

## METHODS FOR MONITORING AND ESTIMATION ATMOSPHERIC PRECIPITATIONS

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**Abstract:** *The monitoring and estimation of atmospheric precipitations are extremely important in the analysis of rainfall risks. The present article presents three methods of precipitation monitoring and estimation, being the most frequently used today, namely, the weather radar, the rain gauge and the satellite. The main objective of this article is to present these three types of instruments and to highlight the errors and limitations that can occur in estimating and determining atmospheric precipitation. Each technique is limited by certain disadvantages and therefore the methods need to be complemented to some extent. This has led to the interconnection of different sensors that combine the strengths of each sensor.*

**Keywords:** *satellite, rain gauges, microwaves, weather radars, precipitations.*

### 1. INTRODUCTION

Precipitation-wise, observations are used in several ways in the process of analyzing rainfall risks (rain, ice, pole, hoar-frost, snow, hail, etc.), including the generation of alerts, and the determination of precipitation levels is a necessary factor. The most used precipitation monitoring techniques are: meteorological radars, rain gauges and satellites. The main objective of this article is to present these three types of instruments and highlight

which errors may occur in estimating and determining atmospheric levels of precipitation.

All three types of tools are used both on a network and individually due to temporal and spatial resolutions. The limitations of each instrument are reduced by combining all of the methods. Satellites offer a great advantage in researching meteorological phenomena because they cover areas which would be either impossible for the other instruments to reach, or too expensive.

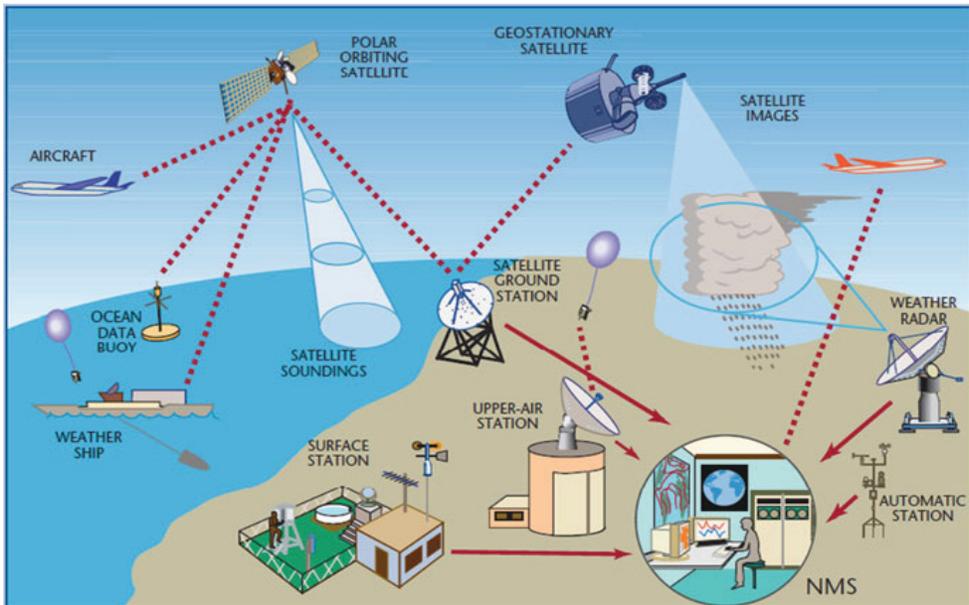


Fig. 1 Global system for observation and measurement of precipitation [16]

## 2. METHODS

### 2.1. WEATHER RADAR

The first operational radar was used for the first time in 1930, with the purpose of detecting and tracking not only the enemy aircraft, but also friendly aircraft, and the first meteorological-wise use was made by England in 1942 [31]. The name of RADAR (Radio Detection and Ranging) was conceived by the US Naval Forces in November 1940. [26]

