FACULTY OF TRANSPORT ENGINEERING 25 YEARS

VII. International Scientific Conference of the Faculty of Transport Engineering

6th – 7th September 2018, Pardubice

RADARS IN TRANSPORTATION

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Abstract

The key concept of radar is relatively simple but its practical implementation could be very complicated. An active radar radiates electromagnetic energy and detects the echo returned from reflecting objects (targets). The nature of the echo signal provides information about the target. The distance to the target determines the time of the radiated energy to travel to the target and back. The angular location defines a directive antenna. A radar can derive the target trajectory, and predict future location. With sufficiently high resolution, the radar can distinguish something about a target's size and shape. Usually, the radar is an active device in that it carries its own transmitter and does not depend on ambient radiation, as do most optical and infrared sensors. The radar can detect relatively small targets at near or far distances and can measure their range with precision in all weather. On the other side, the passive surveillance technology provides an unmatched ability to "see without being seen" and provides the very advanced technology. The described properties are very useful for transportation. The students of University of Pardubice and their teachers have cooperated on the development of various kinds of radars produced in the Czech Republic. Several examples such as air traffic control, river and automotive radars, which are used in transportation, are briefly illustrated.

Keywords

radar, transportation, radar principles, radar applications

1 INTRODUCTION

The basic idea of radar is relatively straightforward but its practical design could be very complex. A radar radiates electromagnetic energy and detects the echo returned from reflecting objects (targets). The character of the echo signal offers information about the target. The time, which radar takes for the radiated energy to propagate to the target and back, determines range, or distance, to the target 0 - 0. The received power at antenna terminals, P_R, is given by

$$P_R = \frac{P_T G_T}{4\pi R^2}\frac{\sigma}{4\pi R^2}\frac{G_R \lambda^2}{4\pi} F_T^2 F_R^2 \tag{1}$$

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where P_T is transmitted power at antenna terminals, G_T is transmitting-antenna gain, G_R is receiving-antenna gain, σ is target radar cross section (RCS), λ is wavelength, F_T is pattern propagation factor for transmitting-antenna-to-target path, F_R is pattern propagation factor for target-to-receiving-antenna path, R is radar-to-target distance (range).

Pattern propagation factors, F_T and F_R, account for the possibility that the target is not in the beam maxima (G_T and G_R are the gains in the maxima) and for any propagation gain or loss that would not occur in free space 0 - 0. The most common of these effects are absorption, diffraction and shadowing, certain types of refraction effects, and electromagnetic compatibility (EMC) considering both multipath electromagnetic interference (EMI) and electromagnetic susceptibility (EMS). For a target in free space and in the maxima of both transmit and receive antenna patterns, $F_T = F_R = 1$.

Simulation tools for long-range propagation prediction in the lower atmosphere, including diffraction and refraction effects, are usually based on physical optics (PO), ray tracing and/or parabolic equation method (PEM). Considering PO Ufimtsev's results an improved approach to analyze propagation over irregular terrain could be used 0. The scattered field can be divided into two parts, i.e. the reflected radiation component, S_{sz}^{ref}, (with the reflection coefficient Γ terms) and the shadow radiation component, S_{sz}^{sh}

$$S_{sz}^{ref}(P) = \frac{|E_0|R_0 e^{j\pi/4}}{2\sqrt{\lambda}} \int_a^b f(\theta_1)\Gamma\left[\sin(\theta_2-\alpha)-\sin(\theta_1-\alpha)\right] \times \frac{e^{-jk(R_1+R_2-R_0)}}{\sqrt{R_1R_2(R_1+R_2)}} \frac{dx}{\cos\alpha} \tag{2}$$

$$S_{sz}^{sh}(P) = \frac{|E_0|R_0 e^{j\pi/4}}{2\sqrt{\lambda}} \int_a^b f(\theta_1)\left[\sin(\theta_2-\alpha)+\sin(\theta_1-\alpha)\right] \times \frac{e^{-jk(R_1+R_2-R_0)}}{\sqrt{R_1R_2(R_1+R_2)}} \frac{dx}{\cos\alpha} \tag{3}$$

where E_0 is the maximum value of incident electric vector at a distance R_0. R_0, R_1, R_2, θ_1, θ_2 and α are shown in Fig. 1, $f(\theta_1)$ is the normalized antenna radiation pattern with phase center at point A at height h_A over the terrain, Γ is the Fresnel reflection coefficient (local reflection coefficient), $k = 2\pi/\lambda$, λ is the wavelength and a, b are limits of the illuminated part S_{il}.

