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Mechatronic Concepts of Automated Weather Radars (a survey)

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Abstract

Quantification of precipitation is currently an important factor for agriculture but also for flood forecasting. In meteorology there is a strong interest in automatic stations and in replacing manually operated precipitation gauges with automated ones. This article mainly deals with measuring precipitation using radar (Radio Detection and Ranging). Standard weather radars can measure precipitation in a large territory, but to measure the local precipitation a vertically pointing radar is more suited. These types of radars use the Doppler effect to measure the speed of falling drops. The article describes some existing radar units, which allow automatic measurement of the present local rainfall. The common principles and methods for measuring precipitation will also be shown.

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Keywords: Doppler effect; measurement; precipitation; radar equation; weather radar.

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1. Introduction

The circulation of the water through atmosphere, earth and oceans is a key feature of the Earth's climate. Therefore, precipitation is one of the most essential atmospheric phenomena. The terrestrial ecosystem depends on the amount and the distribution of the water, and freshwater resources are extremely limited. Knowledge of rainfall and its variability in time and space is now very important. Not only current, but also historical measured data are important for the refinement of the hydrological models. These models are contributing to more accurate precipitation forecasts. This is connected with the earlier flood forecasting and as a result the protection of human lives and property. There have been increasing demands for automatic and maintenance-free systems in many areas

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for last few decades. This tendency also appears in the area of measuring precipitation. Many weather stations are located hundreds of kilometres from civilization and they have to operate without an operator. The weather conditions are also various, from hot deserts to the extreme cold in the polar regions.

The first known reference to rainfall measurement is in Arthasastra by Kautilya in India in the fourth century BC. In this treatise a bowl has been described with diameter of 457 millimetres and the amount of rainfall was determined by the number of filled bowls (rain gauges). These numbers allow to determine the amount of rainfall water in each part of the country and therefore grow crops, which need that certain amount of precipitation [1]. The first long-term continuous measurement of precipitation was in Korea. The gauges were established in the 15th century AD and were used until 1907. The measurements were probably used to aid in the cultivation of rice. There are no records of the actual measurements [2].

Nomenclature

z	radar reflectivity [mm^6m^{-3}]
R	precipitation intensity [$mm\ h^{-1}$]
D	diameter of rain drop [mm]
P_r	received power [W]
P_t	transmitted power [W]
r	distance to target [m]
Greek symbols	
θ	horizontal beam width [rad]
ϕ	vertical beam width [rad]

2. Measuring precipitation

2.1. Precipitation

Precipitation can be defined as all atmospheric water that falls on the Earth's surface (vertical precipitation) or deposited on the surface of objects and soil (horizontal precipitation). The water counted to precipitation is independent of whether it is a liquid (rain, drizzle), solid (snow, snow pellets, hail) or water in hidden form (frost, dew). Some types of precipitation can be a mixture of previous forms as sleet. Precipitation is formed by the combination of two processes: firstly, the condensation or deposition of atmospheric vapours that are produced by evaporation of water surfaces and soil; secondly, the condensation nuclei on which vapours are deposited. These are small aerosol particles with a size from 1 nm to 10 µm (dust, soot, pollen, sea salt, etc.), which are carried by vertical air currents. Microscopic water droplets are formed around condensation nuclei and vertical currents with vapours gradually increase their size during falling [3].

Precipitation most often occurs in the form of rainfall and less often in the form of snowfall. Contribution of other forms of precipitation to the total rainfall is negligible and usually neglected.

Liquid precipitation in form of drizzle has drops with size from 0.2 to 0.5 millimetres. The size of raindrops usually ranges from 0.5 and rarely reaches more than 6 millimetres because they are split with vertical air into smaller droplets, which hold stronger due to surface tension. Speed of drops ranges from 2 to 10 $m.s^{-1}$ depending on the size.

Solid precipitation has more forms than liquid and is created when air temperature is below zero. The temperature specifies which form of crystals and formations will be created. Snowfall also occurs in from of snow pellets which have size from 0.5 to 5 millimetres. Hail is another form of solid precipitation and we distinguish between small hail (from 2 to 5 millimetres), soft hail (same as small, but they are softer) and hail (from 5 to 50 millimetres or even larger) [4].