Experimental research in the field of meteorology began immediately after the end of World War II as a result of the problems caused by meteorological phenomena in the identification and detection of bombers. At that time, it was found

that radars could be a useful tool for remote atmospheric research and observation. The first weather radars were built with surplus war equipment (AN / TPS-2, SCR-717C, AN / APQ-13, etc.), and then new radars were designed. Among the first specially built meteorological radars for this purpose, were: CPS-9, CPS-18, WSR-88D, or WSR-98D

Conventional radars developed after the end of World War II were replaced in 1990 with Doppler radars. Using the Doppler frequency, the radars can measure the intensity and speed of precipitation movement. Generally, a weather radar has a transmitter, receiver, antenna, display system and auxiliary systems, (see figure 2).

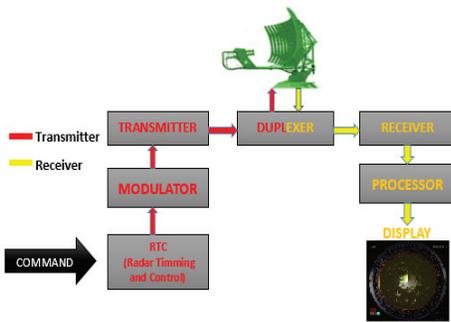


Fig. 2 Block diagram of a weather radar

The operating principle is based upon the emission of electromagnetic energy in the atmosphere in the form of short bursts, high power and very high frequency (see figure 3). When the electromagnetic impulses encounter an object (trees, mountains, atmospheric precipitation, aircraft, etc.), a fraction of the energy is reflected back to the radar. The received signals are amplified, processed and displayed on the indicator depending on the intensity of each received signal [23].

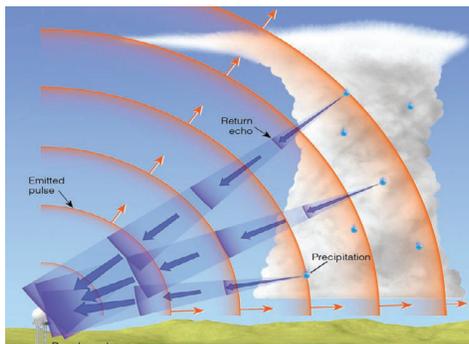


Fig. 3 Emission and reception of electromagnetic waves when the impulse is reflected by rain drops. Red symbolizes the impulses emitted by the radar, and blue represents the reflected waves or the echo signals [25].

When the radars are included in a network, they have the ability to provide qualitative information. The information also offers support in carrying out the data acquisition process for the development of forecast models at convective and mesoscale levels.

To cover as much airspace as possible, the radar has the ability to use multiple scanning angles, providing with the opportunity of having an overview of precipitation variations. The scanning angles can be changed either by adjusting the height of the antenna or by moving the beam horizontally or vertically, which is electronically controlled. Depending on the weather or relief conditions, the scanning strategy can be adjusted by increasing or decreasing the rotation speed of the antenna. The most commonly used frequency bands chosen for weather radars are those in the C or S bands. Radars in S-bands are more expensive and less attenuated due to higher wavelengths, and those in C-band are less sensitive to lighter rainfall.

Radar detection capability depends on a number of factors including altitude, local topography, impulse power, dead cone radius, polarization, etc. On average, the maximum detection radar of a weather radar is between 200 and 300 km. Even if the distance were much larger, the spatial resolution would

be affected by the curvature of the earth and the size of the directionality characteristic proportional to the length. Usually, the directivity feature is aimed at low heights to estimate the amount of precipitation on the ground. The reflected power is given by the reflection ratio and the intensity of the reflection. The parameters are calibrated based on comparisons between rainfall, radar and other precipitation estimation tools.

After upgrading the Doppler-capable radars, they allowed analysis of pulses in frequency, phase or amplitude, which allowed for an estimation of the speed of hydrometeors. The types of precipitation and false signals from other objects (birds, aircraft, land or sea clutter, etc.) can be recognized due to the implementation of Doppler frequency in radar systems.

