EE3-27: Principles of Classical and Modern Radar

Prelude

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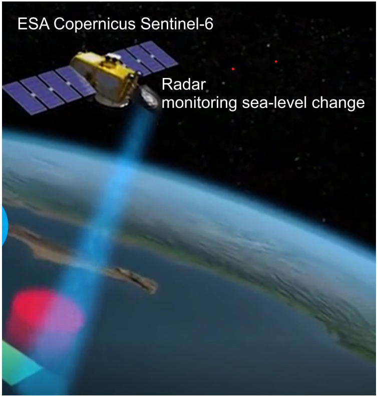


What the Course is About

- The aim of EE3-27 is
  - to give **an overview** of typical classical and modern **radar** systems and **their fundamental and operational principles**

- In particular,
  - to give to our 3rd year students, with little or no previous knowledge of radar systems, a broad understanding of radar systems, subsystem, waveforms and defence/security plus civilian applications.
  - Note: With the deployment of 5G, a radar revolution is also underway with many emerging applications beyond the "defence" and "security" domains/industries.

- This course will provide the fundamentals of classical long-range radar but also the new frontiers of short-range radar for many anticipated "civilian" applications

Useful Connections

- Professor Manikas' web site:
  http://skynet.ee.ic.ac.uk/manikas.html
- Lecture Notes and other course material:
  - Skynet: http://skynet.ee.ic.ac.uk/notes/notes.html
  - Blackboard: https://bb.imperial.ac.uk
  - OneNote - Class Notebook[1]: "Prof A Manikas E327 Radar 2023-24"
  - Microsoft TEAMS: ELEC60031 - Principles of Classical and Modern Radar Systems (Autumn 2023-2024)
- Panopto (video recordings of the Lectures):
  https://imperial.cloud.panopto.eu
  - directory: ELEC60031 - Principles of Classical and Modern Radar Systems (Autumn 2023-2024)

[1] login, online, to "OneDrive Imperial College". Then go to "Class Notebooks" directory where you will find the Course Notebook entitled "Prof A Manikas E327 Radar 2023-24". Open the notebook with OneNote desktop application, pre-installed in your own device (smartphone, iphone, android, iPad, desktop, etc.). You have to do this only once. Then, your device will be automatically synchronised and backed-up.

Coursework and other Important Information

- Coursework = compulsory =100%
  - Radar Assignment = 60%;
    This involves both real and simulated radar received signals
  - MCQ = 40%;
- Examination = $\nexists$ formal examination
- A large number of problems/exercises are available for supporting this course.
- Course GTAs and UTAs:
  - GTA - Ritu Ranjna (r.ranjna23@imperial.ac.uk)
  - UTA - Leo Tsigkounakis (leonidas.tsigkounakis20@imperial.ac.uk)
  - ~~GTA - Nadeem Dar (n.dar20@imperial.ac.uk)~~

Coursework, Course Academic Weeks & Deadlines

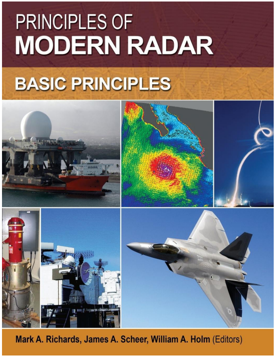
- Table-1 shows the Autum Term academic weeks (A1-A11) and the deadlines of the various parts of the coursework

Table-1 (Academic Year: 2023-24)					
Academic Weeks - Autumn Term			Lectures	Classes	Comments
Week-A1	2 Oct. 2023	8 Oct. 2023	-	-	
Week-A2	9 Oct. 2023	15 Oct. 2023	3h	-	
Week-A3	16 Oct. 2023	22 Oct. 2023	3h	-	
Week-A4	23 Oct. 2023	29 Oct. 2023	3h	-	
Week-A5	30 Oct. 2023	5 Nov. 2023	3h	-	
Week-A6	6 Nov. 2023	12 Nov. 2023	3h	-	
Week-A7	13 Nov. 2023	19 Nov. 2023	3h	-	Publication of the Coursework
Week-A8	20 Nov. 2023	26 Nov. 2023	3h	-	
Week-A9	27 Nov. 2023	3 Dec. 2023	-	3h	
Week-A10	4 Dec. 2023	10 Dec. 2023	-	3h	
Week-A11	11 Dec. 2023	17 Dec. 2023	-	3h	Coursework Deadline: Friday 5:30pm

- N.B. Weeks A2 to A11: for questions and answers please use the *Teams Channel* "Radar Q&A"

Books

- The course is mainly based on the book Principles of Modern Radar: Basic Principles although we will skip several parts of this classically "American" very thick book. However, the reading of this book is nice, there are many illustrations, and not too many equations.



- Note that this book makes frequent reference to military applications. This is natural since it originates from courses partly aimed for US military, but the purpose of EE3-27 is to study the fundamentals of the radar theory and systems, preferably with reference to civilian applications.

- M. A. Richards, J. A. Scheer, and W. A. Holm,
"*Principles of Modern Radar: Basic Principles*".
SciTech Publishing Inc., 2015. (962 pages)

- Merrill Skolnik,
"*Radar Handbook*",
McGraw Hill, Third Edition, 2008 (1352 pages)

- IEEE Signal Processing Magazine,
"*Radar Systems for Modern Civilian Applications, Part 1*",
Vol 36(4), July 2019

- IEEE Signal Processing Magazine,
"*Radar Systems for Modern Civilian Applications, Part 2*",
Vol 36(5), September 2019

- We will also use some supplementary material

E3.27 Learning Outcomes

- To understand the fundamentals of radar and use the radar equations
- To apply the radar theory to various classical and modern radar systems, to classify the various radar architectures and rate their performance.
- To analyse and design the Tx and Rx subsystems of any type of radar system.
- To design radar waveforms and system architectures aiming at improving the solutions of the detection, estimation, tracking and classification of various types of targets/objects/signals in the presence of noise, clutter and interference/jammers.
- N.B.: In this course the terms "targets", "objects", "sources", "emitters" are considered equivalent and will be used interchangeably.

