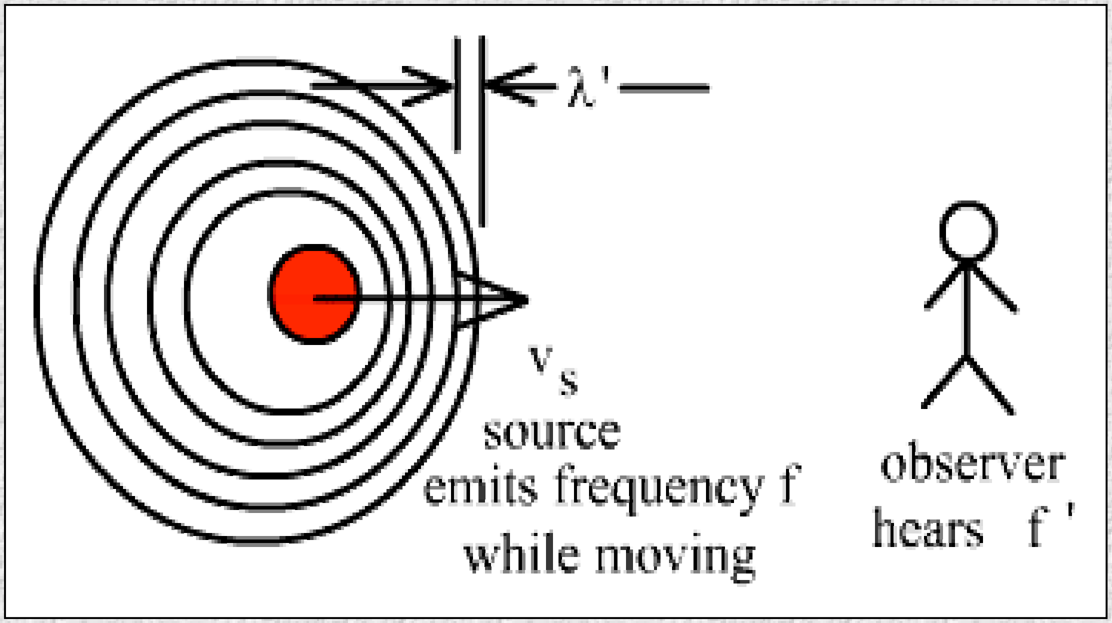
Phased Array/Active Antennas

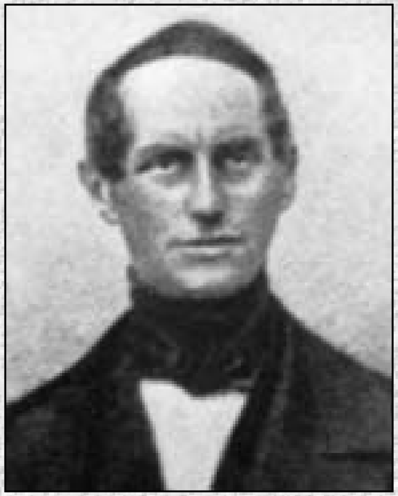


Modern Doppler RADARs

- Doppler effect – First presented by Andreas Christian Doppler in 1842

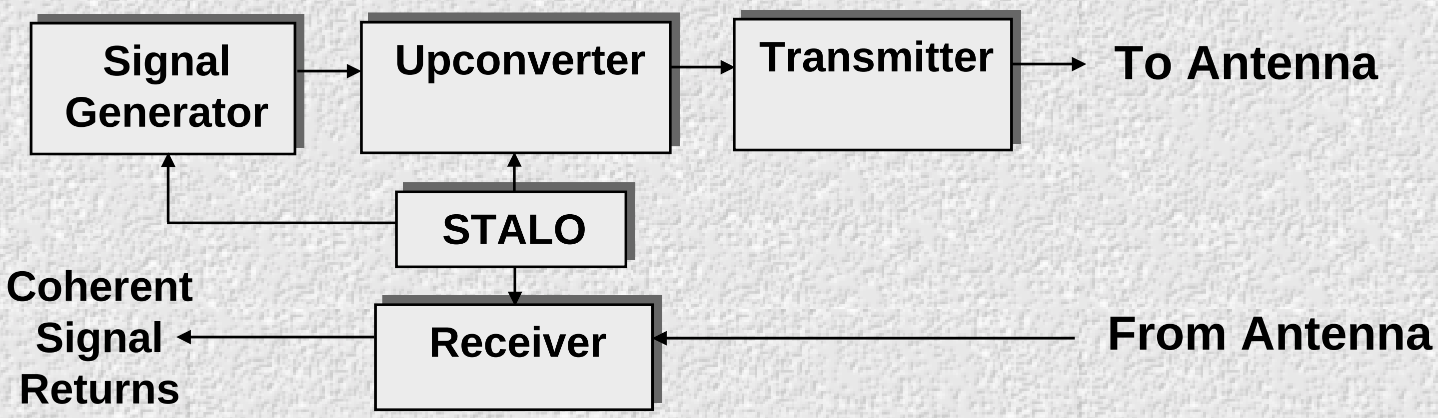




Andreas Doppler

Modern Doppler RADARs

- The Pulse Doppler RADAR:



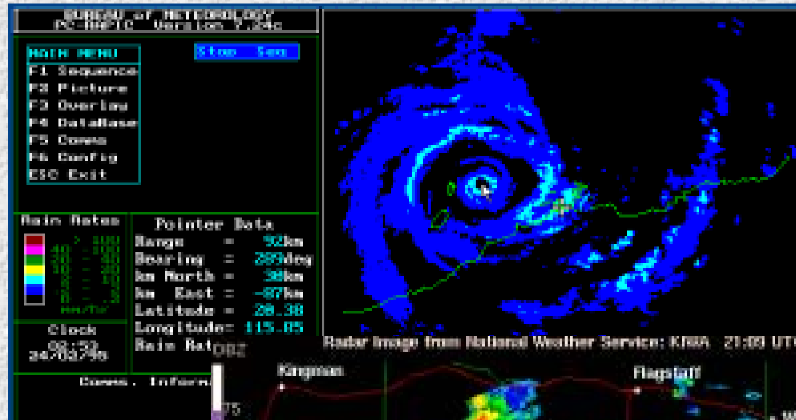
- All timing and operating frequencies are derived from a single source frequency
- The change in phase of a target return from pulse to pulse is a measure of the relative motion between the radar and the target