Recently, new radar technologies have also been implemented with different hydrometeor identification techniques, such as polarimetry. During a period of pulse repetition, each pulse is transmitted with both linear (vertical or horizontal) and circular polarization (with left or right rotation), and the differences on each polarization are recorded and compared. Polarimetry provides additional information on received signals and helps improve data quality. This technique is found in national meteorological networks, including: Great Britain, Japan,

France and the USA.

Recently, X-band radars (3 cm) have also been developed. This type of radar is limited by the attenuation of the signal over longer distances, therefore the maximum distance of action is 60 km, but it ensures a higher sensitivity and lower costs. Also, because of its small size, the radar can be arranged on multiple platforms, even airborne. The data provided by the radars are implemented in different applications for generating weather warnings.

### **2.1.1. Interpreting the results**

The weather radar, like any instrument, comes with both advantages and disadvantages. One of the important advantages is the ability to detect rainfall over a fairly large distance (usually 15000 km<sup>2</sup>), as opposed to a rain gauge, which offers measurements at only one point.

The intensity of precipitation is given by the surface of reflection of the objects, and the uncertainty of conversion between the two is given by the variation of the dimensions, the reduced spectrum, the presence of snow and hail and also, the melted snow increases the surface of reflection and leads to overestimation of the rain intensity.

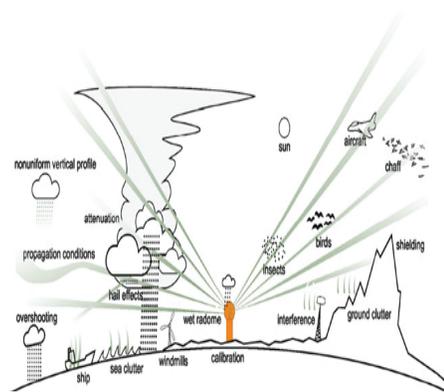
The quality of the data has been and is a main research objective since the first uses of the radar. The estimated precipitation of the radar is made difficult by a series of errors

from different sources. Some of them are also due to the complex process of measuring and processing atmospheric precipitation and they cannot be completely eliminated [29].

The main aspects of data quality depend on the elimination of errors, which may be of hardware, software, scanning strategies, terrestrial, maritime or aerial clutter. Hardware errors include: electronic stability, antenna accuracy, signal processing, along with software errors which include the obtained signal processing algorithms [6].

Other errors are determined by the interference of the electromagnetic energy with other emission sources, located in the near area, the abnormal propagation of the electromagnetic impulses due to the specific atmosphere, the reflection of the waves with different objects in the research space (birds, buildings, airplanes, etc.) [3], see figure 4. Another group of errors is associated with beam geometry, scanning strategy and data interpolation from sampling points [4].

To solve some of the problems listed above, the data provided by a radar network are combined to provide a composite or mosaic image. A series of measures to eliminate non-meteorological echoes can be found in Table 1. Sometimes raw or raw fragments of data from a single radar are also used to provide users with the possibility to obtain their own post-processing algorithms.



**Fig. 4** Phenomena and objects which affects the quality of radar data [15]

However, in order to eliminate unwanted echoes, other than those from rainfall, measures must be taken to eliminate external interference signals, eliminate false echoes from heights greater than 20 km and to very low heights [27].

**Table 1.** Methods of eliminating the non-meteorological echoes

Nr. crt	Methods
1	<b>Spatial interpolation (Kiring)</b> - Necessary for eliminating external interference signals.
2	<b>Jam protection filters</b> - Signals reflected by objects at low heights.
3	<b>Meteosat filter.</b> Provides a preliminary method of removing unwanted echoes. Meteosat distinguishes 20 classes of clouds with classes 1 to 4 assigned to areas that are not covered with clouds. The other unknown areas are treated as false signals and are not taken into account.
4	<b>Artificial intelligence algorithms.</b> For example, neural algorithms are based on the analysis of the reflection structure.
5	<b>Polarimetry.</b> The method involves analyzing the signals emitted with circular and linear polarization. A combination method is the logic fuzzy scheme.