E3.27 Topics

0. **Prelude** ⟵ **[This topic]**

1. **Introductory Concepts**
2. **Radar Fundamentals**
3. **Target Reflectivity & EM-Waves Refresher**
4. **Radar Cross Section (RCS) and Radar Clutter**
5. **Target Detectability, Estimation and Classification**
6. **CW and FMCW Radar**
7. **Bistatic Radar**
8. **Phased-Array Radar**
9. **MIMO Radar**
10. **Other Modern Radar (Passive Radar, OFDM Radar, Cognitive Radar, UWB Radar, Synthetic Aperture Radar)**

Basic Symbols

t	time (variable)	sec
T_p	pulse duration	sec
T_c	chip or compression pulse duration	sec
τ	delay	sec
T_{scan}	scanning time	sec
$R_{xx}(\tau)$	Autocorrelation function	
f	frequency (variable)	Hz
F_c	carrier frequency	Hz
B	Radar bandwidth	Hz
B_{fr}	Radar fractional bandwidth	Hz
$\mathrm{PSD}(f)$	double-sided power spectral density of the radar signal	W/Hz
c	velocity of light	m/sec
R	range or distance from radar	m
ΔR	relative range (or relative distance)	m

Notation

a, A	Scalar
$\underline{a}$, $\underline{A}$	Column Vector
$\mathbb{A}$, $\mathbf{r}$	Matrix
$\|A\|$	Absolute value
$\|\|\underline{A}\|\|$	Euclidian norm of vector
$\|\|\mathbb{A}\|\|$	Frobenius norm of matrix
$\underline{A}^b$	Element by element power
$\exp(\underline{A})$	Element by element exponential of vector $\underline{A}$
$\odot$	Hadamard product
$\oslash$	Hadamard division
$\otimes$	Kronecker product
$\mathbb{I}_N$	Identity matrix $(N \times N)$
$\underline{1}_N, \underline{0}_N$	$N \times 1$ vector of all ones (all zeros)
$\mathbb{O}_{N \times M}$	$N \times M$ matrix of zeros
$\exists, \nexists$	exists (or there is), does not exist (or there is not)
$\in, \ni$	in, ni ("in" in the opposite direction)
$\Longleftrightarrow$	equivalent
$\triangleq$	definition
∞	infinity

Abbreviations

Radar	**R**adio **D**etection **A**nd **R**anging
Tx	Transmitter
Rx	Receiver
N.B.	Nota Bene: "special attention should be given" or "note"
pdf	probability density function
PSD	Power Spectral Density
AWGN	additive white Gaussian noise
DOA	Direction of Arrival
DOD	Direction of Departure
CW	Continuous Wave
RCS	Radar Cross Section
PRI	Pulse Repetition Interval
PRF	Pulse Repetition Frequency
CW	Continuous Wave
ECM	Electronic Countermeasure
OTH-radar	Over-the-horizon radar
JETDS	Joint Electronics Type Designation
ITU	International Telecommunications Union
SAR	Synthetic Aperture Radar

Time and Frequency Domains[2]

	Time Domain (t)	Transformation	Frequency Domain (f)
var	t		f
signal	$x(t)$	$\xrightarrow{\text{Fourier Transform}}$	$X(f)$
signal	$R_{xx}(\tau)$	$\xrightarrow{\text{Fourier Transform}}$	$\text{PSD}_x(f)$
system	$h(t)$=impulse response	$\xrightarrow{\text{Fourier Transform}}$	$H(f)$=Transfer function

- Frequency Domain (spectrum) is very important in Wireless Systems (like Radar)

[2] see Appendix-B for Fourier Transform Tables

How Radar Works - A Very Short Answer!

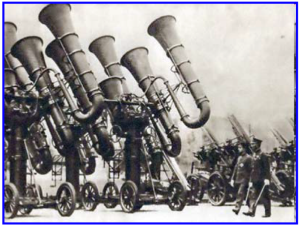
Things are very complex ... but a very simple and short answer could be:

- RADAR transmits a known signal which is radiated in the form of Electromagnetic Energy from the Tx's antenna to propagate in space.
- Some of the radiated energy is intercepted by a reflected object (usually known as target) located at a distance from the radar.
- The energy intercepted by the target is re-radiated in many directions.
- Some of the re-radiated energy (echo) is received by the radar's Rx antenna.
- After amplification by a Rx and with the aid of proper signal processing, a decision is made as to whether or not a target echo signal is present.
  - At that time, study the target and acquire the target location and possibly other information about the target.

- In 1903 a German engineer by the name of Hulsmeyer (a German engineer) experimented with the detection of radio waves reflected from ships. He obtained a patent in 1904 in several countries for radio waves reflected from ships as shown below:

Hulsmeyer

Japanese Acoustic Detection System

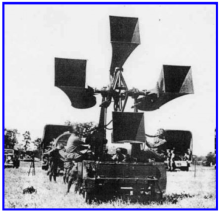


Courtesy of Wikimedia

- Developed and used in first half of 20th century
- Attributes
  - Limited Range
    approximately 10+ miles
  - Limited field of view
  - Ambient background noise limited (weather, etc)
- Used with searchlights at night

US Acoustic Detection Systems

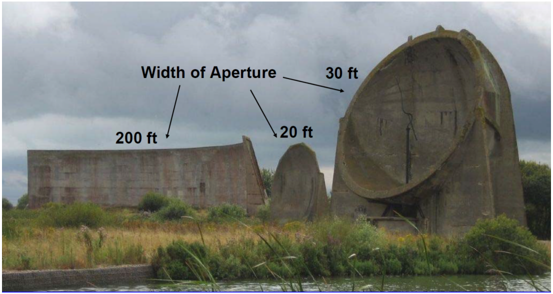
Courtesy of US Army Signal Corps.



Courtesy of US Army Signal Corps.