2.2. Precipitation in meteorology

The amount of precipitation in meteorology is interpreted as height of the water, which has been accumulated on the exposed horizontal surface (volume per area). This height is normally given in millimetres or inches. The height of one millimetre represents volume of one litre on one square metre. Meteorological records are usually kept with 0.1 millimetre resolution. The liquid form of precipitation can be also expressed as the weight of water pre area ($kg.m^{-2}$). The most common precipitation gauges have cylindrical shape and their collecting area is smaller than one square metre. Therefore, it is necessary to modify the measured value to the corresponding standardized unit. Amount of snow is often represented as depth of freshly fallen snow deposited over a specified period (generally 24 h). Solid form of precipitation can also be measured in the standard precipitation gauge, but only after conversion to liquid form. Every measurement also has a time stamp and therefore we can determine the intensity of precipitation ($mm.h^{-1}$). The sums over certain period can also be calculated [5].

2.3. Precipitation gauges

Precipitation gauges, as is clear from the above text, are elemental devices designed to measure liquid or solid precipitation. We can divide precipitation gauges into three categories: manual, mechanical-recording and electronic precipitation gauges.

More than fifty different manual precipitation gauges are used in the world. These precipitation gauges usually have a cylindrical shape with the bottom part laying in the soil. Precipitation enters through an opening at the top and is accumulated inside the precipitation gauge. The accumulated precipitation is measured as the difference of weight between a full and an empty precipitation gauge or simply by measuring volume of water. These measurements are carried out at regular intervals.

The category of mechanical precipitation gauges includes float and weighing type of precipitation gauges. Both of them work on the principle of mechanical power transfer to write a trend line to a drum or strip chart. These precipitation gauges could be equipped with a mechanism for automatic emptying and therefore they can operate relatively independently.

Electronic precipitation gauges are the most common. The main representative of this category is the tipping-bucket rain gauge. It works on the principle of the tipping over of a two-chamber bucket after filling the upper chamber with a specific amount of water. The tip over is electronically recorded and the number of repetitions indicates the amount of precipitation for certain period.

Another very often used precipitation gauge is the electronic weighing rain gauge. This device electronically measures the weight of collected water. The electronic principle allows precise and frequent measurements, but without an automatic emptying system, the collected water must be manually emptied.

A small class of precipitation gauges capable of measuring the size of precipitation particles are known as disdrometers. Disdrometers are able to determine the amount and distribution of precipitation particle sizes. These instruments can work on an acoustic, displacement, capacitive and optical principle. Due to the fact that they do not collect rainwater their maintenance is less frequent. These types of precipitation gauges are usually used as present weather detectors. Disdrometers unlike the receptacle rain gauges are not affected by evaporation and freezing of accumulated water, turbulences and oscillations due to wind.

The next device from the third category is the radar. In contrast to previous devices this measuring device can be placed on the ground or on satellites and covers a large part of the country. The measurements from local precipitation gauges must be extrapolated to achieve the same results, but sometimes result in larger errors.

3. Weather radar

3.1. Historical development of the weather radar

Early radar technology used electromagnetic waves only for the detection of human-made objects. For example, the early warning system for avoiding collision of ships and later in 1934 the device able to detect aircraft.

