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CONCEPT OF THE SECONDARY AUTOMATED NETWORK FOR MONITORING WEATHER CONDITIONS WHITH LOW-POWER RADARS AS SENSORS

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Abstract**—***This article is devoted to creation of the secondary network using base stations of mobile telecommunications operators. General advantages of the secondary networks are discussed. Then we suggest to build a novel network of low-cost small base radars (BSR) by adding the low-power radars to the existent selected base stations' equipment. This gives a possibility to obtain a high-resolution meteorological information in particular about dangerous weather phenomena in real-time and for any region of mobile network coverage. The applications of the proposing network are not limited by meteorology, but includes also some other fields, for example, traffic monitoring, birds and insects' migration observations, etc.*

Index Terms—Secondary network; weather radar; base station; low-cost radar; information radar network.

I. INTRODUCTION

Meteorological information is very important for practically all aspects of mankind life as well as every human. For example, further increasing flight safety is possible in case of timely forecasting and accurate monitoring of the atmosphere with detection of hazardous weather phenomena [1]. Ground-based and space-based facilities are used for permanent remote sensing of the atmosphere today. Large funds are spent for these purposes by developed countries. Despite this, the detail and accuracy of the information being received remain insufficient for an accurate forecast and diagnosis of the meteorological situation, especially in mountain and other regions where relief is complicated. There are many Meteorological Radar System (MRS) installed in many countries and regions of the globe. Normally they are rather powerful. However, the modern network of MRS does not meet requirements, which are increasing gradually. Characteristics of meteorological radar surveillance networks should be significantly improved, including both spatial and temporal resolution.

Meteorological radar observations are very important for studying and forecasting hazardous atmospheric phenomena such as thunderstorms, hail, wind shear, icing, tornadoes, hurricanes, heavy dust storms, low clouds, and more. All these weather conditions can pose a significant risk to flights. Moreover, knowing detailed and operative information on changeable meteorological situation in particular zones even in the framework of a region, even a city region, could improve the quality and effectiveness of meteorological information drastically.

Weather radars play important role as powerful sensors of complex meteorological information. The major difference between MRS and other kinds of radars lies, first of all, in the nature of the targets. Meteorological targets are distributed in space, and they normally occupy a large fraction of the spatial resolution cells observed by the radar. Modern weather radars are mostly coherent or coherent-on-receive systems which are able to measure Doppler frequency and related statistical parameters, like mean and rms Doppler velocity of scatterers moving chaotically in each resolution volume. Today single-polarization and dual-polarization meteorological radars are available [2].

Single-polarization Doppler radar acquires data on reflectivity, radial velocity, and spectrum width, while dual-polarization Doppler radar additionally to the listed above, acquires data on differential reflectivity (ZDR), correlation coefficient (CC), including inter-polarization CC, specific differential phase (KDP), and several other parameters.

As an example, the full-polarimetric research radar – PARSAX [3], developed in the Delft University of Technology has 2 independent polarimetric radio frequency (RF) channels both in transmitter (Tx) and receiver (Rx). The radar has rather high resolution because its bandwidth (B) is up to 100 MHz that corresponds to the potential range resolution ΔR up to 1.5 m. It is high-sensitive system, having Tx power up to +50 dBm per channel and the receivers' noise floor around – 93 dBm.

The PARSAX system is able to process Doppler parameters in up to 5100 complex samples in coherent real-time range profile. In the same time, continuous wave (CW) mode provides range processing of sounding waveforms with signal base (BT-product) up to 100.000 in real time.

What is also very important to mention is that PARSAX is practically a software defined radar with digital generation of agile waveforms and their matched processing at intermediate frequency (IF) in 4 parallel channels of FPGA-based, fully programmable digital receiver. So, it is highly reconfigurable research radar system.

Actually, PARSAX is a unique research radar. It was designed as a research tool but not to be used in operational mode. However, this radar is important to check and investigate different modes and algorithms of waveform generation and signal processing; and some ideas implemented there can be used in novel practical radar systems.