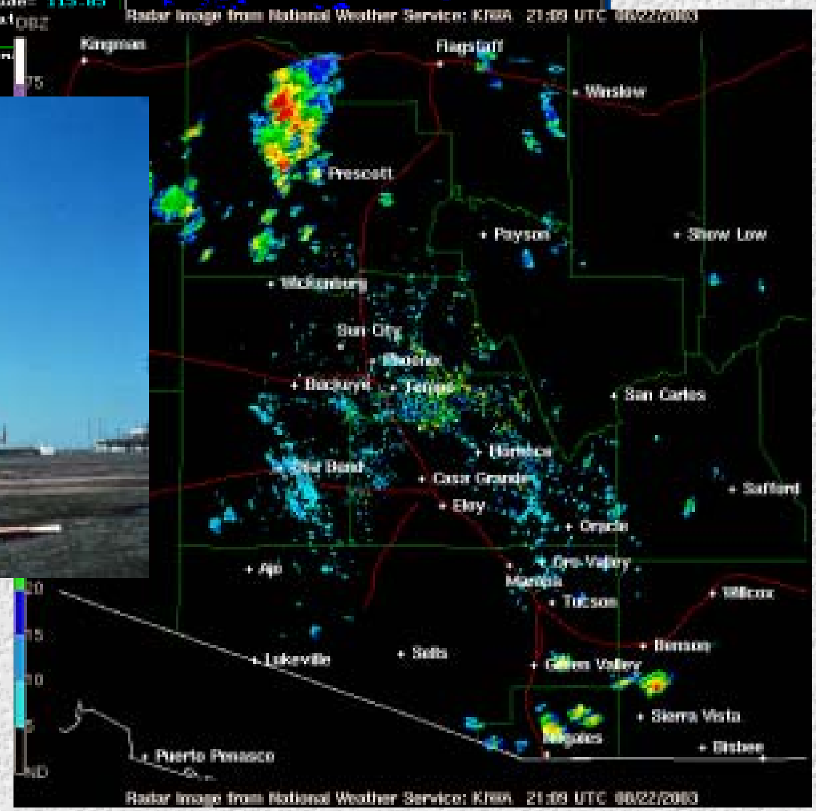
Applications of Pulse Doppler RADARs

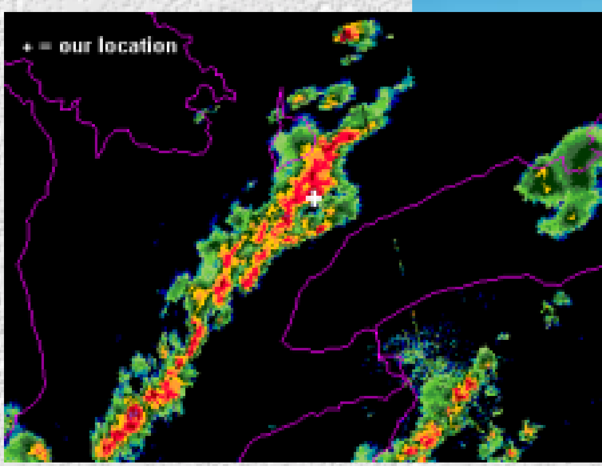
- Radar Guns