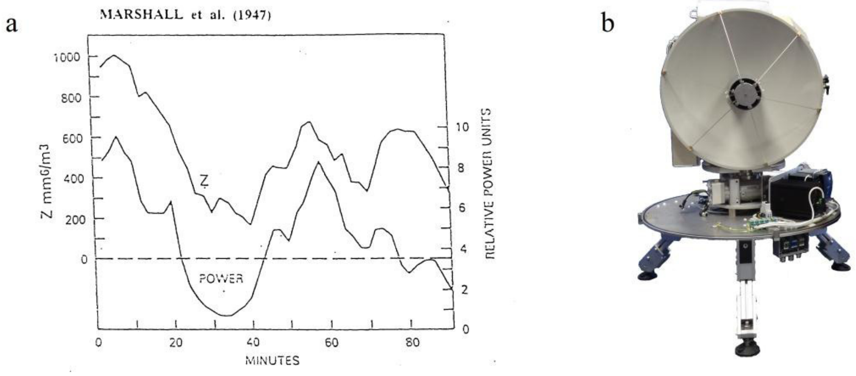

Fig. 1. (a) Time trend of received power and reflectivity of rainfall at range 8.8 km [6]; (b) Portable weather radar working at frequency 9.4 GHz. It has 55 cm parabolic antenna with measuring range 100 km [7].

Early users of radar observed that interferences with weather fronts masked targets or reflected energy from precipitation particles were considered as targets. This finding was firstly regarded as a disadvantage of the radar. The British researcher J. W. Ryde determined the relationship between the reflected power and intensity of rainfall in the early 40s of the 20th century. Thanks to that the research of the weather radar could begin. The first researches with radar used for meteorological purposes have been made by J. S. Marshall. He has worked on the project “Stormy Weather” since 1943. In 1947 he published a work [6], which showed a fine correlation between the received energy reflected from drops and radar reflectivity calculated from the observed samples of rain (Fig. 1a.). The radar reflectivity represents drop size distribution in volume. Marshall also introduced the relationship between the intensity of rainfall and the radar reflectivity:

$$z = 190R^{1.72} \qquad \left[mm^6 m^{-3}\right] \tag{1}$$

His work was as an inspiration to other researchers and therefore the development of the weather radar and the relationship between precipitation and the reflected energy has begun.

At that time, the radar was considered a revolutionary method for determining present precipitation with a large coverage. It was assumed that radar technology will completely replace traditional precipitation gauges, but it did not happen, because the radar does not provide correct information every time [8], [9], [10].

3.2. Description of the radar

One of the great advantages of the radar is its ability to cover a large area, usually from 15 000 to 300 000 square kilometres. This area corresponds to the radius of 70 to 300 kilometres (Fig. 1b.). The radar has the daily deviation of precipitation about 10%, which is also the error of ordinary precipitation gauges. However, stronger thunderstorms can supress shorter wavelengths (C-band) and therefore the measurement error could be up to 40% [5]. The radar can measure also restricted or hard to reach areas and measurements are available immediately, which was not possible in past.

Weather radars nowadays mostly use a rotating parabolic dish antenna, which creates a narrow electromagnetic beam with width from 1 to 2 degrees [11, 8]. Commonly used wavelengths are 3 centimetres (X-band with frequency 10 GHz), 5 centimetres (C-band with frequency 6 GHz) and 10 centimetres (S-band with frequency 3 GHz). These frequencies allow usage of smaller antennas and they are reflected very well by the precipitation particles.

The radar scans the area or the volume around by the rotation and elevation of the antenna. The movement of the radar dish and measurement are discontinuous and therefore adjacent steps should have some overlapping. The radar antenna usually rotates several revolutions per minute and after each revolution the elevation of the antenna is changed. This movement produces a set of nesting conical surfaces, which are available as whole after 1 to 10 minutes. If the some areas were not covered by this method, then they are calculated using extrapolation. Weather radars can usually also identify multiple reflections, which come from precipitation located behind another one. The obtained three-dimensional measurement dataset is called a volume scan or simply a volume.

Weather radar can be constructed as monostatic or bistatic based on the location of the antennas. A monostatic radar consists of a receiver, transmitter and the antenna or antennas in a single system. A bistatic radar has a receiver antenna and transmitter antenna located separately. First weather radars used the bistatic configuration and they continuously transmitted an electromagnetic beam. The current weather radars are usually monostatic and they generate a short pulse of microwave energy with a length of approximately 100 metres. This length ensures sufficient distance resolution.

In the case of a monostatic radar with a parabolic dish antenna the beam of electromagnetic energy is sent by the reflection from the antenna and then the radar is switched to receive mode. Measuring of the time of flight determines distance from target and amount of received energy determines parameter z.