History - Pro-Radar Era

Sound Mirrors Dunge, Kent, UK



- Used for aircraft detection (pre-World War II)
- Short detection range (less than 15 miles)
  - Tactically useful for detecting slow WW1 Zeppelins
  - Not useful for detecting faster WW2 German bombers

History - The Early Days of Radar: 3 Milestones

Three main milestones in the early days of radar

M1: Sir Robert Watson-Watt

- Considered by many "the inventor of radar"
- Significant early work occurred in many other countries, including the United States (1920s and 1930s)
- After experimental verification of the principles, Watson-Watt was granted a patent in 1935
- Leader in the development of the Chain Home radar systems
  - ★ Chain Home, Chain Home Low
  - ★ Ground Control Intercept and Airborne Intercept Radar

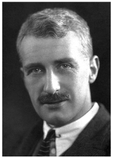
M2: “Tizard Mission” (British Technical & Scientific Mission to US)

- Seven British radar experts and a “Black Box” sent to US in 1940
- The "Black Box" contained cavity magnetron and “nearly everything Britain knew about radar”
- Possession of cavity magnetron technology was critical to Allied war radar development

TIZARD COMMITTEE

Sir Henry Tizard
chairman
(Imperial College)

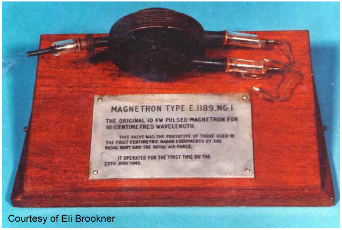
Prof Patrick Blackett
Prof of Physics
(Imperial College)



Prof Archibald V Hill
Prof of Physiology

Harry Egerton Wimperis
Director Scientific Research
Air Ministry

A.P Rowe
Secretary to Committee



Courtesy of Eli Brookner

Figure: cavity magnetron.

M3: MIT Radiation Laboratory (operated between 1940 & 1945)

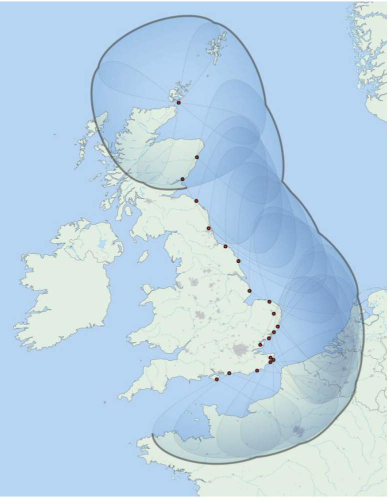
- Exploited British 10 cm cavity magnetron invention (see M2)
- Developed advanced radar systems for war use
- Grew to almost 4000 persons (9 received the Nobel Prize)
- Designed almost half of the radars deployed in World War II
- Created over 100 different radar systems ($1.5B worth of radar)

History - The Early Days of Radar: Chain Home Radar

Chain Home Low Antenna

Chain Home Low Transmitter

- **Twenty four Chain Home Low radar's were added to fill coverage gaps at low elevation angles (< 2°)**
  - **Their low frequency 200 MHz lessened multipath lobing effects relative to Chain Home (20-30 MHz)**
- **Detection range 25 mi at 500 ft**



- The Chain Home Radar (A network of Early Warning Radar Sites)
  - British "Force Multiplier" during the Battle of Britain"
- Timely warning of direction and size of German aircraft attacks allowed British to
  - Focus their limited numbers of interceptor aircraft
  - Achieve numerical parity with the attacking German aircraft
- Effect of Radar on the War
  - Germany was unable to achieve Air Superiority
  - Invasion of Great Britain was postponed indefinitely

History - Nowadays Radar

RADAR, is a classical subject, which constantly find new applications
Nowadays $\exists$ a wide range of radar applications, including (to mention but a few):

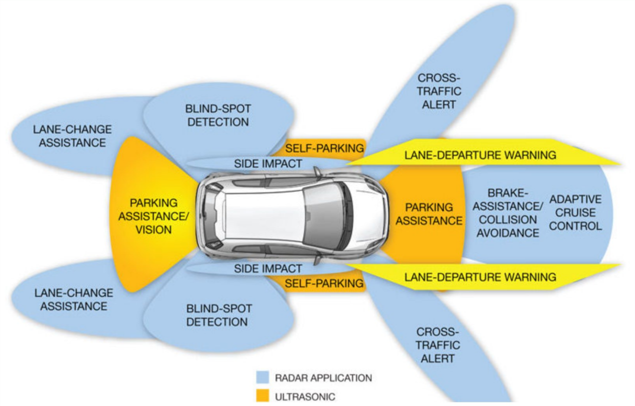
- collision avoidance systems in modern cars,
- robotics and industry automation,
- biomedical applications and remote sensing,
- health care,
- archeology,
- emerging AgTech (Technology in Agriculture) radar,
- weather forecasting,
- remote piloted civilian drones,
- automated driving (automotive radar).
- For a list of 100 radar applications, see Appendix-A.

  http://lidarradar.com/apps/100-radar-uses-or-applications

  - https://atap.google.com/soli/

Example (Automotive Radar)

- Many cars are equipped with advanced assistance systems (ADASs) for highly automated driving (HAD). The performance and reliability of these systems strongly depend on the ability of the radar to sense the environment. For instance, the blue areas below, denote radar employment in future driveless cars



Example (cont.)

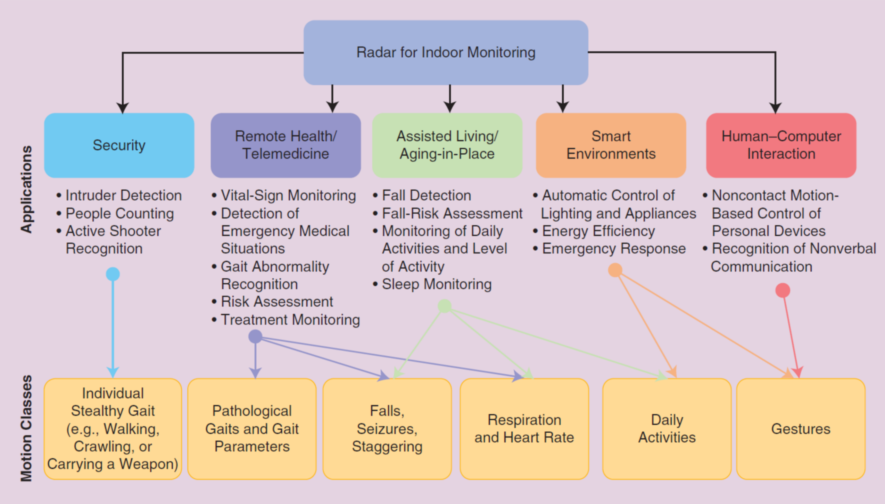
- Note: Radar technology is far more important for HAD than alternative technologies, such as cameras and lidar.
- Long-range radar systems for forward-looking functions especially developed for HAD are commercially available and widely used today. Radar is typically used in current ADASs, such as adaptive cruise control, forward collision avoidance, lane change assist, to name but a few .
- Radar works reliably in bad weather and lighting conditions; can provide accurate and direct measurements of range, relative velocity, and angle of multiple targets; and can provide a high range coverage. Fully autonomous cars of the future will rely on the great capabilities of radar, but the demands by automobile manufacturers on sensor reliability are very high with the goal of reaching the zero-casualties objective.