Applications of Pulse Doppler RADARs

- Meteorological RADAR

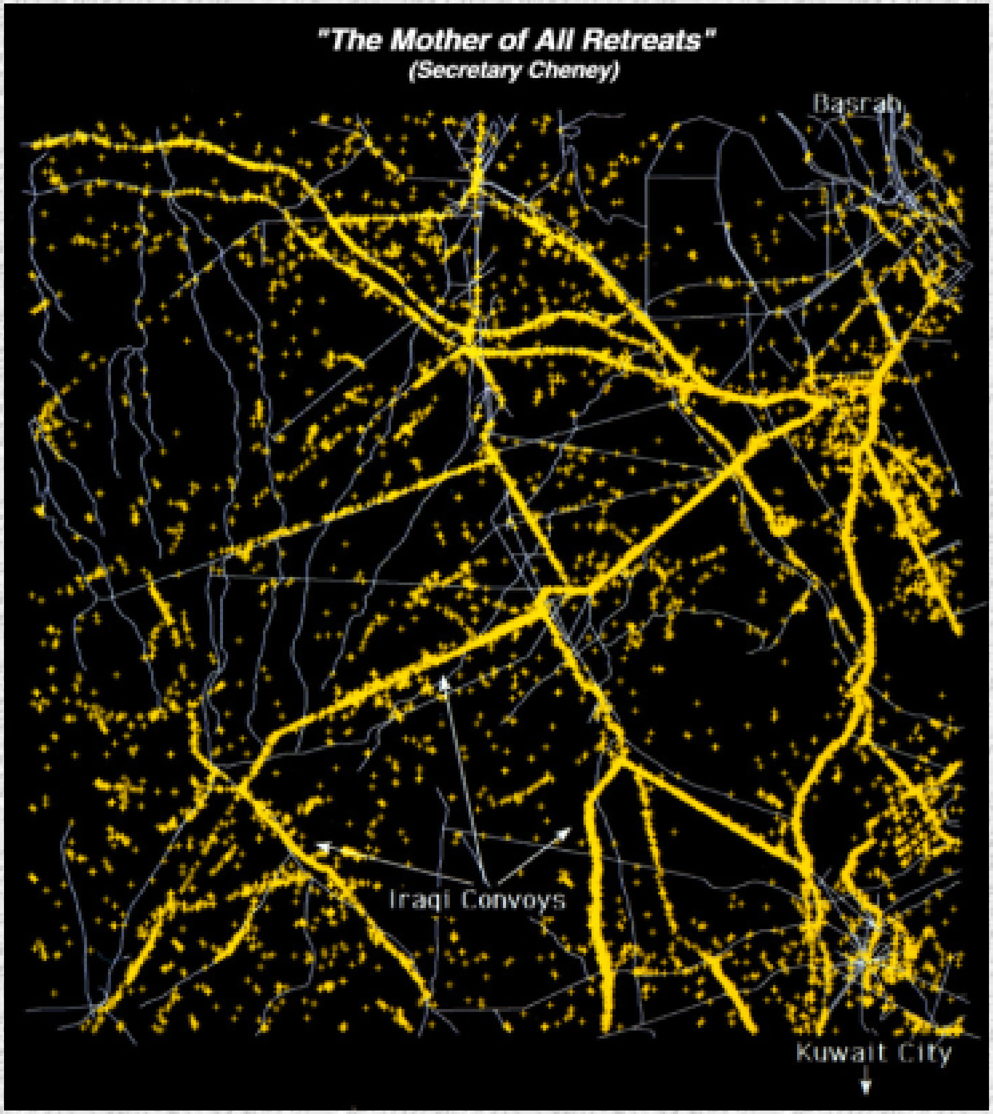






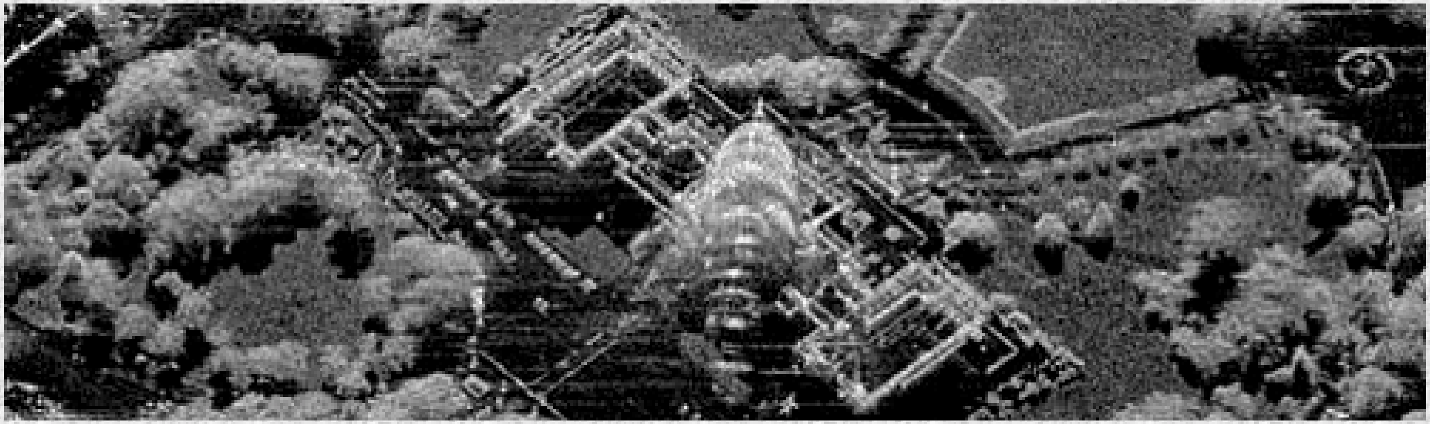