The measured data can be displayed in several ways. Previously only a two-dimensional view PPI (Plan Position Indicator) was used. The display is formed with constant antenna elevation and nowadays it is associated with the geographical layer. This combination allows to accurately find the coordinates of precipitation in the range of the radar. The radar reflectivity or calculated precipitation rate is indicated with a colour spectrum. The CAPPI (Constant Altitude Plan Position Indicator) view is a horizontal cross section at a constant level. This display is created by horizontal intersections of data from a radar and usually is at 500 or 1000 metres [12]. There are also other ways to interpret measured data, for example vertical section of a storm or vertical composition of reflectivity. This view is created from the biggest measured reflectivity in each point of the display.

The weather radar works automatically without human operators and information systems provide processing and sharing measured data to the user.

3.3. Influences to measuring with the radar

The weather radar is affected by many influences, which increase the measurement uncertainty. The measuring of precipitation can be affected by various fall speeds of drops and also by air turbulences which cause fluctuations in the amplitude and phase of each reflected pulse. The weather radar can overestimate precipitation intensity when measuring snowfall and it can underestimate drizzle. The measuring can also be affected by an environment, which deforms transmitted electromagnetic beam.

The pulse weather radar can receive secondary reflections from the first pulse that are processed after transmitting the second pulse. This event causes the creation of weak false targets that are closer than real ones. Devices, which are transmitting at similar frequency also cause a significant impact on the measurements.

4. Determination of rain intensity with the radar

4.1. Radar equation

To determine the intensity of precipitation it is necessary to establish a correlation between the received power and intensity of precipitation from which the transmitted energy was reflected. This relation also depends on the parameter RCS (Radar Cross-Section). The RCS determines how the measured object is visible to the radar and its value depends for example on the material, size and angle to the object. Precipitation has relatively low RCS in comparison with terrain obstacles or aircrafts.

The power received by the weather radar is given by the meteorological radar equation [13]:

$$P_r = \frac{\pi^3 P_t g^2 \theta \phi h |K|^2 lz}{1024 \ln(2) \lambda_t^2 r^2} \quad [W] \tag{2}$$

where g is the antenna gain, h is the length of pulse, $|K|^2$ is the dielectric constant factor for a specific precipitation type, l is the atmospheric attenuation of the beam and λ_t is the wavelength of transmitted radiation.

The radar reflectivity can be interpreted with equation (3). It represents drop size distribution within the measured volume defined in radar equation (2) by radar beam width, height and length.

$$z = \sum_{volume} D^6 \quad \left[mm^6 m^{-3}\right] \tag{3}$$

From formula (3) it is clear that bigger drops have significantly higher reflectivity than smaller ones. Normally the drop size distribution is unknown; therefore parameter z is expressed from equation (2). To simplify the radar equation, the length of pulse is replaced with duration of pulse t_t and propagation speed of radiation c. Then we get equation (4).

$$z = \frac{P_r 1024 \ln(2) \lambda_t{}^2 r^2}{\pi^3 P_t g^2 \theta \phi c t_t |K|^2 l} \quad \left[mm^6 m^{-3}\right] \tag{4}$$

If we substitute all known variables in (4) with parameter c_1, then the simplified form will be:

$$z = c_1 P_r r^2 \quad \left\lfloor mm^6 m^{-3} \right\rfloor \tag{5}$$

The result will be calculated only from data measured by the weather radar: received power and distance to a target.