History - Promising Future of Radar Technology

1. Automotive radar
   - Long & short, backward & forward looking radar for highly automated driving
2. Radar for in-cabin observation
   - Benefits: cost-effective compared with stereo camera; observe the entire cabin; see through things that block the camera's view; cannot provide details of people's faces thus ensuring privacy.
3. Radar for countering drones
4. Radar for earth monitoring
   - Satellite radar can see invisible changes in groundwater levels
5. Metamaterial Radar for delivery drones
   - Delivery drones require light, small-sized, affordable radar as it provides all-weather sensing, long-range and high-resolution
6. Indoor radar (see next slide), e.g. household radar
   - Sense a person's breathing and heart rate
7. Radar for smartwatch gesture recognition
   - Radar detects motion even when the smartwatch has been blocked by sleeve. 145 GHz Radar can take advantage of a full 10 GHz of bandwidth and leads to millimetre-scale resolution.

History - Promising Future of Radar Technology (cont.)

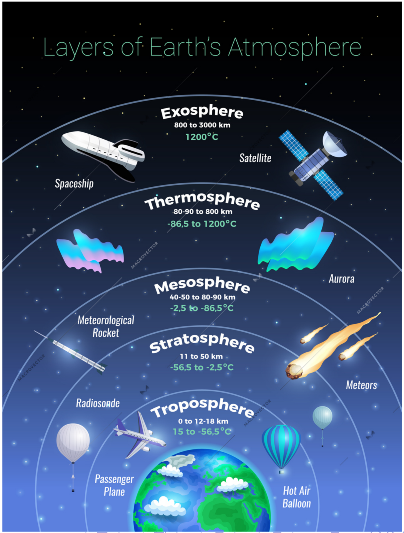
Radar for Indoor Monitoring



Three Broad Types of Radar Systems

1. spaceborne[a] radar: >100km
2. airborne[b] radar: <100km[c]
3. ground based radar
   - outdoor
   - indoor

- N.B.: Radar can be mounted on fixed or moving platforms

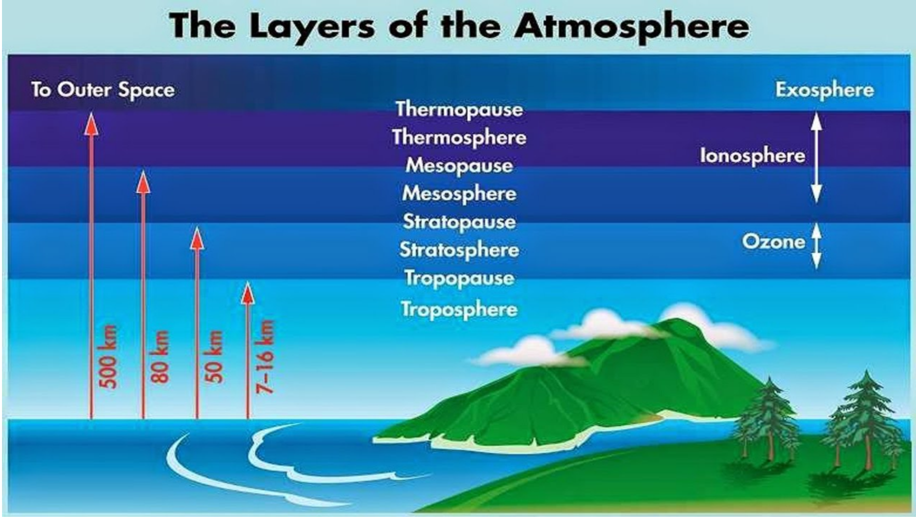


[a] dictionary "spaceborne: operating in or involving equipment operating in outer space"

[b] dictionary: "airborne: carried by or through the air; transported in aircraft, in flight; flying.

[c] 100km = Karman Line

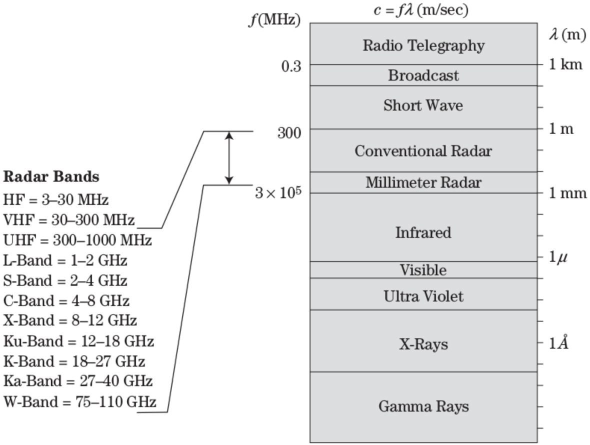
Types of Radar Systems (cont.)



Examples

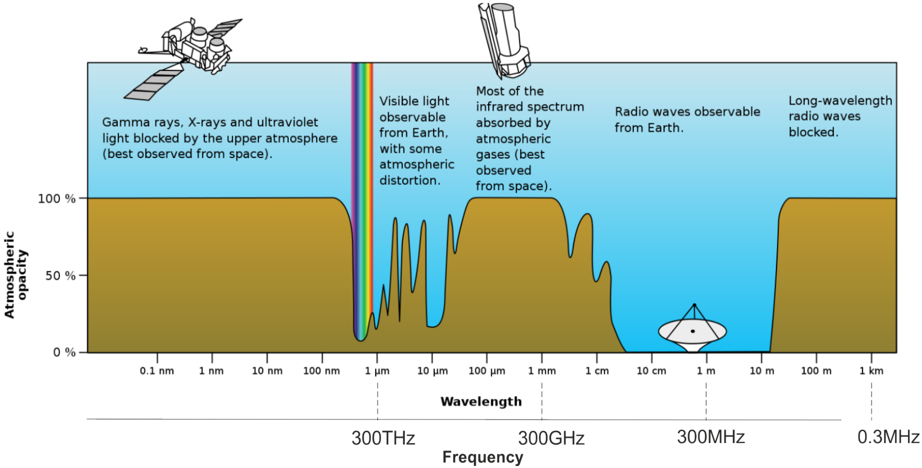
Radar	Ground Based	Automotive, Collision Avoidance Systems
		Ground Penetrating Radar for geology, gas pipe detection, mine detection, archeology
	[redacted]	
	Spaceborne	Astronomy
		Space-borne altimetry
		Space-borne remote sensing (crop, hydrology, geodesy, archaeology, astronomy, defence)
		SAR (Synthetic Aperture Radar) imaging
		Planetary exploration
		Acquisition and tracking of satellites in the re-entry phase, monitoring of space debris.