Existent networks of meteorological radars are equipped with powerful and expensive radar systems spaced by hundreds of kilometers. They do not have enough space resolution, they are very expensive, powerful, and dangerous for the environment. Consequently, the issue consists in the fact that the network of such MRS cannot be made dense enough to provide numerous users with detailed meteorological information with sufficient resolution. Based on this preliminary discussion, one can say that modern networks must be significantly added and modernized because of contradictions between necessity of high resolution and global coverage, low cost, limited radiating power and ecological consideration.

To address this issue, we propose to create an innovative network of low-power meteorological radars with limited range of operation located (at least partially) at the base stations of mobile operators.

II. Meteorological Radar Networks Available Today

In the framework of the World Meteorological Organization (WMO) Programmes the Global Observing System (GOS) has been created and continues being developed. It is a coordinated system of methods and tools for conducting meteorological and other observations of the environment on a global scale. The system consists of ground-based and space-based subsystems, which are reliable in operation. GOS includes means of observation on land, at sea, in the air and in outer space. In particular, the ground-based weather radar networks, upper-air stations, satellite ground stations, surface meteo-stations, polar orbiting and geostationary satellites, which are used as carriers of atmosphere remote sensing facilities, and National Meteo Services are comprised in the GOS. It is reasonable to cite the following conclusion concerning the meteorological radar networks and corresponding WMO Radar database from the Report of WMO [4]:

Doppler Weather Radar is an essential precipitation observing system in meteorology for very large-scale areas. They have been and will continue to be a very important meteorological tool in severe weather warnings, precipitation estimation and its spatial distribution, air traffic management, disaster management, numerical weather prediction (verification and data assimilation), agriculture, hydrological, weather modification and climate applications.

Radar networks have developed in many countries and often have competing requirements resulting in multiple networks created by different internal agencies ... The fourteenth session of the Commission for Instruments and Methods of Observation (CIMO) requested the CIMO Expert Team on Remote-Sensing Upper-Air Technology and Techniques to establish a fully comprehensive database of the global use of weather radars." Figure 1, borrowed from [5], represents the distribution of the both, single- and dual- polarization radars over the globe with indication of frequency band.

Fig. 1. The both, single- and dual- polarization radars' map with indication of frequency band [5]

Due to a very small scale this map demonstrates only general distribution of radars over the world regions but it does not show a number of radars because the signs are overlapped. In reality the distance between radar positions is at least 200-300 km. It is reasonable to consider more details of the European network of operational weather radars as one of the most saturated regions. In Figure 2, which has been created using the same source [5], one can see a part of European network map. More than two hundred (205) weather radars are operational in Europe, and almost half of them (99) are dual-polarization ones. Most of weather radars of European countries (not only EU) are integrated in the European network of operational weather radars established in the framework of the EUMETNET/OPERA program. The time resolution of this network is 15 minutes, and data are provided with 2 km x 2 km horizontal resolution. Measurement range of radars varied from 200 to 400 km, average 248 km.

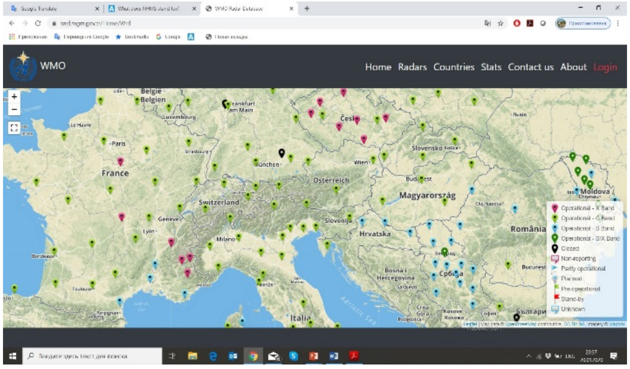

Fig. 2. Larger scale European weather radar network map [5]

Ukraine is a member of WMO from 1948. In Ukraine country, 9 weather radars of different generations are registered as components of WMO details, two of them are located in Crimea peninsula. China joined WMO in 1951, however, according [5], meteorological radars in China are not registered for WMO network so far, although in reality there are many weather radar systems installed in China country.