Source: [11], [12]

More high definition Doppler clutter maps are used. They offer a unique analysis of the digital terrain model, taking into account the obstacles, the topography, the power distribution of the directivity feature for the standard conditions. Part of the potential problems related to the accuracy of observations and coverage are illustrated in Fig. 4. In some cases, they also represent opportunities for study, for example, in the field of emerging aeroecology.

In most cases, the data provided by the rain gauges are used for radar calibration, but there are errors in the data provided by the rain gauges, and in the adjustment schemes an allocation is made for these uncertainties expressed as functions of the ratio between the values of the rain gauges and the radar.

## 2.2. RAIN GAUGE

The rain gauge is the simplest instrument for measuring the atmospheric precipitation that reaches the surface of the soil. According to the study organized by the World Meteorological Organization, between 2008-2009, regarding the techniques of measuring solid precipitation at the weather stations, it turned out that the most used instrument is the rain gauge [13].

Most rain gauges used today originate from the invention of Korean scientist Jang Yeong Sil, who, in 1441 designed this device to measure precipitation for agricultural purposes. In Europe, only in 1662,

Christopher Wren succeeded in inventing the tilting rain gauge [16].

Rain gauges fall into two broad categories: manual and automatic. The manual ones are called SRG (Standard Rain Gauge), and the operating principle is relatively simple and involves collecting rainfall in a cylindrical container with a fixed diameter, see figure 5. It measures the volume or weight of precipitation dropped to the ground according to the type of rain gauge. The manifold hole can be arranged at different heights above the ground or at the same level depending on the maximum expected depth of the snow layer or water level.

For example, the most used height in over 100 countries, for the measurement of solid precipitation, varies between 0.5 ÷ 1.5m [32]. Usually, measurements are made every 24 hours. The diversity of rain gauges (the height or shape of the hole) in most countries makes the measurements made with these devices not strictly comparable [32].

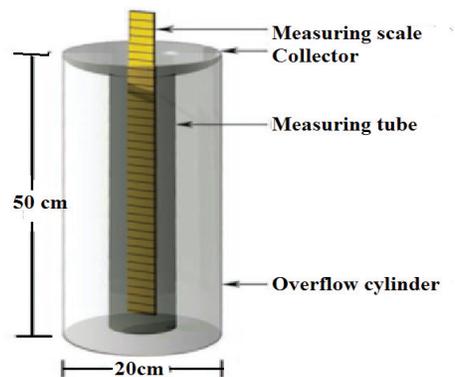


Fig. 5 The components of a standard rain gauge standard [1]

Among the most widespread automatic rainfall meters there are rainfall meters based on tilting and weighing, optical and capacitive. In figure 6, a type of tilting rain gauge can be observed, which includes a funnel that leads to two metal movable collectors attached on a pivot. Collectors accumulate precipitation, and when a certain amount accumulates, the weight of water causes the metal collector to tip over. As the first collector empties, the second collects rainfall. Each time a collector releases the accumulated precipitation, it makes an electrical contact, which is recorded and allows automatic measurement.

In order to verify the data regarding the amount of precipitation estimated by the meteorological or satellite radars, most of the weather stations have at least one rain gauge. This helps calibrate atmospheric precipitation estimation techniques. When choosing the type of rain gauge, it is necessary to take into account a number of factors, including: performance, reliability, cost, maintenance, standards and purpose.



Fig. 6 Example of tilting rain gauge [1]

In 2016, globally, the total area measured with the help of rain gauges was approximately half of the total area of a football field (7140 m<sup>2</sup>) or 0.000000000593% of the total surface of the Earth [9]. The number of existing rainfall meters cited in the literature varies. For example, Sevruc and Klemm (1989b) mention that the total number of existing rainfall globally is over 150,000, while Groisman and Legates (1995) have estimated 250,000.

