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Tracing the development of weather radar technology in Romania and worldwide

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Abstract

Almost 90 years from the radar invention, the radar technology has evolved enormously and today it presents itself as an instrument of great importance in various research areas (meteorology, aviation, astronomy, air-ecology etc.). The main objective of the article is to identify the periods of development at the global level and also in Romania, as well as to identify the technology of most operational weather radars today. The article is based on publications from international journals and scientific books, covering the period of 1930-2018. The overview presentation demonstrates the reasons today's weather radar is a powerful tool for studies concerning the atmospheric precipitations prediction, wind speed and direction, rainfall risk assessment and implementation of weather forecasts. Knowing the technological development is needed for the construction of the new generation radar and for exceeding the actual limits with regard to the accuracy of the radar data and the limits of observation. The purpose of this article is to summarize the evolution of the weather radar, with emphasis on the first experiments carried out during the analogue and digital period.

Keywords: *weather radar, electromagnetic waves, microwaves, precipitation*

Rezumat. Urmărirea dezvoltării tehnologiei radarului meteorologic în România și la nivel mondial

La apropape 90 de ani de la invenția radarului, tehnica radar a evoluat extrem de mult, iar astăzi se prezintă ca un instrument de mare importanță în diferite domenii de cercetare (meteorologie, aviație, astronomie, aeroecologie, etc.). Obiectivul principal al articolului este de a identifica perioadele de dezvoltare la nivel global și în România precum și identificarea tehnologiei prezente în majoritatea radarelor meterologice operaționale. Articolul se bazează pe publicații din jurnale internaționale și cărți științifice, care acoperă perioada 1930-2018. Prezentarea de ansamblu demonstrează motivele pentru care astăzi radarul meteorologic este un instrument puternic pentru studiile privind estimarea precipiațiilor atmosferice, viteza și direcția vântului, analiza riscului pluviometric și realizarea prognozelor meteo. Cunoașterea evoluției tehnologice este necesară pentru construirea noilor generații radar și depășirea limitelor actuale în ceea ce privește precizia datelor radar și limitele de observare. Scopul acestui articol este de a rezuma evoluția radarului meteorologic, punându-se accentul pe primele experimente desfășurate în perioada analogică și digitală.

Cuvinte-cheie: *radar meterologic, unde electromagnetice, microunde, precipitații*

Introduction

The meteorological radar is one of the key instruments in weather forecasting and monitoring especially of convective storms producing severe weather (e.g., intense precipitation, large hail, tornadoes). The radar technology of today was developed over the last 90 years through the research efforts of engineers, meteorologists, and other scientists. Mostly, the use of radar for meteorological purposes is due to the intensive projects during the period of the Second World War and post-war, when the theoretical foundations of the meteorological radar were laid.

The development of the weather radar depended on the technology evolution. Therefore, although some theories were known, they could not be implemented (e.g. the Doppler Effect).

This article describes the history of the meteorological radar from the early stages of development until today. The aim of this paper is to highlight the main periods of development at global scale and in Romania, as well as to identify the current technology in most operational weather radars worldwide. Early research conducted by weather national agencies are discussed here, as well as the first experiments which lead to the construction of the first operational radars. A part of the early history of the radar is described in Marshall (1953), Atlas (1990), Zhang et.al. (2011), and Galati (2016). This paper focuses only on weather ground-based radar, and tackles the early experiments, the pioneer.

1. Early experiments

The term RADAR (RAdio Detection And Ranging) was used for the first time by the United States Navy in November 1940 (Swords, 2008), as suggested by two American officers, S.M. Tucker and F.R. Furth. In the United Kingdom the term was adopted in 1943, but before that they used RDF (Radio Detection and Finding), also known under the name of "Cuckoo", in the military circles. The Italians used the term RDT (Radio Detector Telemetro), the French DEM (Detection Electromagnetique) and the Germans "Funkmessgeraet" (Galati, 2016; Swords, 2008). After the

Second World War, the term was used by the rest of the world as well.

In 1930, the radar technology was operational for the first time to detect and track aircrafts (Whiton et al., 1998). The first use of radar for meteorological purposes occurred in England in 1942 (Atlas, 1990). However, previous research had been already performed in the 19th century.

The first scientist with fundamental contributions to the development of the radar techniques was James Clerk Maxwell (1831–1879). He formulated the theory of electromagnetic radiation, and noted that, although mathematical approach of individual electric and magnetic phenomena existed, no general theory was proposed at that time. Therefore, in 1864, he published the theory of the electro-dynamic field, which included the four equations and macroscopic theory of electromagnetic field (Mahon, 2003). In 1893, Maxwell published a mathematical theory by which he predicted that the electromagnetic interference should propagate through space at the speed of light.