Applications of Pulse Doppler RADARs

- MTI Radar



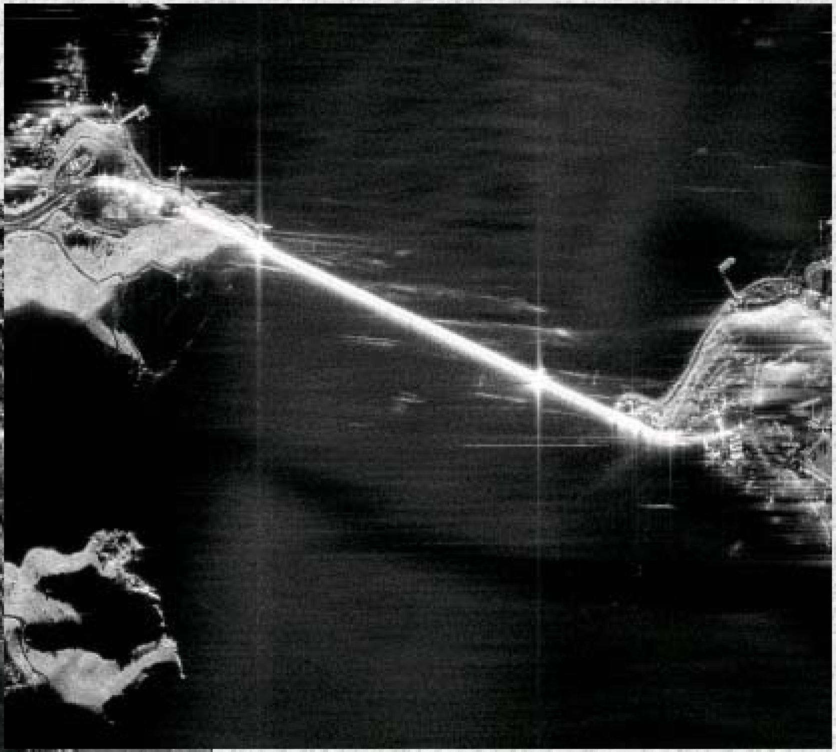
Applications of Pulse Doppler RADARs

- Synthetic Aperture Radar (SAR)