III. TYPICAL FEATURES AND LIMITATIONS OF EXISTING WEATHER RADAR SYSTEMS

In the operational network different types of weather radar of different generations are working. Perhaps, the most numerous are radar systems of NEXRAD (Next Generation Radar) US network. The basis of the NEXRAD hardware is the multifunctional Doppler radar WSR-88D [6], which operates at 10 cm wavelength (S-band). Initially, the WSR-88D was developed specifically for tornado prediction, accurate detection and positioning of vortex and turbulent flows, wind shear profiles, and assessment of the boundaries of hail formation regions. The nominal range of each radar is 230 km. Reflectivity (proportional to average received power), average radial velocity, and Doppler spectrum width with a resolution of 1 degree per 1 kilometer (at a distance up of 460 km) were selected as the recorded values during operation.

In 2011 the modernization of WSR-88D to introduce dual polarization on transmission and receive was started. After gaining the ability to operate in dual polarization mode, in addition to the aforementioned parameters, they began to record differential reflectivity, correlation coefficient between orthogonal polarization signals and differential phase shift.

Another type of modern network meteorological radar is European radar system named METEOR of German production. An example of such radar, in particular, METEOR-635 was purchased by Ukraine before EURO 2012 football championship. This is a C-band (5.64 GHz) dual-polarization coherent-on-receive radar with magnetron transmitter of more than 400 kW peak power. Different modification METEOR 1700 is equipped with klystron transmitter of 250 kW.

Australian weather radar system from ESS Weathertech is also a C-band radar with operating frequency 5200–5700 MHz, pulse width of 0.2–2.0 µs, range resolution > 16 m (typical 36 m), pulse repetition frequency 200–2400 Hz (user selectable), and range up to 600km (typical 300 km), peak power is 350 kW. Normally this radar system is equipped with prime-focus parabolic reflector antenna of 4.2 m diameter dish.

In addition, there are some operational meteorological radar systems of previous generations, particularly, in RF, Moldova and other countries of Central and Eastern Europe, also in Asia. Among them MRL-1, MRL-2, and MRL-5 developed in former USSR; MRL-5 was later modernized in RF. They are high-power non-coherent single polarization radar systems, sometimes dual wavelength.

In the context of our consideration, one can easily note that typical ground-based weather radars are rather big systems with significant range of operation, powerful transmitters, and more or less sensitive receivers. The value of peak power of such a radar is usually 250 to 400 kW and may reach 800 kW (S-band channel of MRL-5). The cost of a modern dual-polarization radar is typically much greater than $1,000,000. Depending on the operational frequency band, it may require a very large antenna dish and a powerful motor to power it. Due to a significant value of peak power the sanitary protection zone of such a radar is usually at least hundreds of meters. That means that such large weather radars have obvious disadvantages from economic and environmental views. They are not desirable to be installed on the opinion of people who live or work in the vicinity of such radar systems. However, these are even not the most important disadvantages.

In addition to discussed above, the impact of terrain, shading mountains and other obstacles does not allow to cover all necessary area to get full information. Moreover, the most important meteorological information, which influences to human being, concerns the low layers of the atmosphere, up to 3000 m, and for civil aviation up to 10000 or maximum 11000 m, and for such high altitudes, at route flights, the airborne weather radar information is preferable.

Let us consider, what actually is the covered zone on height for a ground-based meteorological radar with a typical range of observation. At first, assume an ideal case, when the beam of an antenna, located in point *A* at a height h_1 above the earth's surface, is directed tangentially to the spherical earth surface and neither refraction nor earth influence exist during the wave propagation. The geometry of this case is shown in Fig. 3, where h_1 is ground-based radar antenna height, h_2 is the height of a radar resolution volume in point *C*, which corresponds to maximum range of radar operation. Since the range is $R = AB + BC$, it can be easily found from two triangles as a function of the two heights (h_1 and h_2) and the radius of the sphere R_o. Then we solve the formed equation $R = f(h_1, h_2, R_o)$ for the height h_2, and from a rather cumbersome quadratic equation we find an only real solution:

$$h_2 = -R_o + 0.5\Big(4R_o^2 + 4R^2 - 8R\sqrt{2R_oh_1 + h_1^2} + 8R_oh_1 + 4h_1^2\Big)^{1/2}.$$