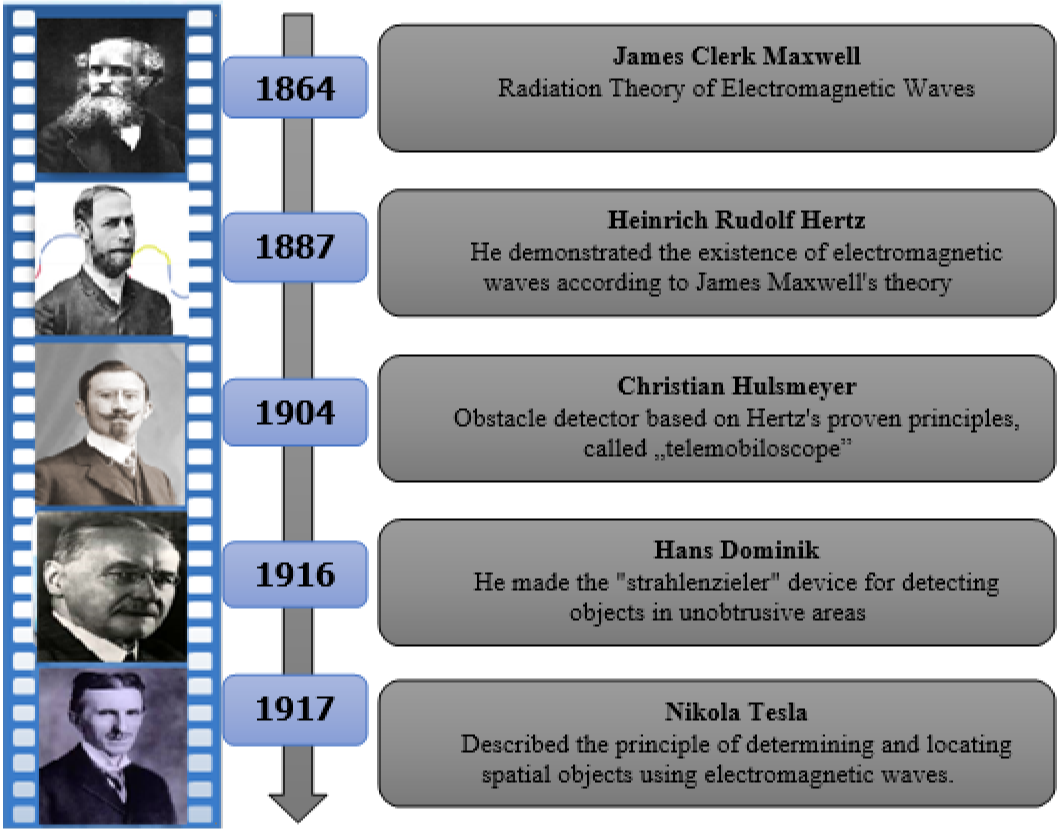

Fig. 1: The precursors of the development and emergence of the first radar (Maxwell, 1954; Garratt, 1995; Shaw, 1994; Dominik, 2007; Faccio et al., 2006)

Heinrich Rudolf Hertz (1857–1894) was the first to apply the mathematical theory of Maxwell on the transmitting and detection of the electromagnetic waves. In 1887, while he was Professor of physics at the Polytechnic University of Karlsruhe, Hertz designed a set of experiments to test Maxwell's theory. His work demonstrated the existence of electromagnetic waves, which reinforced Maxwell's conclusion, namely that light is an electromagnetic wave (Bevilacqua, 1984).

The first use of the principle of determination and location of spatial objects by electromagnetic waves is unclear. The first mention of this principle was formulated by Nikola Tesla (1856–1943). In august 1917, Tesla stated that "... we can produce, when needed, from a broadcaster, an electric effect, anywhere in the world; we can determine the relative position or course of a moving object, such as a ship at sea, the distance traversed and the speed ... "(Galati, 2016, p. 24). Tesla described the radar operation principle to locate metal objects, but he did not take into account other disturbing factors, such as the attenuation of the radio waves on contact with water. The system was called "electric ray" and, at that time, his idea was revolutionary.

On April 30, 1904, Christian Hulsmeyer (1881–1957) applied in Germany for a patent for the so-called telemobiloscope. The system consisted of a transmitter and a receiver meant to detect metal objects, using the electromagnetic waves. The system was intended to avoid collision of ships (Sengupta and Sarkar, 2003). The first demonstration of the telemobiloscope was held on 18 May 1904. Hulsmeyer's device was able to detect ships at a maximum distance of 3 km and operated at wavelengths between 40÷50 cm. However, the military and naval authorities did not show any interest, but during the WWI, experts became interested in using this device (Galati, 2016). Most of his devices were destroyed during the WWII (Sengupta and Sarkar, 2003).

Another contribution to the development of radar is due to the research carried out in 1916 by Hans Dominik (1872-1945). He built a device called "strahlenzieler", which could detect targets in places with no visibility (Galati, 2016). The location of these targets was based on the reflection of electromagnetic waves by metallic surfaces. On the 16th of February, 1916, Dominik received financial funds to advance his research and he succeeded to build a device with 10 cm wavelength. A month later, he was asked to build a device to be used during the WWI, but Dominik failed to finish it on time.

In 1936, Watson-Watt (1892-1973) managed to invent the first radar, and for this he is recognized as the "father of radar" (Probert-Jones, 2014). His device was based on the research described in Figure 1.

2. The Pioneers and the development of analog radars

Research on meteorological radars between 1936–1970 was conducted mainly in the United Kingdom, United States, India, China, and Japan, which not only acknowledged their potential to investigate meteorological phenomena, but also had the technological capability to implement applications.

The military usage boosted the progress. One of the research purposes concerning the signals received from atmospheric phenomena was represented by obstacles in locating aircraft or bombers. The period is limited to the analogue era and to the implementation of the Doppler frequency in radar equipment.