The range of reflectivity varies widely from 0.001 mm^{6}m^{-3} during fog to 36 mm^{6}m^{-3} during a hailstorm with particles the size of a softball ball. It is usually expressed in dB of reflectivity or dBZ:

$$Z = 10 \log_{10} \frac{z}{1 mm^6 m^{-3}} \quad [dB] \tag{6}$$

As mentioned before, to determine intensity of precipitation from reflectivity we need to know the drop size distribution within the transmitted beam. Therefore, the simplified form was introduced which describe relationship between reflectivity z and precipitation intensity R:

$$z = AR^b \quad \left\lfloor mm^6 m^{-3} \right\rfloor \tag{7}$$

where constants A and b are empirically determined. There were many combinations of these constants in the past, but the most commonly used is the Marshall-Palmer relationship [5]:

$$z = 200R^{1.6} \quad \left\lfloor mm^6 m^{-3} \right\rfloor \tag{8}$$

When we express the unknown intensity of precipitation, then we get formula (9) where the constant C=0.036 mm.h^{-1} and Z is reflectivity in dBZ.

$$R = C10^{0.0625Z} \quad \left\lfloor mm.h^{-1} \right\rfloor \tag{9}$$

4.2. Radar with Doppler mode

In meteorology Doppler radars are used more often since the 70s. Nowadays, it is a standard part of most weather radars. The Doppler radar works on the principle of measured change between the transmitted and received frequency. This difference determines the horizontal speed of the precipitation particles and by that wind speed [14].

5. Vertically pointing Doppler radar

5.1. Description of the vertically pointing Doppler radar

Vertically pointing Doppler radars are very similar to standard weather radars. These radars tend to have smaller dimensions and lower radiation power with lower power consumption. Initially they were used as detectors indicating precipitation occurrence, but later they were used to determine the intensity of precipitation

Due to the vertical position the Doppler radar is able to estimate the fall velocity of precipitation particles from the difference between received and transmitted frequency. This velocity is lowered by the influence of the horizontal wind. Therefore, for better accuracy it is appropriate to compensate this effect. If the speed of the wind v_w is known, then we can calculate the real falling velocity of particles v_t:

$$v_t = \sqrt{{v_w}^2 + {v_r}^2} \qquad \left[m.s^{-1}\right] \tag{10}$$

In order to determine the intensity of precipitation, we need to know which diameter of particles corresponds to a specific falling velocity. The relationship between the diameter of a drop and terminal fall velocity of the drop was published in [15] as:

$$v_t(D) = 9.65 - 10.3e^{-0.6D} \qquad \left[m.s^{-1}\right] \tag{11}$$

This equation is well suited for drops with diameter larger than 0.4mm. Its disadvantage is the calculation of negative values at smaller drop diameters. Lately other approximations that do not produce negative values were published, but those have lower accuracy. Equation (11) is plotted in Fig. 2a., there we can see the settlement of speed of larger drops, because drops larger than 6 millimetres are split to smaller ones.

Rainfall consists not only of one size of drops, therefore, measured data are Doppler spectrum of frequencies or speeds (power density spectrum). This spectrum needs to be analysed by FFT (Fast Fourier Transform) to get particle size distribution within the measured volume. This corresponds with equation (12):

$$S(v_t) = N(D)\sigma(D)\left(\frac{dD}{dv_t}\right) \qquad \left[mm^2 m^{-3} m^{-1} s\right] \tag{12}$$

where *S*(v_t) is the Doppler spectrum, which quantifies how much power from each speed range was received, *σ(D)* is the backscatter cross section of a drop of diameter *D* and fraction dD/dv_t is the relationship between the drop diameter and terminal fall velocity [16]. The drop size distribution *N(D)* can be defined as an exponential distribution and equation (13) is one possible representation. According to the Marshall-Palmer drop size distribution coefficients are: $N_0 = 8000$ m^{-3}mm^{-1} and $\Lambda = 4.1R^{-0.21}$ mm^{-1} [17].

$$N(D) = N_0 \exp(-\Lambda D) \qquad \left[m^{-3} mm^{-1}\right] \tag{13}$$

The equation for the drop size distribution (13) is often used to calculate the intensity of the rainfall from measured reflectivity. However, this characteristic depends on the geographic location, type of storm, season and other factors. To better represent the drop size distribution a modified formula was published. This formula is in form of a gamma distribution:

$$N(D) = N_0 D^{\mu} \exp(-\Lambda D) \qquad \left[m^{-3} mm^{-1}\right] \tag{14}$$

where parameter μ can be from -3 to 8.