Radar Frequency Bands (Spectrum)



- Typical radar applications can be found from a few MHz to a few 100GHz (i.e. wavelength $\lambda = [100\text{m} - 1\text{mm}]$).

Opacity of the Atmosphere vs Frequency



- Windows of transparency are available in the electromagnetic spectrum (NASA).

Summary - Main Properties and Advantages

Radar:

- can work in the entire frequency spectrum from MHz to THz;
- dimensions (antenna included): can go from very small (centimeters) to large (tens of meters);
- emitted power: from a few watts to tens of megawatts;
- cost: from a few hundred of £ to millions of £;
- are generally used as outdoor "sensors", but the safety, reliability, portability, and affordability of small radar devices have made them prime candidates for also being used as indoor sensors inside office buildings, hospitals, homes, and schools. In this last scenario, radar possesses unique advantages that complement other sensors, e.g., those that are visual, infrared, or wearable;

Summary - Main Properties and Advantages (cont.)

- Radar is a noncontact device that is insensitive to lighting conditions
- Radar signals are capable of penetrating opaque objects, such as tables or walls, protecting the privacy of the individuals being monitored.
- In essence, radar backscattering signals can reveal human motion independent of clothing, making it ideal for sensitive environments, such as hospitals, assisted living facilities, restrooms, and bedrooms, where people would not be comfortable placing video cameras.
- Whatever the application and the platform, radar systems have the advantage of being used in
  - all weather and light conditions, meaning they can function without interruption or large losses in the quality of service all day and throughout the year.

Conclusion

Depending on the

- application,
- size,
- cost, and
- expected performance,

radar systems require

sophisticated comms and signal processing techniques

to extract the necessary information from the observed data that are corrupted by the various kinds of disturbances embedding the useful signal.

Appendix-A: 100 Radar Applications/Uses

1	Detection and search	Radar can be used in early warning systems to detect objects in the air such as surface to air missiles by the military.
2	Missile guidance	Radar is used to guide missiles and other weaponry to specific targets across over a long distance
3	Biological research	It is used to track birds and insects to trace their migration. This is also important in keeping the birds out of flight paths with an aim of preventing potential crushes by airplanes
4	Air traffic control radar	This is used to monitor and guide airplanes in the air and at airports
5	Weather sensing radar	These are used to monitor the weather patterns such as wind direction and the amount of precipitation.
6	Space probes	They use radar signals to study the composition of the planets and objects they come across.
7	Storm forecasting	Meteorologists use radar signals to track and forecast storms and hurricanes
8	Radio telescope arrays	This technology uses radar to study distant celestial bodies and to gather information regarding these bodies that help researchers to make decisions.
9	Vessel tracking	Naval vessels use radar to track other vessels and their respective positions and avoid potential collision.
10	Aircraft collision avoidance	Aircrafts are also equipped with radar to ensure they detect other aircrafts and avoid collision in mid-air.
11	Aircraft landing	Radar signals can be used by air traffic controllers to help in landing an airplane on a runway that has poor visibility caused by fog and mist.
12	Military usage	Large military aircrafts carry radar signals to help in detecting other planes and objects in the air.
13	Measuring vessel distance	Marine radar is also used to measure the distance between two vessels for identification and for collision avoidance
14	Vessel traffic radar	These are used in ports or harbors for the purposes of monitoring and regulating ship movements in busy sea waters
15	Geology	Geologists have used specialized ground penetrating radar to study the composition of the earth's crust.
16	Speed radar	These are used by police officers on the roads to monitor the speeds of vehicles on these roads and potentially arrest over-speeding drivers
17	Traffic radar	These are used by police and other traffic marshals to monitor the traffic situation on roads and advise motorists accordingly
18	Biological radar	These are mainly used to detect human body movements such as heart movements, finger gestures and sleep patterns.
19	Door opening	Some automated doors employ the use of radar signals to send instructions to the door to open or close
20	Light activation	Automated light switching use radar signals to switch the bulbs on or off.
21	Movement detection	Radar signals are also used by security firms and other installments to detect movements within a building or in a room and activate alarms
22	Vehicle anti-Collison systems	Most modern vehicles have employed the use of radar signals to detect other object within a distance of 30 meters and trigger a warning to the driver of possible collision.
23	Vehicle parking assistance	Modern vehicles are designed with automatic parking assistance that gives your car the ability to self-park without instructions from the driver. This technology uses radar signals to detect objects and avoid collision
24	Ground analysis	Radar signals are used in geophysics to study the ground and create soil profiles by researchers
25	Radar imaging	Radar is also used in airports and other military installments to see through walls and other surfaces for the purposes of finding concealed weapons.
26	Civil engineering	Radar is used to detect water supply lines and power cables that run through walls in the event that one needs to drill through the wall. Instead of drilling through the unseen cables and supply lines, radar devices are scanned over the area to map out where the lines run through.
27	Surface topography	Radar signals are used to map out the surface topography of an area. Through radar imaging, the data sent from the surface after reflection is transferred in form of an image and this helps in creating the topography of the surface
28	Crustal change	Geologists rely on radar equipment to measure and track the change in the crustal structure and form and use this data to detect and forecast the possibility of an earthquake or the magnitude of the earthquake to be expected.
29	Land use monitoring	Researchers rely on radar imaging equipment to track and monitor the use of land through 3D mapping. The data relayed will show the demarcation of the land and how it has been used.
30	Environmental monitoring	Radar signals are used by environmentalists to monitor the environment and gather data on environmental degradation and other activities on the environment.