During the Second World War, the military radar systems that were used were classified information (secret), which limited their use for meteorological purposes. Starting with the 1950, the manufacture of radar became easier due to the emergence of solid-state electronics. In the 1970s, the digital revolution began, which allowed the implementation of new functions within the weather radar operation (e.g. the Doppler Effect). The end of the 1970s represented the beginning of a new generation of radar, called the NEXRAD (Next-Generation Radar).

Advances in the field of electronics during WWII and Post-war period allowed the radar technology to develop. For example, after developing the cavity magnetron, radars were able to use higher frequencies for research purposes, such as 4 GHz or 10 GHz (Raghavan, 2003; Dummer, 1983). The following sections outline the development in different countries.

2.1 Great Britain

In the UK, research in the field of meteorological radar has begun with Wattson Watt, the so-called "the father of radar". Wattson worked at the British Meteorological Office where, in 1936, he managed to build a device that could determine the position of aircrafts (Probert-Jones, 2014). The imminence of the war made radar evolution grow very fast. During WWII, centimetre wavelength radars (10 cm) were mounted at General Electric Company (GEC) in Wembley and at the Swanage Air Ministry, Dorset. Both radars were able to detect the weather from short distances, and the first storm tracking report was reported on July 21, 1941 (Ligda, 1951). This event marks the start of operational meteorological radar research in the UK.

During the war, research was carried out at GEC and Telecommunication Research Establishment (TRE). After the war ended, the investigations continued in several parts. The British Meteorological Office installed a S-band radar station at East Hill near Dunstable, Bedfordshire (Atlas, 1990). Research has also been done at Cambridge University, the Department of Meteorology (London Imperial College) and TRE, which has changed its name to Royal Radar Establishment (1957).

During the analyzed period, the display of received signals was limited by the use of cathode ray tubes as they only displayed two parameters, and the received signal had four (azimuth, distance, height and intensity). Therefore, three types of display had been studied: Plan Position Indicator (PPI), Range-Height Indicator (RHI), and A-scope. These were implemented in the new radar.

J. W. Ryde and Telecommunications Research Establishment laid the theoretical foundation of the meteorological radar until the end of the war. After the war, J. E. Hooper and A. Kippax began a program to test Ryde's theories.

Using an operational radar on a 3.2 cm wavelength, they investigated the dependency of the received power on the duration of the impulse, the measurement of precipitations, the ratio between echo signal's intensity and wavelenght, the intensity of the echo signal from the snow and the melting band. Following the research, Hooper and Kippax confirmed the wavelength dependence of the echo signal intensity (Probert-Jones, 2014).

From 1948 on, I. C. Browne studied clouds using a radar system operable on a wavelength of 3 cm (Atlas, 1990). Among other things, he also measured polarizing of melting bands and fluctuations of radar echoes in precipitation.

In 1950, Frank Ludlam began his research by studying the severe storms in southern England, but believed that more violent storms occurred more often in northern Italy, so in 1958 he moved to Italy. Here he gained a vast experience which he used to participate in a observation program in England, 1958. They had 5 radar stations on 3, 4, 7 and 10 cm wavelengths. They managed to investigate atmospheric circulation classes from severe storms through mesoscale phenomena at fronts and cyclones (Atlas, 1990; Probert-Jones, 2014).

In 1967, the British Meteorological Office set up a cooperative association with Plessey Radar Ltd. to investigate the use of radar in determining and quantifying the amount of precipitation. Thus, an operable radar on the 10 cm wavelength was installed in northern Wales.

As it has happened in other countries, problems with equipment instability, lateral lobes, and equipment limitations have slowed progress down, but it has been an impressive research that has led to the development of a meteorological radar.

2.2 U.S.A.

In 1944, the US Air Force Corps initiated a program for training officers in meteorology at Army Electronics Training Center (AETC) in Cambridge, Massachusetts. Here, students had the opportunity to use S-band (8÷10 cm) radars (SCR-717A and SCR-720) for studying the atmospheric phenomena. For the first time they were able to detect and track precipitations, such as rain or storms. After the program completion, they were sent to the WEMS Department (Weather Equipment Methods Section) in New Jersey.

During the period of 1944-1946, Herbert B. Brooks, William C. Kellogg (1867 - 1957), Donald H. Rudd and Donald M. Swingle conducted applied research and modified military radars for meteorological observation. Using the radars SCR-58 and SCR-717B, they tackled precipitation studies, storm detection, winds measurement and discrimination of storm echoes caused by abnormal propagation, birds and other factors. As a result of technical reports received from England, Swingle managed to develop the first meteorological radar equation, which was implemented in the new radars (Wexler, 1947).

In 1945, Swingle established the technical documentation and the necessary requirements for achieving the weather radars. Radars were generally designed to detect winds and storms and were intended to be used by trained meteorologists, with additional skills in interpreting the data.

After WWII, the Radar Branch from U.S.A., decided to set up a radar station in C-band (4÷8 cm). The first radar specially designed to perform meteorological observations was CPS-9 (Atlas, 1990). Due to the narrow width of the beam and of the sensitivity control function in time, the radar had greater discovery possibilities (Fig. 2).

Fig. 2: Overview of the radar AN / CPS-9

Source: http://www.radartutorial.eu

From 1947 to 1950, Swingle expanded his research at Signal Corps laboratories. His main work was the use of SCR-584 radar to investigate clouds and precipitations (Atlas, 1990).