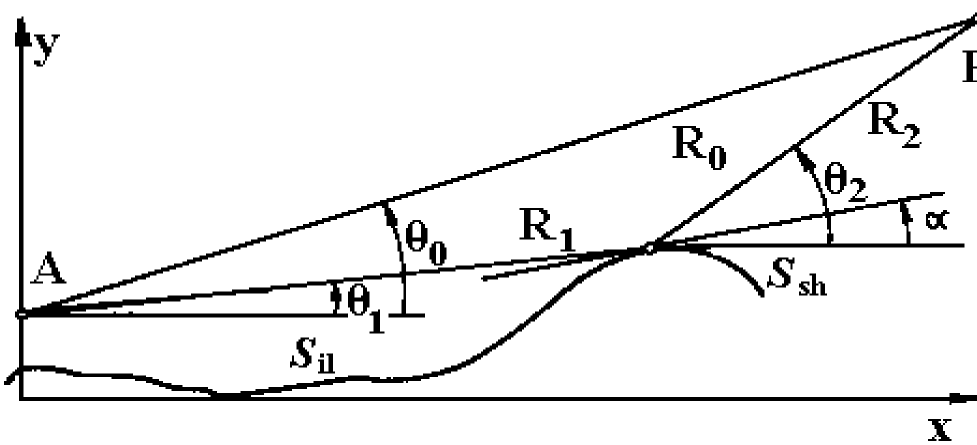

Fig. 1 Propagation geometry.

The reflected component, S_{sz}^{ref}, depends on the local reflection coefficient. On the other hand, the shadow radiation power is equal to the total power incident on a scattering object and it does not depend on the reflection coefficients. According to the shadow contour theorem, it does not depend on the whole shape of the scattering object and is completely determined only by the size and the geometry of the shadow contour. For the shadow region at a finite distance from the scattering object (behind the object), the shadow radiation for very short wavelength can be considered as a wave beam that asymptotically cancels the incident field and the reflected beams asymptotically vanish. The shadow radiation gives origin to edge waves, creeping waves, and surface diffracted rays. That means that (2) and (3) could be used for calculation for both illuminated and shadow region. The computation of scattered field can be done for higher altitudes (greater differences between the reflected and incident rays) as well as for lower altitudes (i.e. it is not necessary to consider the low altitude propagation and transient zone). The numerical simulations using (2) and (3) offer much more consistent solution, which takes into account the polarization (even for the shadow region).

Fig. 2 compares the physical optics (PO) analyses with the maximum (MEAS MAX) and minimum (MEAS MIN) measurement values 0. Fig. 3 shows the comparison of measurements and numerical simulations using PEM and PO, i.e. calculations of (2) and (3) for various heights 0.

The **radar coverage diagram** comprises a volume inside which the field is greater than the minimum useful value. Vertical coverage diagrams of system and radiation patterns of free-space

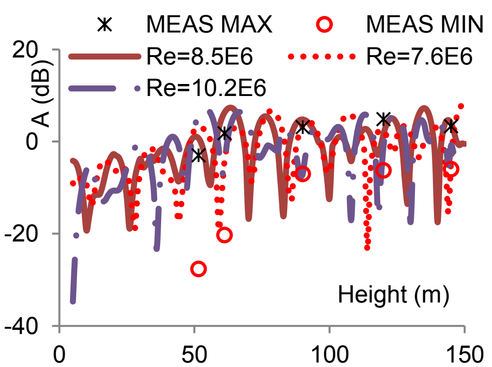

Fig. 2 Comparison of measurements and PO analyses for various effective radiuses R_e.

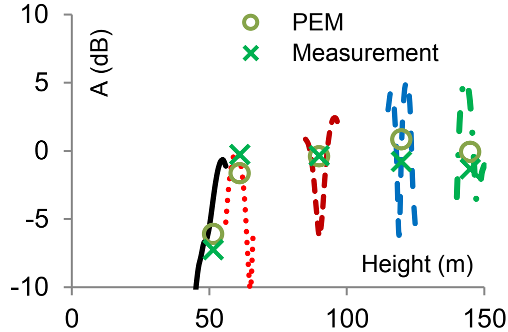

Fig. 3 Comparison of measurements with 0.65 m diameter, PEM and PO numerical simulations for heights of 51, 61, 90, 120 and 145 m.