31	Soil moisture measurement	The moisture of soil is an important factor in determining the capability of the soil to grow crops. Radar remote sensing can penetrate vegetation and the soil to measure the quantity of the moisture in the soil.
32	Mapping forest cover	Radar technology is also used to map out the extent of forest cover together with other forest attributes such as tee height, quality and canopy structure.
33	Mapping wetlands	Scientists and other researchers use radar remote sensing to map out wetlands such as flooded and non-flooded areas.
34	Monitoring photosynthetic processes	Advanced radar detection systems are used to monitor photosynthetic processes in forests such as the potential length of trees during the growing season.
35	Crop classification	The multi-surface reflection ability of radarremote sensing is important in classifying the crops and types of crops on a farm. This technology allows researchers to identify the type of crops based on factors such as the nature of the leaves and the height of the crops.
36	Crop acreage estimation	Radar signals are used to collect data on crops that would show the estimation of the vastness of the crop cover over an area. Using this data, researchers can be able to tell the exact or near exact acreage of a crop.
37	Crop condition detection	Radar signals can collect data on crops using factors such as crop canopy and crop height to provide information on the overall condition of crops in an area.
38	Identification of planting and harvesting dates	An important agricultural use of radar signals is the identification of the harvesting dates of crops based on the nature of the crops. This data can also be used to identify the planting dates for the next season.
39	Crop yield modelling and estimation	Radar remote sensing can also be used to make an estimation of the expected crop yields over a period of time based on data such as the health and quality of the crop.
40	Identification of pests and diseases	Radar remote sensing can also be used to monitor the crop for signs of pests and diseases and provide this information for the benefit of the farmer. This technology has already been used in South Korea.
41	Drought monitoring	Meteorologists use radar remote sensing to track patterns of drought and record them and then use the data to forecast any potential drought occurrence. This data can then be used to devise mitigation plans.
42	Land cover and land degradation mapping	Radar is also instrumental in mapping out land cover over an area. This information is crucial in determining the nature and quantity of land cover and the extent of land degradation.
43	Identification of problematic soil	Radar remote sensors are also used in the profiling of soils and separating quality soils from problematic soils. This helps in ensuring the soils used for crop production remain of high quality.
44	Measuring of sea state	Radar altimeters are used to measure the height of waves in the sea during storms and during calm. The information is later used to advise sea farers on the nature of the sea and its safety.
45	Measuring ocean topography	Radar signals through radar altimeters are used to measure the ocean topography and the resultant differences in sea level
46	Climate monitoring	Radar remote sensing is also used to monitor the different climatic conditions over long periods of time on the earth's surface
47	Detection of oil spills	Radar remote sensing is also used in detection of oil spills over the sea surface. Initially, these spills were monitored using very expensive equipment that were time consuming. Radar remote sensing is not only affordable especially if performed over a wide area but it is also time saving.
48	Basin screening of Natural oil seepage	Radar remote sensing is important in the detection of oil spillage from the sea basin and help in identifying potential oil deposits from the sea basin
49	Identification of minerals	Radar signals through 2D and 3D imaging is important in identifying the mineral deposits from the soil and even estimating the amount available
50	Map compiling and updating	Radar remote sensing is used to continuously map land surfaces and marine environment and updating the existing maps
51	Mapping the ocean	Thanks to radar systems and technology, the ocean are no longer mysterious in the world today. We can now get 3D imaging of the ocean depths and understand what exactly lives there.
52	Ground mapping	Radar signals has enabled us to see the ground from above in a totally different dimension. We can now be able to see what happens in areas which were reviously inaccessible.
53	Climate comparison	Radar technology is also useful in detecting climatic conditions and changes in these conditions. The data can also be used to make comparison between various areas
54	Tracking global phenomena	Thanks to Radar remote sensing, we are now able to access data that provide information on global phenomena such as migratory patterns of animals and so on
55	Early warning signs	Radar remote sensing has been used extensively by researchers to obtain early warning signs of famine and other adverse weather patterns that are likely to affect human population

56	Assessing parks' biodiversity	Radar remote sensing data can be used to assess the biodiversity in parks and to weed out intruding species and detect other risks such as forest fires that could be harmful to the animals.
57	Identification of ground water	Radar sensing is also used to identify locations that have ground water and mapping these locations for services such as drilling of wells and other uses.
58	Observation of population growth	Advance radar remote sensors are instrumental in monitoring population change of an area over a period of time. This is done by monitoring land use and changes in land use over time
59	Monitoring of biodiversity	Radar is also being developed to help keep track of the biodiversity of an area through remote sensing
60	Measuring the rise of sea level	Radar remote sensing is used to measure the rise of sea level caused by several factors among them global warming
61	Detection of archeological sites	Radar sensors are also used to detect archeological fossils from beneath the earth surface which help in discovery of fossils for the study of human history
62	Pinpointing location on earth	One of the most important use of radar data is the pinpointing of positions on earth. Radar can be used to determine the exact position of an object on the surface.
63	Population mapping	Radar signals are used in mapping of populations over a given geographical area. This data shows population statistics such as poverty levels and population density.
64	Tracking potential hazards	Radar data can also be used to predict a variety of potential hazards and help in preparation of special response over time.
65	Tracking sediments into rivers	Radar remote sensing is important in tracking where the sediments that float on flowing water end up and what can be done to reduce their effects on aquatic life.
66	Precision farming	Radar data is also important in precision farming where a specific farmland is prepared for the growth of a particular crop with predetermined crop yields.
67	Controlling deforestation	Radar data is also useful in tracking forest activities that include felling of trees for logging. This helps the authorities keep track of the activities in the forest and hence preventing deforestation and environmental degradation.
68	Search and rescue	Radar technology has also been instrumental in the search and rescue mission where the radar remote sensors help in mapping an area and identifying the objects in the area
69	Road mapping	Radar technology also comes in handy when mapping roads to help identify areas where the road might be in need of repair. This way, contractors and governments are able to offer services to the public at very low costs.
70	Aerial view of property	Sometimes when purchasing property, the buyer wants to see an overall view of the property from above and its surroundings. Radar technology has enabled this through the use of things such as RC drones for aerial photography.
71	Monitoring of volcanoes	Radar remote sensors such as thermal imaging is important in studying and monitoring the activities of volcanoes and their potential eruption in order to save millions of lives.
72	Monitoring potential landslides	Countries like japan have invested in thermal imaging and other radar technology solutions to predict things such as earthquakes and landslides and prevent fatalities in case they happen.
73	Fishing	Radar technology can also be used in detecting areas in the sea or ocean where there is fish hence saving fishermen time and resources in real time when fishing
74	Preventing disease migration	Disease migration can also be controlled through usage of radar technology that tracks migration of people from one place to another.
75	Getting distance between two points	Radar technology is used to calculate distances between two points on the earth surface. This helps in estimating the time taken to move between the two points.
76	Assessing ground damage	Radar remote sensors come in handy when people want to assess the damage done on land by a disaster such as land. They are able to tell how much of the land can be reclaimed and how much has been damaged for good.
77	Military weapon targeting	Radar is used extensively on the military in areas such as weapon targeting where the weapon is targeted at a specific object and the damage is assessed after the hit.
78	Mapping enemy locations	Military personnel and strategists use radar to map out the locations of enemy hideouts and help in targeting missiles and other weapons in those locations.
79	Planetary observation	Radar is also used in planetary observation where data regarding different planets is collected and assessed to get the exact location and condition of the planet.
80	Sea ice mapping	Radar is also used to map the extent of sea ice and to monitor the rate at which the ice is melting and contributing to the rise in sea level.