Following the recognition of the radar techniques potential to observe various weather events, a new set of radars called the AN/MPS-34 were developed. The radar was designed with greater sensitivity and came with an RF preamplifier, which led to an increase in the minimum detectable signal.

2.3 India

The first research in India was conducted within the India Meteorological Department (IMD) since 1940, using modified war equipment, which was very useful for the initial research. Among the radars used for meteorological applications one can mention Baby Maggie no. 3, MK III AN / TPS-2, AN / APQ-13 and SCR-717C. The equipment was modified to detect the wind, and to study the nature of reflections from the atmosphere, precipitations and storms.

At the beginning of the 1950s, IMD initiated a program in order to install a radar network on the Indian Territory for detecting severe phenomena. The Indian Meteorological Department chose two wavelengths for the radar network, one in the X-band (2,5÷4 cm) for detecting storms and one in S-band for the detection of cyclons around the coast. Figure 3 shows the distribution of radars in the S-band of IMD.

In 1954, India purchased its first meteorological radar which was installed at the airport of Calcutta. The first detection radar of the storms in the X-band was installed in 1970 at New Delhi, and the first S-band radar became operational only in 1970 on the East coast of India at Visakhapatnam (Atlas, 1990). It is northworty to mention that the meteorological radar program of India was enterly developed by its own resources. The principal meteorological researches were focused on interpretations and classifications of the signal coming from the storms, precipitations, cyclonic storms, monsoon, and land and sea clutter.

Fig. 3: The network of radars in the S-band of India Meteorological Department (Atlas, 1990)

2.4 Canada

The history of meteorological radar in Canada began in 1953 in Ottawa, when the project Stormy Weather was established. The project belonged to the Canadian Army and was led by Stewart Marshall (1911-1992). At first, Stormy Weather were equipped with a height detection unit using microwave and early warning radars, and the first meteorological observations focused on continuous rainfall events. By 1947, Marshal and his team determined the relationship between the ratio of rain, the water content and reflection, by introducing the Z symbol.

The intensity of estimated radar precipitation (R) is based on radar reflections (Z). Estimation of precipitation is based on identifying the best relationships between these two parameters (Atlas et al., 1997). Marshal and Palmer (1948) showed that between Z and R there is the following relationship: Z = aRb, where Z is the reflection, R the precipitation intensity, and a and b are empirical parameters. and that drop size distribution is approximately exponential with a parameter of the R function, resulting in the following values of a = 200 and b = 1.6. Subsequent studies have been led to different values for parameters (see, for example, Battan 1973). The radar used at that time was a TPS-10 positioned in several locations. (Marshall, 1953).

The CPS-9 radar replaced the TPS-10 in 1954, improving the airspace scanning mode, by the use of Fast Azimuth Slow Elevation (FASE) to get the most out of FASE technique, Canada developed a new indicator named Constant Altitude Plan Position Indicator (CAPPI) (Legg, 1960).

In the summer of 1956, the Group Stormy Weather began its research in Alberta area with Decca radar type 41 (produced by the British Company Decca), as a result of the disasters caused by the extreme weather that had taken place (Atlas, 1990). Despite the severe attenuation in larger nuclei of storms, the radar succeeded to measure the echoes height and to determine the link between the height and the hail probability (Hitschfeld, 1986).

In 1967, the FPS-502 radar was deployed in Alberta. An important feature of the radar was its capacity to use different polarizations in sending and receiving electromagnetic waves. The research carried out by this radar showed that the use of polarimetry can identify particles of hail, rain or snow. Meteorological Radar Conference held in 1968 was opened by installing the FPS-18 (10 cm) radar.

2.5 Japan

In Japan, the research using meteorological radar started in 1954 by building radar in X-band, which was installed in Tokyo by the Meteorological Reaserch Institute (MRI) and conducted by Dr. H. Hatakeyama (Galati, 2016). Shortly after the installation of the first radar, a research program was initiated to investigate the statistical relationship between the storm occurrence and the signal reflection from the upper part of the atmosphere.

In 1964, a Doppler radar was constructed that ran on the wavelength of 3 cm. By means of this Doppler radar, the vertical structure of precipitations was investigated. The research was enhanced also by the typhoon disaster of 26 September 1959, when about 5000 people lost their lives. Therefore, the first operational radar functional on X-band for observing the typhoons was built in Osaka. The X-band radar was shortly replaced by a C-band radar due to signal attenuation through the rain. The first two C-band radars were installed at Fukuoka and Tokyo in 1955.

By 1970, the Japanese meteorologists published hundreds of articles in the field of radar meteorology which meant that they made a huge research effort. After 1970, most Japanese radar started a new stage of modernization by converting analogue to digital signals.