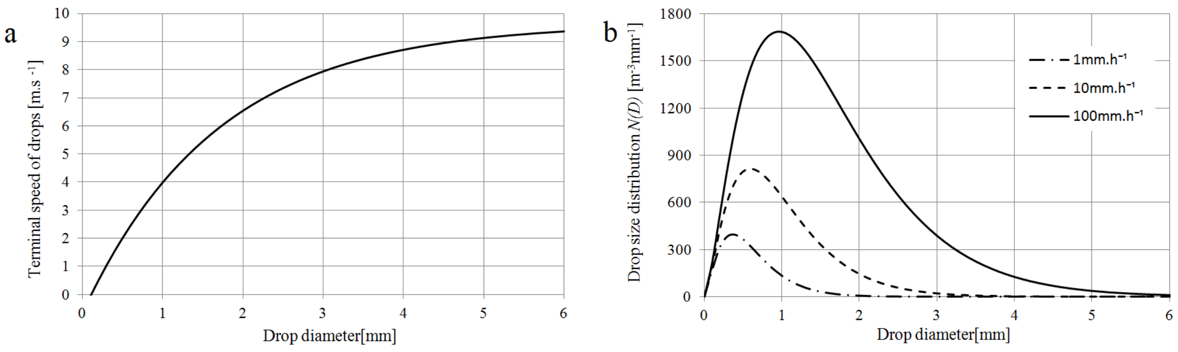

Fig. 2. (a) Terminal velocity of drops according to equation (11); (b) Drop size distribution according to (14), parameter μ=1.5.

To determine the distribution of solid particles (snow, hail) other coefficients are used. Another equations were also published in [17].

The resulting intensity of precipitation we determined based on the formula:

$$R = \frac{\pi}{6}\int N(D) v_t(D) D^3 dD \qquad \left[mm.h^{-1}\right] \tag{15}$$

5.2. Influences to measuring with a vertically pointing radar

Influences on a vertically pointing radar are similar to those of a standard weather radar. The following list defines influences that are specific to this type of radar [18]:

- Mie scattering (when radiation meets particle then reflection, absorption, refraction and interference occurs)
- vertical wind; shifting the power spectrum along the velocity axis
- broadening of the Doppler spectrum due to turbulence
- flattening of large drops due to air resistance
- microwave attenuation
- variation of the terminal fall velocity of rain drops with altitude

Some influences, such as attenuation and variation of the terminal fall velocity with altitude, are of minor importance when the distance to particles is small. Relatively large influence is caused by drop scattering, which depends on the wavelength of incident wave, the diameter of the particle and complex refractive index as a function of the material properties and the temperature.

5.3. Variations in design

In 1985 a small Doppler radar was developed for the automatic detection of precipitation occurrence, type and intensity [19]. It measures Doppler spectrum of a small volume immediately above the device. The spectral mode is used to identify the type of precipitation and the spectral power is used to calculate the intensity of the precipitation.

The receiver and transmitter are housed separately and their antennas are identical smooth-walled rectangular pyramidal horns. The antenna axes are oriented 20° from the vertical so that they intersect midway between the two antennas 31 cm above the horizontal plane through the centre points of the radomes (Fig. 3a.).

Two aluminium plates were mounted vertically between receiver and transmitter to increase the isolation between antennas. The transmitting Gunn diode was used, that continuously radiates at 10.525 GHz (X-band) with nominal power 100 mW. The scattered signal is detected by the receiver and homodyned with the transmitted signal via semirigid coaxial cable. The resultant Doppler signal is amplified by an 84 dB gain amplifier with a pass band frequency range from 35 Hz to 1 kHz.