Applications of Pulse Doppler RADARs

- Synthetic Aperture Radar (SAR)



References

"Hertz, Heinrich Rudolph." The Great Idea Finder Web Service.
8 Jan, 2003 <http://www.ideafinder.com/history/inventors/hertz.htm>

"Coulomb, Charles Augustin de." School of Mathematics and Statistics
University of St Andrews, Scotland.
1 Jul, 2000 <http://www-history.mcs.st-andrews.ac.uk/history/Mathematicians/Coulomb.html>

"Volta, Alessandro." The Great Idea Finder Web Service.
7 Jan, 2003 <http://www.ideafinder.com/history/inventors/volta.htm>

"Sketches of a History of Classical Electromagnetism." Jeff Biggus, The HyperJeff Network.
14 Jan, 2002 <http://history.hyperjeff.net/electromagnetism.html>

"Volta, Count Alessandro." Energy Quest Web Service. California Energy Commission.
1 Jan, 2003 <http://www.energyquest.ca.gov/scientists/volta.html>

"Ampere, Andre Marie." Energy Quest Web Service. California Energy Commission.
1 Jan, 2003 <http://www.energyquest.ca.gov/scientists/ampere.html>

References

"Gauss, Johann Carl Friedrich." School of Mathematics and Statistics
University of St Andrews, Scotland.
1 Jul, 2000 <http://www-gap.dcs.st-and.ac.uk/~history/Mathematicians/Gauss.html>

"Gauss, Karl Friedrich." Eric Weisstein's World of Biography. Wolfram Research, Inc. Web Service.
Unknown Date <http://scienceworld.wolfram.com/biography/Gauss.html>

"Gauss, Johann Karl Friedrich." University of Pennsylvania, Dept. of English Web Service.
Unknown Date <http://www.english.upenn.edu/~jlynch/Frank/People/gauss.html>

"Maxwell, James." Eric Weisstein's World of Biography. Wolfram Research, Inc. Web Service.
Unknown Date <http://scienceworld.wolfram.com/biography/Maxwell.html>

"Maxwell, James." Clark Bennett. University of South Dakota, Dept. of Physics Web Service.
Unknown Date <http://www.usd.edu/phys/courses/phys300/gallery/clark/maxwell.html>

"Maxwell, James Clerk." School of Mathematics and Statistics
University of St Andrews, Scotland.
1 Nov, 1997 <http://www-gap.dcs.st-and.ac.uk/~history/Mathematicians/Maxwell.html>

References

"Hertz, Heinrich." Eric Weisstein's World of Biography. Wolfram Research, Inc. Web Service.
Unknown Date <http://scienceworld.wolfram.com/biography/HertzHeinrich.html>

"The Discovery of Radio Waves, Heinrich Hertz." John Jenkins. SparkMuseum Web Service.
Unknown Date <http://www.sparkmuseum.com/HERTZ.HTM>

"Radar." Wikipedia, The Free Encyclopedia Web Service.
23 Aug, 2003 <http://www.wikipedia.org/wiki/Radar>

"Radar Family Tree." Martin Hollmann. Radar World Web Service.
1 Jan, 2001 <http://www.radarworld.org/index.html>

"Radar Personalities, Sir Robert Watson-Watt." Dick Barrett. The Radar Pages Web Service.
18 Dec, 2000 <http://www.radarpages.co.uk/people/watson-watt/watson-watt.htm>

"Watson-Watt, Sir Robert Alexander." Britannica Concise Encyclopedia. Encyclopædia Britannica Premium Web Service.
28 Aug, 2003 <http://www.britannica.com/ebc/article?eu=407727>.