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Tabel 1: Main technical characteristics of the first weather radar used by the USA, Canada, China, India and Japan

Parameters	S.U.A.							CHINA			JAPAN			CANADA		INDIA
	CPS-9	WSR -74C	FPS -77	TPS-68	WSR-1	WSR-57M	WSR-88D	711	713	714	MRI -X	MRI -C	MRI -K	Decca -41	FPS-103	APQ-13
Frequency (MHz)	9368	5656	5551	5353	2855	2855	2855	9993	5995	2997	8000÷ 12000	4000÷ 8000	18000÷ 27000	9368	9368	9368
Wavelength (cm)	3.2	5.3	5.4	5.6	10.5	10.5	10.5	3	5	10	3.75÷ 2.5	7.5÷ 3.75	1.67÷ 1.11	3.2	3.2	3.2
Pulse duration (µs)	Sh pulse: 0.5 Ln pulse: 5	3	2	2	Sh pulse: 1 Ln pulse: 2	Sh pulse: 0.5 Ln pulse: 4	Sh pulse: 1.57 Ln pulse: 4.7	1	2	1.3	1	2	0,5	Sh pulse: 0.2 Ln pulse: 2	2.25	MD-12: 0.5, 1.12, 2.25 MD-38: 0.5, 0.75, 2.25
Peak transmitter power (kW)	250	250	250	165	50	500	750	-	-	-	250	300	32	30	45	40
Effective antenna system gain (dB)	41.5	40	36.5	38	-	38.1	45	38	38	36	45	42	55	-	30	33
Antenna reflector diam. (m)	3.6	2.4	2.4	1.9	1.8	3.6	8.5	1.5	3.7	4.0	2	3	2,6	90	0.76	0.76
Pulse repetition frequency (s^{-1})	Sh pulse: 931 Ln pulse: 186	259	324	375	Sh pulse: 650 Ln pulse: 325	Sh pulse: 650 Ln pulse: 164	Sh pulse: 318-1304 Ln pulse: 318-452	-	-	-	-	-	-	250	400	1350, 675, 270
Receiver sensitivity (dBm)	-103	-104	-104	-104	-	-108	-113	-	-	-	-	-	-	-	-106	-83
Beamwidth azimuth (º)	1	1.6	1.6	2	4	2	1	1.5	1.2	2	1	1,39	0,25	0.6	3.6	3
Beamwidth elevation (º)	1	1.6	1.6	2	4	2	1	1.5	1.2	2	1	1,39	0,25	2.8	3.6	3
Antenna mobility (º)	360	360	360	360	360	360	360	360	360	360	360	360	360	-	360	360

3. Meteorological radars in the digital age

The digital revolution began around the year 1970 and it was due to the evolution of technology in electronics, which made that the meteorological radar be developed in an accelerated pace. The conversion from analogue to digital signal allowed the data storage in binary format, a considerable reduction in errors and implementation of new functions such as Doppler frequency.

The main difference between the two generations of radars, analogue and digital, is that the prior technology transmitted the information under the form of electrical pulses with variable-amplitude, while the new one did this in a binary format of 0 and 1. Within this development, it was introduced the radial velocity of the weather phenomena, due to the Doppler Effect. Most of the radars with Doppler capabilities were developed in the 1970s. For example, in the USA, at NSSL (National Severe Storms Laboratory) in Oklahoma a radar in S-band with Doppler capabilities was installed.

The end of 1979 marked the beginning of a new radar generation, namely NEXRAD. After nearly 10 years, the first radar of NEXRAD generation, WSR-88D was inaugurated, and the last one was installed in 1997. The project led to the construction of a US radar network, consisting of 159 radars that covered the whole territory (Galati, 2016).

Meanwhile, staring with 1970, the meteorologists were able to process also radar images from different angles of height, due to the development of antenna systems, RHI indicators (Range Height Indicator) and CAPP (Constant Altitude PPI).

By the end of 2000, several countries, such as Canada, Australia, USA and China, developed radar networks with doppler capabilities. For example, the Canadian network was fully completed in 1998. A similar situation occured in Europe, where different countries implemented this type of radar. For example, in 2010, the ARAMIS network in France had 22 Doppler weather radars, out of which 10 were able to use dual polarization (Galati, 2016). Since 2010, European countries have provided the national territory with radar networks, and the data were made available to the public, via internet, such us the European Operational Program for Exchange of Weather Radar Information (OPERA) (Huuskonen et al., 2014; Sireci et al., 210).

In India, Japan and U.S.A. the situation is different due to the extreme weather phenomena that occurred. The first network was developed in 1975 with MULTIME radars, and in 1980, India succeeded to build its first equipment, which met the meteorologist's requirements, before many radar developers countries (Atlas, 1990). In 2011, India had a network composed of 40 radars in X and S-bands, out of which five radars with Doppler capabilities (they became between 2002-2006).

Another significant step in the radar performance, after the introduction of the Doppler Effect, is the polarimetry. The polarimetry has been studied since 1980, but at the operational level it was implemented in 2000. Using this technique, more information can be obtained from the reflection of the precipitation signals.

During the period 2000-2003, USA scientists analyzed the operational advantages and the performance of using the polarimetry within the Joint Polarization Experiment (JPOLE), which resulted in the implementation of technology in all weather radars in the US meteorological service, and the first NEXRAD radar transformed in polarimetrical radar, took place on March 3, 2011.

4. The evolution of weather radar in Romania

The first radar meteorological research in Romania began in 1967, when the first Plessey 42 X radar was installed in Bucharest (Apostu et al., 2005). Two other radars of the same type were installed in Cluj-Napoca (1969) and Mihail Kogalniceanu (1970). The activities were carried out within the Central Meteorological Institute within the structure of the Ministry of Air and Marine (Official Gazette No. 266 of November 14, 1936; Burcea, 2011).