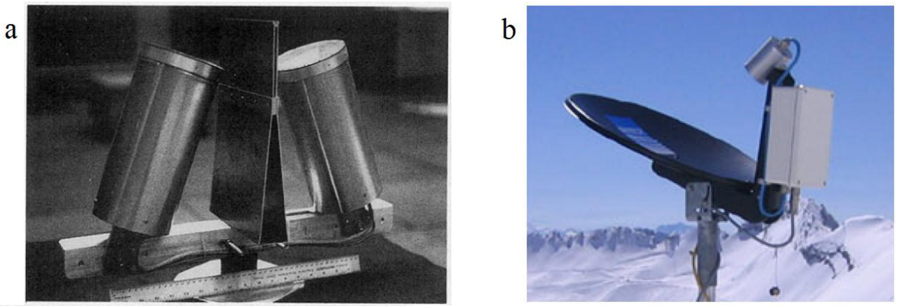

Fig. 3. (a) Photograph of POSS (Precipitation Occurence Sensor System) small Doppler radar [19]; (b) Vertically pointed FM-CW radar named MRR [20].

The METEK company developed a vertically pointing, height-resolved distribution Doppler radar called MRR (Micro rain radar). The MRR was originally designed to measure precipitation from buoys in the North Sea and to avoid error from sea spray [21] (Fig. 3b.). It is a FM-CW (Frequency Modulated Continuous Wave) radar, which is able to modulate transmitted frequency and continuously radiate [18]. The heart of the radar is a frequency-modulated Gunn diode oscillator at nominal frequency 24 GHz. This frequency can be changed depending on measurement in the range from 0.5 MHz to 15 MHz. The transmitted electromagnetic wave has a power of 50 mW and is focused by a 50 cm offset parabolic antenna. The resulting beam has a 3° width. The transmitted frequency is modulated with a signal in form of a sawtooth wave. A receiver receives shifted transmitted signal, which is the result of the distance of the illuminated particles from the radar (time delay) and the fall velocities of the particles (Doppler shift). These properties provide adjustable altitude resolution from 20 to 200 m at level 300 to 3000m. The integrated RCPD (Radar Control and Processing Device) uses a DSP (Digital Signal Processor) to process the measured data and calculates the power spectrum 25 times per second. The collected data contain information about particle size distribution in selected altitude and layer thickness.

Under the State Hydro Meteorological Service of the Russian Federation an inexpensive Doppler radar has been developed and constructed [22]. It is based on a mass-produced microwave unit, which is commonly used for interior alarm systems. The oscillator, as in previous systems, uses a Gunn diode oscillating at a frequency of approximately 11 GHz. The microwave unit has a rectangular pyramidal horn antenna, which radiates the microwave energy to the environment (Fig. 4a.).

We can measure precipitation with the use of conventional Doppler radar units in form of a microwave sensor designed to detect approaching vehicles [23]. This study was made by the Czech company Radan s.r.o. Measurements have shown that the size of the amplitude, but also the shift of power spectrum was due to the influence of rain.

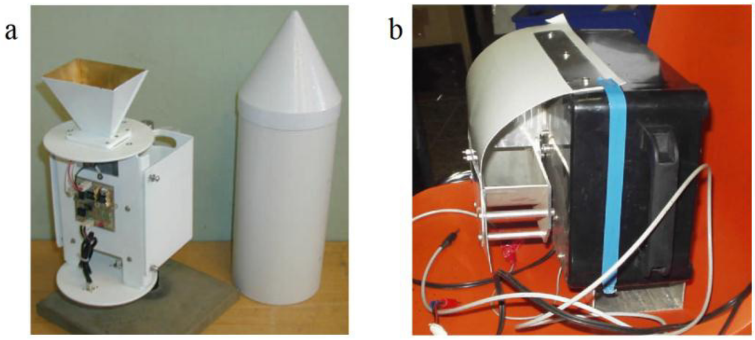

Fig. 4. (a) View of the open Doppler radar with a single rectangular pyramidal horn antenna [22]; (b) Vertically pointing Doppler radar, originally used for detection of approaching vehicles [23].

6. Conclusion

The article shows an introduction to the possible ways of measuring precipitation in meteorology. The main focus of the article was radar technology used in this segment. Currently automatic meteorological stations come to the forefront due to their ability to work without maintenance for very long periods. These stations are to be used in different areas of the Earth; therefore, in some cases using the vertically pointing Doppler radar is the most suitable solution. This type of precipitation gauge does not tend to jam with sand or freeze. In the article we also listed variations of these types of radars and also experimental versions.