### 2.2.1. Interpreting the results

As with other types of instruments, the rain gauge has certain limitations regarding the accuracy of the observations. The inaccuracy of the data comes from both calibration and electromechanical problems as well as from other factors, which are presented in table 2. Errors can be caused by wind, buildings, trees, collector size, etc. To reduce such errors, different techniques are used and certain measures are taken. For example, to reduce the effect of the winds, so-called shields are used. In most cases, for the calibration of instruments, the reference rainfall values are used. In areas with lower temperatures, snow may block the instrument or prevent reading. The instrument may also be affected by the vegetation around the instrument, insects or animals. In order to eliminate or limit these problems, many countries have set standards

for the installation, operation and evaluation of the uncertainty of the results [20], [30]. Measurements serve as the primary source of data for area analysis.

Even if rainfall is well measured, it is only for a certain area limited by the physiographic homogeneity of the region, the local topography or the accumulation period. Other sources of precipitation measurement, such as radars or satellites, are used to quantify and define the spatial distribution of precipitation. In most cases, the three data sources are integrated to provide accurate estimates.

Changing the position of the rain gauge, the installation height or the choice of another type of instrument can cause temporal or spatial inhomogeneities [19]. Calibration techniques based on statistics help to eliminate inhomogeneities and to correct measurements, to eliminate the errors induced by the wind or other parameters. The initial records and correction formulas must be kept because these corrections have uncertainties, and any changes in observation methods must be documented.

Knowing the position and number of each instrument is important because it determines how well the measurements are made and represents the actual amount of rainfall in the area. Corrections for

precipitation calculation by area and topography can be found in WMO (1992a).

**Table 2.** Errors that may appear during the measurements of atmospheric precipitations

Nr. crt	Errors
1	<b>Leveling.</b> If the rain gauge is not installed at a 90° angle then the instrument will have an error of about 1% at each inclination level. [10]
2	<b>Evaporation of water.</b> The water can be retained by the funnel residue, which will then evaporate. The material from which the funnel is made must be carefully chosen, to allow for the best flow of water.
3	<b>Collector size.</b> For example, in the case of manual measurements, if the collector is too large and the water too little, the measurements will be inaccurate.
4	<b>Positioning.</b> The location of the instruments must be chosen to represent the surrounding area. Positioning in an area near trees, buildings or other objects influences rainfall accumulation. Ideally, a rain gauge should be installed at least 4 times the height of the instrument.
5	<b>The effects of the wind.</b> The wind prevents the capture of precipitation in the proportion of 5-50%. One of the methods of protection against this effect is "the shield" or shield of the instrument. The rain gauge should be arranged where the air currents are as horizontal as possible

Nr. crt	Errors
6	<b>Splashing.</b> The surface around the instrument must be covered with gravel or turf to prevent the raindrops from spreading inside the rainfall accumulation cylinder.
7	<b>Exposure.</b> The instrument should be placed as close to the ground as possible if the wind speed increases with the height, but it should also be taken into account that if a position that's too low is chosen, then there is a possibility that the water will enter the instrument after it reaches the ground.

From a technological point of view, the rain gauges with mechanical or manual recording and the development of those with electric recording have led to the emergence of automatic rain gauges that can record, measure and transmit the measurements in real time to users. The availability of near real-time measurements greatly increases the utility for hydrological or meteorological applications.

Usually, in areas with low or smooth terrain where precipitation is more homogeneous, simpler measuring tools are used, and in more complex areas where different factors occur in accurately measuring data, more complex instruments are used. Geostatic approaches are also used to adjust the meteorological radars, but the key factor in determining the accuracy of the results is the density of the rainfall networks [17].