Being aware of the importance of the meteorological radar, the authorities decided to expand the radar research area by acquiring new radars. Thus, since 1973 and until 1990, Russian MRL-2 and MRL-5 production radars have been purchased. Radar stations were installed in Bucharest, Oradea, Iaşi, Timişoara, Craiova and Tuzla (Apostu et al., 2005; Perez et al., 1999).

MRL-5 was specifically designed for hail detection. The radar was designed on two frequency channels (x and s band) and had the advantage of measuring rainfall using two methods. The first method was based on the measurement of the reflection factor on a single wavelength, while the second one measured the attenuation of the signals on both wavelengths. Both methods required different corrections to obtain reliable data (Collier and Chapuis, 1990; Dinevich et al., 2004). The disadvantages of the MRL-5 station included: too much time needed for data processing, manual operation, and technology exceeded by the current needs. Radar data determined by MRL-5 were not available in real time, and this was done only every 3 hours because the operator had to manually draw radar echoes on the map (Burcea, 2011; Apostu et al., 2005; Collier and Chapuis, 1990).

In 2000, two DWSR 2500 C-band Doppler radars were implemented in the meteorological radar network. Radars were manufactured by the American company Enterprise Electronics Corporation and were installed in Bucharest and Craiova. Acquisition of these radars marks the beginning of the digital era and Doppler technology in Romania.

The DWSR 2500 was built in solid state technology (without electronic tubes) and includes digital receivers, Doppler processors, Windows-based operating systems. The radar has the ability to analyze the evolution of storm winds for detecting and tracking severe phenomena, and also allows rainfall to be measured, hail conditions and floods to be detected.

In November 2000, the National Meteorological Administration started the modernization of the meteorological phenomenon monitoring and forecasting network, by implementing the National Integrated Meteorological System (SIMIN) project. Thus, in 2001 and 2004, two METEOR 500C radar systems were installed in Oradea and Baia Mare. Radar stations were produced by the German company Selex ES-Gematronik and provide reliable high resolution data to support meteorological analysis in a very short time. To generate high-frequency pulses, the radar uses a magnetron-based transmitter.

The SIMIN system also involved the installation of WSR-98D type radars supplied by the American company Lockheed Martin. The WSR-98D radars has the ability to research the airspace with a high accuracy over a maximum distance of 300 km. In Figure 4, the current SIMIN architecture in Romania is presented.

In 2003, the SIMIN program ended. Thus, five S-band WSR-98D Doppler radar radars have been installed on the Romanian territory. Existing radar stations in the 1960s were replaced by Doppler radar, 5 WSR-98D in the S band and 4 C-band radars to form a 9-radar network.

WSR-98D radars are valuable tools for detecting heavy convective precipitation, heavy rainfall and typhoons, and are based on meteorological algorithms developed in the US for more than 30 years (Ioana et al., 2004). Today, Romania has the most modern and unique meteorological networks in Europe, which incorporates 3 types of radar stations, the DWSR-2500C, the METEOR 500C and the WSR-98D.

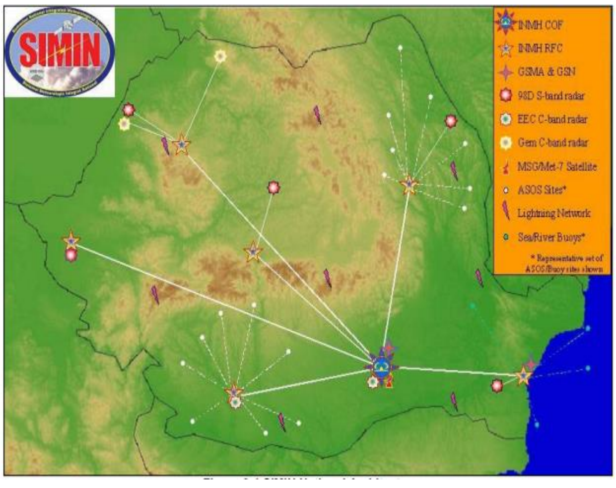

Fig. 4: Architecture of Romania INMS (Ioana et al., 2004)

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Each system generates data every 6 minutes, and the national mosaic is generated every 10 minutes. Through telecommunication systems, the data from radar stations is available anywhere in the NMA system, almost in real time.

In Romania, research in the field of meteorological radar is being done continuously. Research includes both methods and algorithms for estimating atmospheric precipitation, as well as research for the analysis of severe phenomena based on radar data. Among those who studied precipitation estimation are Burcea (2011), Bell, Seed and Bunn (2013), Poalelungi (2011), Burcea et al. (2012), Maier (2011) and Breza (2008).

The increasing occurrence of severe meteorological phenomena has led to increased interest in their research. For example, Paraschivescu (2010) studied the cases of severe weather, Bell, Sed and Bunn (2013) studied the radar characteristics of severe tropical storms and methods of estimating echo radar movement, Apostol and Machidon (2009) investigated hailstones in the Bârlad basin in which he used radar data, and Carbunaru et. al., (2014) analyzed hail detection.

A current concern is also finding new methods for estimating quantitative precipitation (QPE) based on radar observations. These estimates actually help meteorologists make predictions and alert the population in real-time when severe phenomena are going to happen. Crăciun and Catrina (2016) proposed a method of improving QPE compared to rainwater measurements and average polarization adjustment.

Studies have also been done to better understand precipitation data, for example, Burcea et al. (2012) analyzed several measurements in Romania. Also, Georgakakos and Spenser (2009) analyzed real-time rainfall in Romania using radar data.