(Ant. diagram) and PO approximations (Ground refl.) are shown in Fig. 4 0. The vertical coverage diagrams, which demonstrate the effect of transmitting output power, are shown for comparison only. Verifications of the radar coverage diagrams have been done by test flights performed at various flight levels for numerous airports and various radar types. An example of test flight is shown in Fig. 5 0.

Usually the same antenna is used for transmitting and receiving (monostatic radar). The angular location of the target is found with a directive antenna (one with a narrow beamwidth) to sense the angle of arrival of the echo signal 0 - 0, 0 - 0. If the target is moving, a radar can derive its track, or trajectory, and predict the future location.

The shift in frequency of the received echo signal due to the doppler effect caused by a moving target allows a radar to separate desired moving targets (such as aircraft) from undesired stationary targets (such as land and sea clutter) even though the stationary echo signal may be many orders of magnitude greater than the moving target. With sufficiently high resolution, a radar can distinguish something about a target's size and shape. Radar resolution may be obtained in range or angle, or both. Range resolution requires large bandwidth. Angle resolution requires (electrically) large antennas. Resolution in the cross-range dimension is usually not as good as the resolution that can be obtained in range.

However, when there is relative motion between the individual parts of a target and the radar, it is possible to use the essential resolution in doppler frequency to resolve in the cross-range dimension. The cross-range resolution of a synthetic aperture radar (SAR) for imaging a scene such as terrain can be explained as being due to resolution in doppler.

Usually, radar is an active device in that it carries its own transmitter and does not depend on ambient radiation, as do most optical and infrared sensors. Radar can detect relatively small targets at near or far distances and can measure their range with precision in all weather, which is its chief advantage when compared with other sensors.

The Czech industry has been interested in radars since the end of World War II 0 - 0. There were two or three big enterprises in the former Czechoslovakia delivering most of the radar and

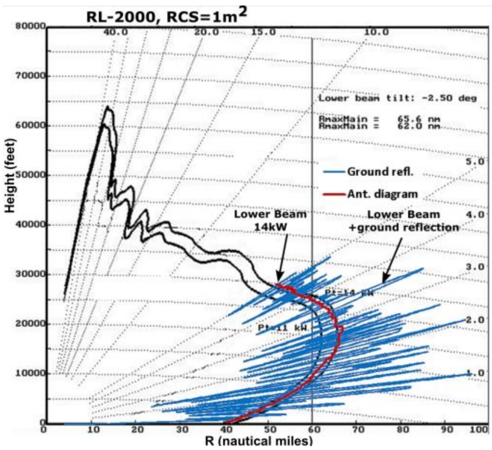

Fig. 4 Vertical coverage diagrams of system and radiation patterns of free-space (Ant. diagram) and PO approximations (Ground refl.).

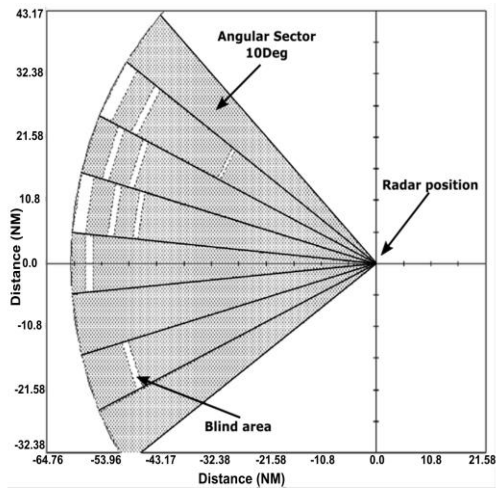

Fig. 5 Test flight.

microwave communication products with their own or closely coupled research plants such as Tesla Pardubice with its Radio Research Institute Opocinek, supported by antenna system producer LET Kunovice. Microwave semiconductor devices were designed and produced by WST Prague both for radar and for communication equipment. They were converted into several private companies. Several well-established companies mastering modern technology and getting relatively stable crews operate at the market. New devices and modernization of their products are developed mainly in their own facilities, and research projects are solved in cooperation with Universities and other academic organizations.

The paper deals with various radar properties, which are very useful for transportation. The students and employees of University of Pardubice have taken opportunities to cooperate mostly with Pardubice producers on the radar development. Various kinds of radars such as air traffic control, river and automotive radars are demonstrated.

2 RADAR APPLICATION

The principle of radar has been applied from frequencies of a few megahertz (HF, or high-frequency region of the electromagnetic spectrum) to well beyond the optical region (laser radar). The particular techniques for implementing a radar differ greatly over this range of frequencies, but the basic principles remain the same. Radar was originally developed to satisfy the needs of the military for surveillance and weapon control. Military applications have funded much of the development of its technology. However, radar has significant civil applications for the safe travel of aircraft, ships, cars and spacecraft; the remote sensing of the environment, especially the weather; and law enforcement and many other applications.