81	Mapping rain regions	Radar technology is also important in helping airport personnel in mapping rain regions in the area around the airport with the aim of reducing the risk of flight accidents at the airport.
82	Vehicular warning	Some vehicles are fitted with radar detectors that help in triggering a warning when a collision is imminent or when there is an object in a blind area that the driver cannot see
83	Terrain avoidance	Military planes that fly low rely on terrain avoidance feature to help them avoid collision with high grounds such as mountains and also with other objects within the path of the airplane.
84	Ship safety	Radar technology is also found in ships and other sea vessels to help in detecting other vessels in the sea when they are in need of help. The radar will provide the distance and probable location of the next ship and help in calling for help when they are in need.
85	Space vehicles	Radar has been used by space vehicles for the longest time now. Most space ships rely on radar for clocking and for landing on the moon.
86	Satellite tracking	Some ground based radar are important in detecting satellites in space and also detecting other objects from the ground. This helps ground personnel in knowing how many satellites are in space and how many are actively relaying data.
87	Non-contact measurement of sp	One of the main uses of radar technology is the measurement of speed and distance. It can be used to independently calculate the speed and distance between two moving objects.
88	Cemetery and grave location	Radar imaging services are used to detect areas that need to be used as grave sites. This is because they are able to detect objects that are beneath the earth surface and tell whether an area is conducive for use as a cemetery.
89	Location of buried objects	Although not advanced, research is still being conducted on the possibility of using radar to detect objects or even bodies that are buried beneath the ground by criminals.
90	Bedrock studies	Radar 3D imaging is important in the study of bedrocks underlying the earth's surface. Geologists have been able to employ the use of radar technology to gather information regarding the structure of the rocks and the shifts in these structures.
91	Border surveillance	Instead of having security personnel lined up at the border posting along borders, countries are now using radar technology to provide surveillance services along these borderlines and reporting of any intrusion if there is any.
92	Cruise control	Modern cars are fitted with cruise control technology that allows the vehicle to cruise at a specific speed while sensing other potential objects on the road. When the vehicle senses an object on the road, it will automatically trigger an alarm and in some cases activate its braking system.
93	Medical diagnosis	Radar technology is also being used in hospitals for disease diagnosis. The technology is used to scan body vitals and tell the doctors which organs have a problem in the body.
94	Detection of meteors	Radar sensors are used in the detection of meteors in space and help in tracking their movements and potentially avoid any catastrophic landing on earth that would cause harm to humans.
95	Mine inspection	Radar is used to carry out frequent mine inspection and in mines with an aim of preventing the collapsing of mines hence causing death and destruction. These inspections are meant to identify potential areas of weaknesses on the mine walls and effect corrective measures.
96	Tunnel wall inspection	Contractors often use radar to inspect tunnel walls after construction to ensure that the walls are securely fitted in place and that there is no chance of the wall collapsing.
97	Navigation	Vessels especially sea vessels use radar signals to find direction and for navigation purposes from one place to another. These signals helps direct the vessel towards the show or towards another vessel.
98	Communication	Communication is one of the most common uses of radar technology. Radar technology can be found in television and radio communication as well as radio calls.
99	Measuring snow depth	Radar is used to measure the depth of snow. Instead of setting out in the cold to try and manually analyze how much snow there is out there, radar technology has made it simple and economical to obtain the same data more efficiently.
100	Object stability	Contractors have been using radar technology to try and analyze the stability of buildings at certain times of the year and to prevent weak buildings from collapsing

http://lidarradar.com/apps/100-radar-uses-or-applications

Appendix-B: Fourier Transform Tables

	Description	Function	Transformation
1	Definition	$g(t)$	$G(f)=\int_{-\infty}^{\infty} g(t).e^{-j2\pi ft}dt$
2	Scaling	$g\left(\frac{t}{T}\right)$	$\lvert T\rvert .G(fT)$
3	Time shift	$g(t-T)$	$G(f).e^{-j2\pi fT}$
4	Frequency shift	$g(t).e^{j2\pi Ft}$	$G(f-F)$
5	Complex conjugate	$g^*(t)$	$G^*(-f)$
6	Temporal derivative	$\frac{d^n}{dt^n}g(t)$	$(j2\pi f)^n.G(f)$
7	Spectral derivative	$(-j2\pi t)^n.g(t)$	$\frac{d^n}{df^n}G(f)$
8	Reciprocity	$G(t)$	$g(-f)$
9	Linearity	$A.g(t)+B.h(t)$	$A.G(f)+B.H(f)$
10	Multiplication	$g(t).h(t)$	$G(f)*H(f)$
11	Convolution	$g(t)*h(t)$	$G(f).H(f)$
12	Delta function	$\delta(t)$	1
13	Constant	1	$\delta(f)$
14	Rectangular function	$\mathbf{rect}\{t\} \triangleq \begin{cases} 1 & \text{if } \lvert t\rvert < \frac{1}{2} \\ 0 & \text{otherwise} \end{cases}$	$\mathbf{sinc}\{f\} \triangleq \frac{\sin(\pi f)}{\pi f}$
15	Sinc function	$\mathbf{sinc}(t)$	$\mathbf{rect}\{f\}$
16	Unit step function	$u(t) \triangleq \begin{cases} 1 & t>0 \\ 0 & t<0 \end{cases}$	$\frac{1}{2}\delta(f)-\frac{j}{2\pi f}$
17	Signum function	$\mathrm{sgn}(t) \triangleq \begin{cases} 1 & t>0 \\ -1 & t<0 \end{cases}$	$-\frac{j}{\pi f}$
18	decaying exp (two-sided)	$e^{-\lvert t\rvert}$	$\frac{2}{1+(2\pi f)^2}$
19	decaying exp (one-sided)	$e^{-\lvert t\rvert}.u(t)$	$\frac{1-j2\pi f}{1+(2\pi f)^2}$
20	Gaussian function	$e^{-\pi t^2}$	$e^{-\pi f^2}$
21	Lambda function	$\Lambda\{t\} \triangleq \begin{cases} 1-t & \text{if } \quad 0\le t\le 1 \\ 1+t & \text{if } -1\le t\le 0 \end{cases}$	$\mathbf{sinc}^2\{f\}$
22	Repeated function	$\mathbf{rep}_T\{g(t)\}=g(t)*\mathbf{rep}_T\{\delta(t)\}$	$\left\lvert\frac{1}{T}\right\rvert \mathbf{comb}_{\frac{1}{T}}\{G(f)\}$
23	Sampled function	$\mathbf{comb}_T\{g(t)\}=g(t).\mathbf{rep}_T\{\delta(t)\}$	$\left\lvert\frac{1}{T}\right\rvert \mathbf{rep}_{\frac{1}{T}}\{G(f)\}$