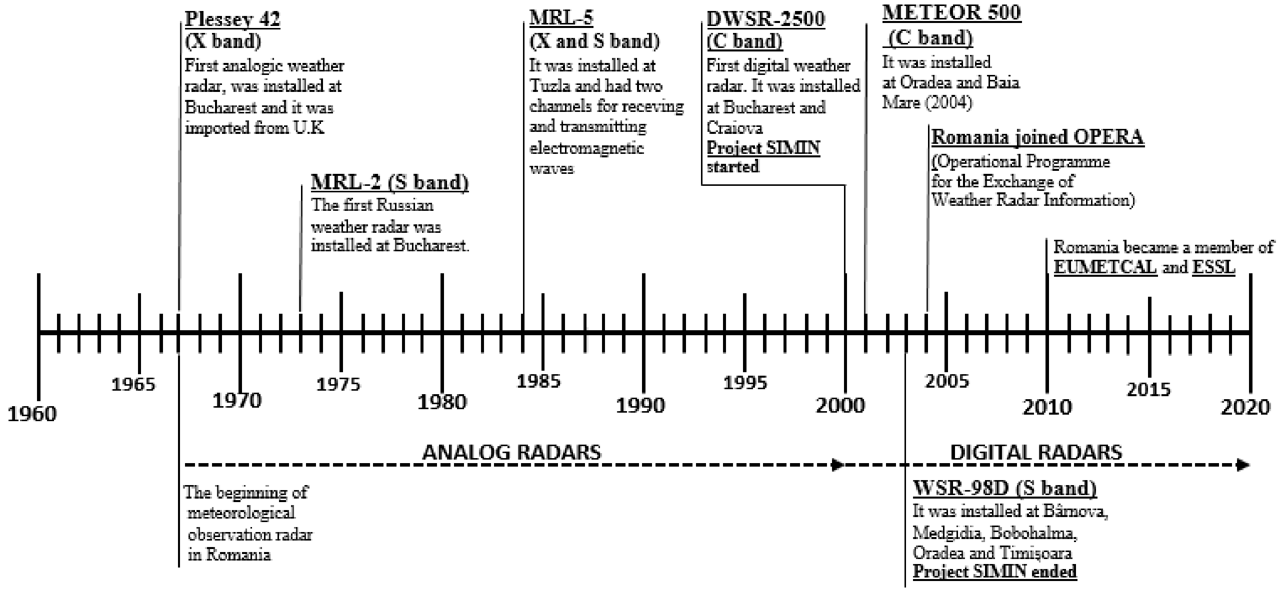

Fig. 5: Evolution of weather radar in Romania, 1967-2010 (Burcea, 2011; Ioana et al., 2004; Apostu et al., 2005; Perez et al., 1999)

5. Recent developments of weather radars

To improve the detection of meteorological phenomena, especially extreme weather conditions, continuous research is being done in the field of weather radar. The first discovery that has made substantial contributions to the analysis of weather phenomena is the Doppler effect. This technique describes the change in the frequency of the signal emitted by the reflective surface of a moving object. With this new capability, new radars can determine the direction and speed of movement of atmospheric precipitation.

Christian Johann Doppler (1803-1853) discovered this method in 1842 (White, 1982). The limitations of the analogue equipment delayed the implementation of the Doppler principle in weather radar, and it was only in the early 1970s that it was applied with the advent of digital techniques (Sundaram et al., 2004; Doviak and Zrnic, 1993).

A first step in improving data provided by radar is faster scanning of the atmosphere. Traditional radars are limited by the mechanical scanning of the antenna, so phased array antennas (PAR) have developed. The Phase Antenna directivity characteristic is electronically controlled and is displaced almost instantaneously in azimuth and angles of elevation, see Figure 5 (Zrnić, 2007; Isom et al., 2013). PAR technology is used for both meteorological phenomena research and aircraft tracking (multipurpose radar) (Newman, LaDue and Heinselman,2008; Cheong et al., 2013).

Most of the current meteorological radar (MRL-5, METEOR 500C, WSR-88D, etc.) are monostatic or bistatic, meaning the receiver and the transmitter are co-located. The performance of these types of radar has been improved by using the new methods of digital signal processing.

When space objects are irradiated by electromagnetic waves, the reflection of waves occurs in all directions. Therefore, several receivers are needed to capture all the energy of the electromagnetic waves. To overcome this limitation, multi-static radars with antenna networks are used, where each antenna has its own transmitter and receiver (Papoutsis, Baer and Griffiths, 2004; Yeary, et al., 2010).

The distribution of hidrometeors at meteorological radars made that the compression of the impulses to be used only for military surveillance radars. This technique, along with other signal processing techniques, has begun to be studied and applied to new meteorological radars.

IEE 686-2008 defines pulse compression as "… a method for obtaining the resolution of a short pulse with the energy of a long pulse of width T by internally modulating the phase or frequency of a long pulse so as to increase its bandwidth B >> 1/T, and using a matched filter (also called a pulse compression filter) on reception to compress the pulse of width T to a width of approximately 1/B" (IEEE, 2018, p.31).