The high degree of safety in modern air travel is thanks to successful applications of radar for effective, efficient and safe control for air traffic. Airports employ an **Airport Surveillance Radar (ASR)** for observing the air traffic in the vicinity of the airports.

A microwave beacon system, like a radar, transmits a pulsed RF wave to locate a target, using the time delay of the “echo” to determine distance and using antenna directionality to determine angular location. The distinguishing feature of a beacon system is that the target cooperates in this process, using on-board electronics to enhance the returned RF wave with amplification, frequency shifting, or coding. Beacons are thus highly accurate and reliable surveillance systems and also can provide some data-link capability. Beacon systems typically consist of transponders and interrogators. *Transponders* are the active devices carried by the target to provide the enhanced echo. Transponders are usually located on moving platforms, although fixed transponders may be used to mark hazards, navigation points, or calibration points. *Interrogators* employ equipment similar to that of conventional pulsed radars, i.e., a transmitter which produces replies from the transponder and a receiver to detect and process the replies. The most widely deployed beacon system is the military Identification Friend or Foe (IFF) system and its civilian derivative **Air Traffic Control Radar Beacon System** (ATCRBS). The civilian systems are also known internationally as **Secondary Surveillance Radar (SSR).** All systems have similar waveforms and share common frequencies of 1030 MHz for interrogation and 1090 MHz for reply. Polarization is always vertical.

The Precision Approach Radar (PAR) is a type of radar guidance system designed to provide lateral and vertical guidance to an aircraft pilot for landing, until the landing threshold is reached. After the aircraft reaches the decision height (DH) or decision altitude (DA), guidance is advisory only. The Czech radar industry has been interested in the development and production of reflector as well as phased arrays for PAR. Controllers monitoring the PAR displays observe each aircraft's position and issue instructions to the pilot that keep the aircraft on course and glidepath during final approach. It is similar to an instrument landing system (ILS) but requires control instructions.

In the early 80´s Leningrad VNIIRA and Tesla Pardubice agreed on joint development of the microwave landing system (MLS), which is more advanced than the ILS. Tesla was interested in design of the MLS scanning beam antennas including steering electronics and software. It was the most mature phased array program reaching the stage of completely developed and field tested equipment containing azimuth and elevation antennas at the time. The beam positioning as a function of time was kept to an accuracy of hundredths of degree to fulfill the ICAO and FAA recommendations. The whole MLS was tested at a USSR airport under real flight situations. Unfortunately, the program was stopped due to the unclear position of the whole MLS program.

More than 700 **river radars** of several types were done in the Czech Republic and exported to various countries. The slotted waveguide linear antenna arrays were used with the river radars.

Ultra wideband (UWB) radars, which transmit narrow pulses, are used for a location of buried objects and bodies (ground penetrating radars). Special through-wall radars enable looking inside through the walls and thus facilitates the actions such as against terrorists 0, 0. Monitoring and localization systems enable tracking the movement of fire fighters and rescue teams in complicated environmental areas and thus facilitates the organization of these teams. The Pardubice RETIA Through-Wall Imaging System is a **unique small portable radar** detecting living entities behind a wall or a non-metallic barrier. Thanks to its technology, the radar can detect living entities both in motion and at rest. The signal processing optimized for the detection of small changes triggered human or animal movement, enables localization, for example, of a human being based only on breathing. Small dimensions, low weight and long operation period makes this radar a highly portable device suitable for multi-purpose usage, for special police and military units.

Automotive radars are mostly based on the Linear Frequency Modulated Continuous Wave (LFMCW) principle 0. Mastering of low cost high definition continuous wave radar at 77/79 GHz carrier frequencies with maximal frequency bandwidth of 4 GHz enables radar to enter automotive business. Thanks to utilization of 4 radars for one car, the traffic circumstances could be continuously monitored with avoiding of blind areas. That means the yearly production is estimated more than 200 millions of car radars. Nevertheless, the quest to manufacture radar for automotive functional safety purposes in large series while keeping the cost of sensor within reasonable boundaries is still an ambitious task considering new 5G communications.

Close Vehicle Warning for Bicyclists is based on Frequency Modulated Continuous Wave (FMCW) radar 0. The radar works at frequency 24.1 GHz with 180 MHz bandwidth and it is intended to detect cars behind a bicyclist. The implementation of the signal processing is tested in the simulation and it is realized in Field Programmable Gate Array System On Chip and with low-cost FMCW radar. The system is installed on the bicycle.