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References

[1] R. Shamasastry, Kautilya's Arthasastra, Bangalore Government Press, Bangalore, 1915.
[2] Y. Wada, Scientific memoirs of the Korean Meteorological Observatory, first ed., Chemulpo, 1910.
[3] A. Musy, Ch. Higy, Hydrology: A Science of Nature, Presses polytechniques et universitaires, Lausanne, 2010.
[4] W. Brutsaert, Hydrology An Introduction, Cambridge University Press, New York, 2005.
[5] WMO (World Meteorological Organization), Guide to Meteorological Instruments and Methods of Observation, seventh ed., WMO, Geneva, 2008.
[6] J.S. Marshall, R.C. Langille, W.K. Palmer, Measurements of rainfall by radar, J. Meteor. 4 (6) (1947) 186-192.
[7] MicroStep-MIS, s.r.o., Mini-portable Meteorological Radar MMR50: User's Guide, Bratislava, 2013.
[8] I. Strangeways, Precipitation, Theory, Measurement and Distribution, first ed., Cambridge University Press, Cambridge, 2006.
[9] B. Muller, Radar-introduction: History of Weather Radar, [online], Available: http://opwx.db.erau.edu/faculty/mullerb/Wx365/Radar_intro/radar_intro.html.
[10] J.C. Kurtyka, Precipitation Measurement Study, State Water Survey Library, Illinois, 1953.
[11] I. Virgala, P. Frankovský, M. Kenderová, Friction Effect Analysis of a DC Motor, Am. J. Mech. Eng. 1 (1) (2013) 1-5.
[12] I. Holleman et al., (2006), Quality information for radars and radar data. [online], Royal Netherlands Meteorological Institute, Available: http://www.knmi.nl/publications/fulltexts/opera_wp12_v6.pdf.
[13] B. Muller, Radar equation, [online], Available: http://wx.db.erau.edu/faculty/mullerb/Wx365/Radar_equation/radar_equation.pdf.
[14] B. Muller, Doppler Radar Formulas, [online], Available: http://wx.db.erau.edu/faculty/mullerb/Wx365/Doppler_formulas/doppler_formulas.pdf.
[15] A.C. Best, Empirical formulae for the terminal velocity of water drops falling through the atmosphere, Quart. J. Roy. Meteor. Soc. 76 (329) (1950) 302-311.
[16] L. León-Colón, S.L. Cruz-Pol, S.M. Sekelsky, Active rain-gauge concept for liquid clouds using W-band and S-band Doppler radars, SPIE 9th International Symposium on Remote Sensing, Crete, 2002.
[17] R.J. Dovniak, D.S. Zrnić, Doppler Radar and Weather Observations, second ed., Dover Publications, New York, 2006.
[18] M. Löffler-Mang, M. Kunz, W. Schmid, On the Performance of a Low-Cost K-Band Doppler Radar for Quantitative Rain Measurements, J. Atmos. Oceanic Technol. 16 (3) (1999) 379-387.
[19] B.E. Sheppard, Measurement of Raindrop Size Distribution Using a Small Doppler Radar, J. Atmos. Oceanic Technol. 7 (2) (1990) 255-268.
[20] S. Kneifel et al., Observation of snowfall with a low-power FM-CW K-band radar (Micro Rain Radar), Meteor. Atmos. Phys. 113 (1-2) (2011) 75-87.
[21] D. Klugmann, K. Heinsohn, H.J. Kirtzel, A low-cost 24-GHz FM-CW Doppler radar rain profiler, Contrib. Atmos. Phys. 69 (1) (1996) 247-253.
[22] A. Koldaev et al., The Low Cost Radio Frequency Rain Meter, WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation, Bucharest, 2005.
[23] O. Pokorný, Measurement of precipitation with Doppler radar sensor, Radan s.r.o., Živanice, 2009.