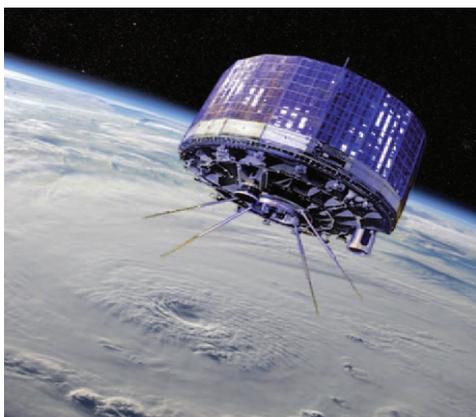
### 2.3. Satellites

Unlike the estimation methods presented above, satellites provide

rainfall estimates on a global scale and fill in areas that are not visible, which cannot be covered by rainfall or radar. To achieve this, the satellites are equipped with instruments to determine the precipitation, the temperature of the clouds or the characteristics of the specific atmosphere. These instruments have an antenna or telescope, visible radiation detector, microwave or infrared and a scan mechanism. The measurements are in the form of electrical voltages, which are digitized and transmitted to the reception stations on the ground.

The use of satellites has made it possible to know the distribution of precipitation in all areas of the globe, including over the oceans and in other areas where the use of other instruments would have been impossible or very expensive. The numerical weather prediction models depend on satellite measurements, which are generally three quarters of the data; for example, in France, the satellites provide 93% of the data used in the Météo-France's Arpège model [14].

The first use of satellites for meteorological purposes was carried out by NASA with the TIROS-1 experimental spacecraft, on April 1, 1960 (see figure 7). The satellite operated for a period of 78 days, during which time it provided 23,000 images, where air masses, wind fields and frontal systems could be observed [28].



**Fig. 7** TIROS-1-The first satellite used for meteorological purposes, launched on April 1, 1960(source:<https://eosps0.gsfc.nasa.gov/missions/television-infrared-observation-satellite-program>)

In general, there are two types of meteorological satellites, which are defined by orbit classes, namely polar and geostationary. Both kinds produce different types of data, and a method of combining and integrating the pieces of information is achieved through the implementation of data fusion techniques.

The geostationary satellites orbit at an altitude of 36,000 km above the equator and are synchronized with the rotation of the Earth around its own axis. As a result, geostationary satellites ensure high temporal resolution through continuous surveillance of Earth and space. However, spatial resolution is limited compared to polar satellites due to the arrangement height. Unlike geostationary satellites, polar ones are arranged at lower altitudes,

between 800 and 1200 km and provide data beyond the observation of geostationary satellites. The satellites orbit synchronously with the Sun and can observe almost any area of the Earth. It also offers much higher spatial resolution data than geostationary ones due to the altitude at which they are arranged, and data collection is done periodically, providing useful information for long-term comparisons. Table 3 shows the number of existing meteorological satellites, as well as the orbital position of each. Also, some satellites include additional sensors for monitoring carbon dioxide, ozone, for observing space and other components.

### 2.3.1. Interpretation of results

The interpretation of the observations offered by the satellite requires the application of certain atmospheric corrections on the instruments on board. Limitations due to accuracy, coverage and resolution require the combination of products from several sensors.

The concept of precipitation measurement, by combining passive sensors and microwave radars from a single satellite, was born in the early 1980s in the form of TRMM (Tropical Rainfall Measuring Mission). The TRMM project was developed by NASA and the Japanese Aerospace Exploration Agency, and the goals are to map and understand the role and structure of latent heat, to obtain monthly average rainfall across the

tropics and to examine the tropical rain cycle [8], [16]. The resulting data are used to quantify contributions to stratiform and convective rainfall, study how rainfall influences and to improve prediction. Although meteorological satellites contribute to improving knowledge about the global distribution of rainfall, many issues remain uncertain and invalidated, such as the daily cycle of rainfall, amount of rainfall or rain rate.