Appendix-C: Woodwards's Notation and FT

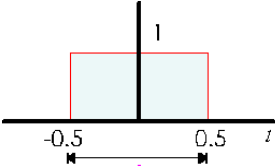
- The evaluation of FT, that is

$$\text{FT}\{g(t)\} = G(f) \triangleq \int_{-\infty}^{\infty} g(t).\exp(-j2\pi ft).dt \quad (1)$$

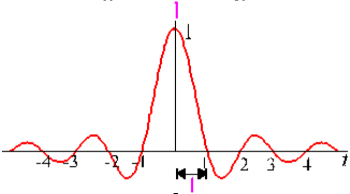
$$\text{FT}^{-1}\{G(f)\} = g(t) \triangleq \int_{-\infty}^{\infty} G(f).\exp(+j2\pi ft).df \quad (2)$$

  involves integrating the product of a function and a complex exponential - which can be difficult; so tables of useful transformations are frequently used.
- However, the use of tables is greatly simplified by employing Woodward's notation for certain commonly occurring situations.
- Main advantage of using Woodward's notation: allows periodic time/frequency functions to be handled with FT rather than Fourier Series.

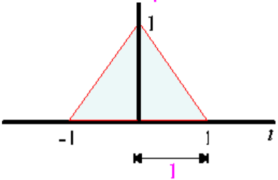
1. $\mathrm{rect}\{t\} \triangleq \begin{cases} 1 & \text{if } |t| < \frac{1}{2} \\ 0 & \text{otherwise} \end{cases}$



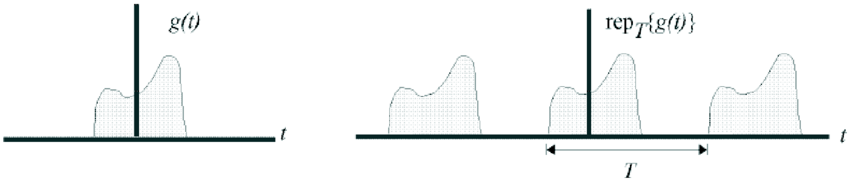
2. $\mathrm{sinc}\{t\} \triangleq \dfrac{\sin(\pi t)}{\pi t}$



3. $\Lambda\{t\} \triangleq \begin{cases} 1-t & \text{if } 0 \leq t \leq 1 \\ 1+t & \text{if } -1 \leq t \leq 0 \end{cases}$

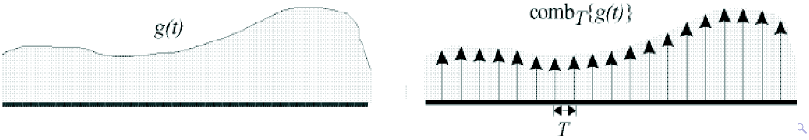


4. $\text{rep}_T\{g(t)\} \triangleq \sum_{n=-\infty}^{+\infty} g(t-nT) \qquad \forall n: .... -2, -2, 1, 0, 1, ...$



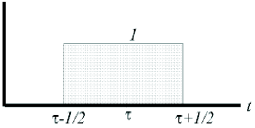
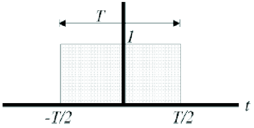
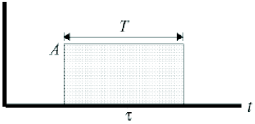
5. $\text{comb}_T\{g(t)\} \triangleq \sum_{n=-\infty}^{+\infty} g(nT).\delta(t-nT)$

also known as **sampling function**

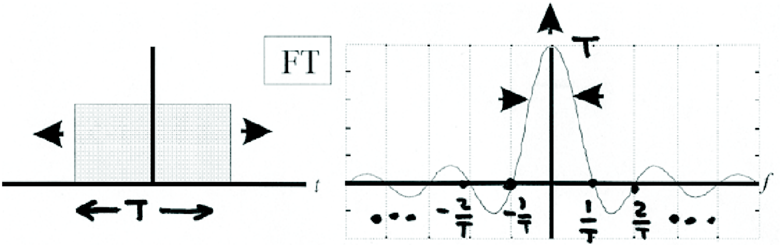


Examples of "rect" function

- we can generate any desired "rect" function by scaling and shifting - see for instance the following table

shifting	scaling	shifting+scaling
$g(t) = \text{rect}\{t-\tau\}$	$g(t) = \text{rect}\left\{\frac{t}{T}\right\}$	$g(t) = \text{rect}\left\{\frac{t-\tau}{T}\right\}$
		
$-\frac{1}{2} \leq t-\tau \leq \frac{1}{2}$	$-\frac{1}{2} \leq \frac{t}{T} \leq \frac{1}{2}$	$-\frac{1}{2} \leq \frac{t-\tau}{T} \leq \frac{1}{2}$
$\Downarrow$	$\Downarrow$	$\Downarrow$
$\tau-\frac{1}{2} \leq t \leq \tau+\frac{1}{2}$	$-\frac{T}{2} \leq t \leq \frac{T}{2}$	$\tau-\frac{T}{2} \leq t \leq \tau+\frac{T}{2}$

Effects of Scaling



as $T \to \infty$ $\Rightarrow$ FT becomes **narrower** and amplitude **rises**

$\Rightarrow$ δ-function at 0 frequency when $T \to \infty$