The Czech Republic is one of world leaders in the field of law enforcement traffic solutions 0. The **radar speed cameras** represent an effective tool how to affect behavior of drivers with the aim of improving road safety and reducing occurrence of hazardous situations on the road. The mobile system as well as the non-intrusive fixed one have won recognition and popularity in many countries of the world.

The **indirect holographic techniques**, previously applied to the determination of antenna radiation patterns, can be adapted for the imaging of passive objects 0 - 0. The transformation of the holographic intensity pattern into the Fourier domain enables the isolation of the terms required for complex field reconstruction to be isolated from the remaining terms. Back-propagation techniques have also been included to reconstruct complex fields at the position of the scattering objects. That could be used for transport safety issues such as resolution of concealed guns at airports or various stations. A composite aperture that produces images using two sub-apertures operating at different frequency ranges was designed 0. The lower resolution, K-band system makes use of frequency diverse metasurface aperture antennas for imaging of human-sized targets, while a high frequency (75 GHz) dynamic holographic metasurface antenna is used for obtaining higher resolution images of smaller regions. Although demonstrated for security-screening applications, the proposed imager has significant potential to be employed in a variety of applications, including biomedical imaging, non-destructive testing and remote-sensing, where high-resolution and fast image reconstruction are required over dynamically adjusted constrains. The synthesized spotlight aperture can readily be extended to even higher frequencies to achieve finer resolution limits.

Passive Radars (Multilateration Systems) use the receiving stations, which receive the signals transmitted by target and retransmit it to the central processing station by microwave links. There the Time Differences of Arrival (TDOA) at the individual stations are measured. Moreover at the central station the signals are analyzed and the messages are evaluated. Typically three receiving stations are needed for 2D location of the aircraft and four stations are needed for 3D location. The system achieves a very high position accuracy, independent altitude measurement (with high accuracy) and is more cost effective than the SSR systems 0 - 0, 0. The Pardubice ERA is a leading supplier of next-generation surveillance and flight tracking solutions for the air traffic management, military, security and airport operations markets.

The **passive coherent location (PCL)** uses commercial transmitters such as FM radio broadcasting. The transmitter-receiver pair creates a bistatic radar. Contrary to applications, where the useful signal is roughly above a noise level (such as in case of the primary and secondary radars and communications), the reflected signal level in PCL systems is many orders of magnitude under the levels of direct signal, clutter and noise. Therefore, very sophisticated signal processing should be used 0, 0 - 0.

The Czech industry has developed several types of **meteorological radars** starting from 1963 0. That are very useful for transportation, especially air traffic control. A few meteo-radars uses variable linear/circular polarizations. The Institute of Atmospheric Physics, Prague, has been developing a 35 GHz frequency-modulated continuous-wave (FMCW) cloud radar 0, 0.

3 CONCLUSION

The radar can detect relatively small targets at near or far distances and can measure their range with precision in all weather. Usually, the radar is an active device in that it carries its own transmitter and does not depend on ambient radiation, as do most optical and infrared sensors. The active radar radiates electromagnetic energy and detects the echo returned from reflecting objects (targets). The nature of the echo signal provides information about the target. The distance to the target determines the time of the radiated energy to travel to the target and back. The angular location defines a directive antenna. A radar can derive the radar trajectory, and predict future location. With sufficiently high resolution, the radar can distinguish something about a target's size and shape. On the other side, the passive surveillance technology provides an unmatched ability to "see without being seen" and provides the very advanced technology.

The described properties of both active and passive radars are very useful for transportation. Even if radars were originally developed to satisfy the needs of the military for surveillance and weapon control and military applications have funded much of the development of its technology, the radar has abundant civil applications for the safe travel of aircraft, ships, cars and spacecraft; the remote sensing of the environment, especially the weather; and law enforcement and many other applications. The Czech industry has been interested in radars since the end of World War II. Today, several well-established companies mastering modern technology and getting relatively stable crews operate at the market all over the world. New devices and modernization of their products are developed mainly in their own facilities, and research projects are solved in cooperation with Universities and other academic organizations.

The paper demonstrates various kinds of radars such as air traffic control, river and automotive radars and deals with various radar properties, which are very useful for transportation. The students and employees of University of Pardubice have cooperated on the radar development. This is confirmed by numerous projects, journal and conference papers, and master and Ph.D. theses.

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