In general, in addition to the TRMM concept, the main types of technique include microwave and infrared based assessments. Of the two types, those with microwaves provide more accurate estimates of precipitation, but have a lower spatial resolution and are less frequent. Performance depends on a number of

factors, including signal processing algorithms, sensor choice and atmospheric conditions. A variety of techniques have been developed for signal processing, among which are those based on physical, conceptual or data.

Each new generation of built satellites also includes advanced techniques to improve accuracy and resolution, and also some priorities for research includes: algorithm optimizations, calibration of sensor uncertainty and development of performance measurements. Also, products that combine satellite data and other tools that provide real-time data have also been developed. The radar used by the TRMM proved to be an important tool for real-time calibration and evaluation.

**Table 3.** Current geostationary and polar satellites

Actors	Geostationary weather satellites		Polar weather satellites	
	Name	Satelites orbital position	Name	Satelites orbital position
SUA	GOES-15	East Pacific	DMSP-F13 <sup>1</sup> , DMSP-F16, DMSP-F17, DMSP-F19 <sup>2</sup>	Early Morning Orbit
			DMSP-F18	Morning Orbit
	GOES-13, GOES-14 <sup>2</sup>	West Atlantic	Suomi-NPP, DMSP-F14 <sup>1</sup> , DMSP-F15 <sup>1</sup> , NOAA-15 <sup>1</sup> , NOAA-18, NOAA-19	Afternoon Orbit
Europa	Meteosat-9, Meteosat-11 <sup>2</sup>	East Atlantic	Metop-A, Metop-B	Morning Orbit
	Meteosat-7	Indian Ocean		
India	INSAT-3C, Kalpana-1, INSAT-3D, INSAT-3A	Indian Ocean	-	-
Russia	Electro-L N1 <sup>1</sup>	Indian Ocean	Meteor-M N1 <sup>1</sup>	Morning Orbit
China	Feng-Yun-2D, FY-2E	Indian Ocean	FY-3C, FY-3A <sup>1</sup>	Morning Orbit
	FY-2F <sup>2</sup>	West Major Atlantic	FY-3B	Afternoon Orbit
Koreea	COMS-1	West Major Atlantic	-	-
Japonia	Himawari-6, Himawari-7	West Major Atlantic	-	-

Source: Adapted from OECD, 2014 [14]

### 3. CONCLUSIONS

Most weather radars are implemented in networks to improve data accuracy and cover missing areas. As for signal processing, compared to the use of the Doppler frequency, complex signal modulation techniques, solid state transmitters, polarimetry and pulse compression are also being used. If NEXRAD radars are limited by the mechanical scanning of the airspace, the newer radars have the possibility of using the networks phased by antennas which can be electronically moved both horizontally and vertically. This reduces the data processing time. An example of a radar that combines these methods is CPPAR (Cylindrical Polarized Phased Array Radar) [33].

The satellites are managed by agencies from India, Japan, Korea, Russia, USA, China and Europe under the coordination of the World Meteorological Organization (WMO). Currently, there are 18 geostationary and 17 polar satellites (see table 3).

The conversion of each radar component from analog to digital is one of the radar development trends, as well as the fact that more emphasis is placed on engineering. The information provided by the radar complements the observations made with rainfall meters and compensates for certain sources of error.

The rain gauge provides direct measurements on only one location at a time. The most commonly used types of rain gauges are those which operate by tilting and weighing. The accuracy of the estimates increases proportionally with the density of the rainfall network and makes a major contribution to the calibration of the radar. The data provided by the satellites has a lower spatial resolution and smaller intervals than the weather radar. A variety of techniques and sources are available in real time, combining microwave observations from polar satellites with visible and infrared observations from geostationary ones, managing to eliminate some of the errors.

In recent years, several sensors have begun to be used, some of which are not only linked to a certain observation system. Their role is to provide a more accurate estimation of precipitation from a wider range of sources. For individual measurement systems (radars, rain gauges or satellites), there are international intercomparison studies, which allow users to compare data and algorithms.

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