References

"History of Radio Research at Ditton Park." World Data Centre for Solar-Terrestrial Physics Rutherford Appleton Laboratory. Ditton Park Archive Web Service.
1 Jul, 2003 <http://www.dittonpark-archive.rl.ac.uk/histTime.html>

"Parabolic Transmitter." The Marconi Collection. MarconiCalling Web Service.
Unknown Date <http://www.marconicalling.com/museum/html/objects/apparatus/objects-i=1.001-t=3-n=0.html>

"A Look at Early RF Detectors (from Radioactivities, Newsletter of the Argonne Amateur Radio Club, April 2002)" C. Doose. QSL.net Web Service.
1 Apr, 2002 <http://www.qsl.net/w9anl/newsltrs/0204/0204.doc>

"The Coherer." World of Wireless Virtual Web Museum Web Service.
Unknown Date <http://home.luna.nl/~arjan-muil/radio/coherer.html>

"Marconi Magnetic Detector." John Jenkins. SparkMuseum Web Service.
Unknown Date <http://www.sparkmuseum.com/MAGGIE.HTM>

"Radar Equipment." USS Francis M. Robinson (DE-220) Association Web Service.
1 Jan, 2000 <http://www.de220.com/Electronics/Radar/Radar.htm>

References

"The Wizard War: WW2 & The Origins Of Radar." Greg Goebel / In The Public Domain Web Service.
30 Jul, 2003 <http://www.vectorsite.net/ttwiz.html> (and linked pages from this site)

"Interwar Europe." Matthew White. Historical Atlas of the 20th Century Web Service.
1 Feb, 2002 <http://users.erols.com/mwhite28/euro1935.htm>

"Tour the Battlefields of Normandy." Unknown Author.
Unknown Date <http://britmore.bravepages.com/britmore.htm>

"Radio and Television, Timeline." National Academy of Engineering. Great Achievements Web Service.
1 Jan, 2000 <http://www.greatachievements.com/greatachievements/ga_6_3.html>

"A Brief History of Radio." Ian Poole. Radio-Electronics.com Web Service.
Unknown Date <http://www.radio-electronics.com/info/radio_history/radiohist/radio_history.html>

"Surfing the Aether." bchris@northwinds.net. Northwinds.net Web Service.
15 Nov, 2000. <http://www.northwinds.net/bchris/> (and linked pages from this site)

References

"The Chain Home Radar System." Dick Barrett. The Radar Pages Web Service.
18 Dec, 2000 <http://www.radarpages.co.uk/mob/ch/chainhome.htm>

"The Magnetron." C.R. Nave. Georgia State University, HyperPhysics Web Service.
1 Jan, 2000 <http://hyperphysics.phy-astr.gsu.edu/hbase/waves/magnetron.html>

"Valve Receiver Circuitry." Bev Parker. The History of Radio Web Service.
Unknown Date
<http://www.localhistory.scit.wlv.ac.uk/Museum/Engineering/Electronics/history/valvedetails.htm>

"National Weather Service Historical Highlights." STORMFAX, Inc. Web Service.
1 Jan, 2003 <http://www.stormfax.com/history.htm>

"RA-2." European Space Agency Web Service.
Unknown Date <http://envisat.esa.int/instruments/ra2/>

"Introduction to the principles of operation of a satellite radar altimeter and their uses over ice sheets." Cooperative Institute for Research in Environmental Sciences, University of Colorado. CIRES Web Service.
Unknown Date <http://cires.colorado.edu/steffen/classes/geog6181/Bamber/summary.html>

References

“ERS-1 satellite marks a decade of watching Earth.” ESA Press Release. Spaceflight Now Web Service.
18 Jul, 2001 <http://spaceflightnow.com/news/n0107/18ersat10/>

“Doppler, Christian Andreas.” School of Mathematics and Statistics
University of St Andrews, Scotland.
1 Jul, 2000 <http://www-gap.dcs.st-and.ac.uk/~history/Mathematicians/Doppler.html>

“Applications of the Doppler Effect.” W.R. Johanson.
Unknown Date <http://bill-johanson.com/doppler/doppler_basics.htm>

“NEXRAD Doppler Radar.” WeatherSavvy.com Web Service.
Unknown Date <http://www.weathersavvy.com/Doppler.html> (and linked pages from this site)

“Sandia National Laboratories.” Sandia National Laboratories Web Service.
Unknown Date <http://www.sandia.gov/> (and linked pages from this site)