The new weather radar must provide a great temporal and spatial resolution. By using a high frequency band, higher resolutions are possible than with NEXRAD radars. Temporal resolution for severe phenomena is a critical aspect because severe weather changes in a matter of seconds rather than minutes (NEXRAD provides a 4-minute temporal resolution and 6-minute WSR-88D).

Greater resolution is needed, and this can be improved by using the PAR technique.

Polarimetry is another technique present in new weather radars. Unlike the conventional radars, where emission and reception are realised by single polarization, the new radars allow using two types of polarisation (vertical and horizontal) (Figure 6) (Kumjian, 2013).

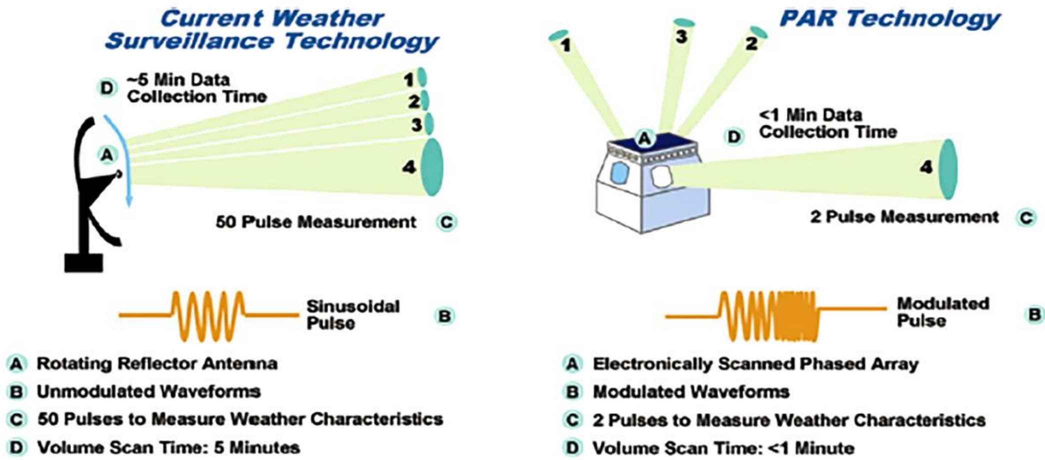

Fig. 6: The differences between traditional radar, and phased array antenna radar (PAR) (Zrnic, 2007)

This has led to a differentiation of radar reflection power Z, which ultimately helps, among other things, to distinguish hail from rain drops. An example of a radar incorporating phased array antenna technology, polarimetry and pulse compression is the CPPAR radar (Cylindrical Polarized Phased Array Radar), developed at the Oklahoma Radar Research Center (Zhang et al., 2011).

Figure 7 shows a photograph of this radar. The CPPAR system provides fast 360° coverage by flexibly adjusting the azimuth beam and height angle. The radar operates in the S band and provides a peak impulse output of only 1.5 kW.

Fig. 7: Cylindrical Polarized Phased Array Radar (Mark, 2014)

The progress made in technology through the development of integrated circuits, the digital processing of Doppler signals and the development of display systems have led to the improvement of radar technology. But the study of radar data has also played an important role in research into atmospheric studies, particularly in terms of cloud physics, the evolution of severe storms, precipitation estimation and hurricane tracking. Such knowledge has led to the development of new algorithms for data processing.

Conclusions

There is a huge effort made by many countries to investigate the atmospheric phenomena using the radar technique. In most countries, the efforts were put in parallel and involved diverse techniques with different approaches. Almost all researches were performed in order to understand the severe weather phenomena and to warn the population about them, but also because they represented obstacles to identify certain space objects. For example, during WWII, the precipitation, storms, tornadoes, etc., represented real problems in identifying own aircrafts or the enemy's aircraft. Early experiments had a huge impact on the new equipment built today, which are found in many countries. From the accidental detection and observation of precipitation on the circular observation gauges until today, technology has evolved continuously.

The history of the meteorological radar has also given rise to new concepts. For example, in 1952 M.G.H. Ligda invented the term of "Mesoscale" to describe the phenomena observed by the meteorological radar.

The meteorological radar was and still is highly used in meteorology due to its ability to operate in all weather conditions and airspace research. Several technological developments have succeeded in producing Doppler radars, radars in impulse, mono-impulse, networks phased array antenna, solid state transmitters, radar components digitizing as well as complex techniques of modulation of signal transmitted. All these techniques can be found in almost all modern radars, which, most of the times, are implemented in meteorology national and global networks. The data provided by each radar sensor provides real-time observation of meteorological phenomena and have an important role in warning.

Researches on meteorological radar technology are widespread and are motivated by the needs of society to improve the prediction of severe weather phenomena and to warn the population on short-term events. Today, researchers are focusing more on engineering in order to develop new tools. In the future, the trend of technology advancement will lead to the construction of passive radars, multi-mission radars, to share the electromagnetic spectrum and to digitize any radar equipment. An example of multi-mission radar can be considered the TPS-79 (R). This radar is mainly used for the air space surveillance and the air traffic control, but it also has the ability to determine up to 6 levels of atmospheric precipitations.

Generally, the information concerning the types of radars used at the international level are rare, but some trends can be deduced. Most radars operate in C-band and S, but most recent, those used the X-band are also used. For example, in October of 2013, the European weather radar network included 202 operational radars, out of which 184 had Doppler capabilities. The network included 169 radars that operated in the C-band and 33 radars in the S-band (Huuskonen et al., 2014).

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