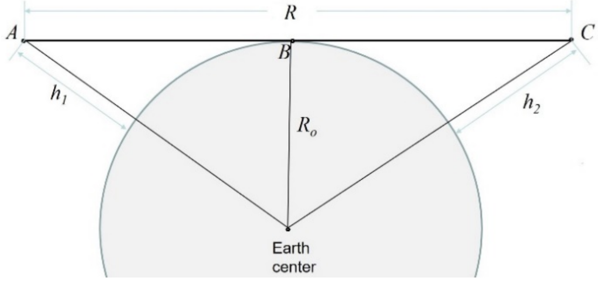

Fig. 3. The geometry of ideal case: the Earth is a sphere, electromagnetic wave propagates without any refraction, antenna elevation is zero, that is, radar beam propagates from point *A* to point *C* being tangent to the surface in point *B*, and the Earth does not affect to the situation

The plot of this solution is presented in Fig. 4, where actually the minimum value of height, which can be observed at given range from the radar at different heights of antenna position and zero elevation angle, if the influence of refraction and earth is ignored.

Even from this idealistic consideration one can see that parts of troposphere located at 1 km height can be observed up to ranges of 90–100 km, not more. More realistic case consideration [7], which takes into account arbitrary antenna elevation angle θ (in degrees) and influence of refraction, which is accounted as increasing the equivalent earth radius, using the multiplier k_e = 4/3 at R_o, is reduced to the following expression:

$$H(R,\theta) = \sqrt{R^2 + (k_eR_o)^2 + 2Rk_eR_o\sin\left(\frac{\theta}{57}\right)} - k_eR_o + h_1.$$

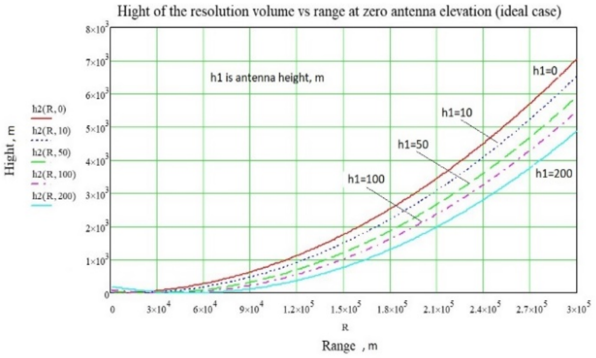

Fig. 4. Dependence of the height of observation as the function of the distance from the radar under the ideal conditions (zero elevation and no influence of the earth and atmosphere) at different values of the radar antenna height: h_1 =0, 10, 50, 100, and 200 m

The results of calculation using this expression are shown in Fig. 5. We can see, that at maximum range of 300 km even in case of very small elevation (1 degree), the radar can receive a reflected signal from weather objects located on heights above 10 km, however

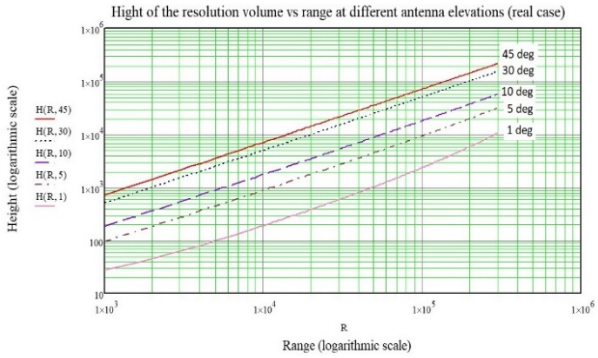

Fig. 5. Dependence of the height of observation *H* as the function of the distance from the radar at different elevation angle θ = 1, 5, 10, 30, and 45 degrees taking into account the refraction during wave propagation. Antenna is located at a height of h_1=10 m

Useful is also dependence of minimum height of observation versus antenna elevation angle at different maximum radar range that is presented in Fig. 6.

Due to the curvature of the Earth and the change in refractive index with height, the radar cannot observe below a certain height above the ground for a given elevation angle of the antenna.

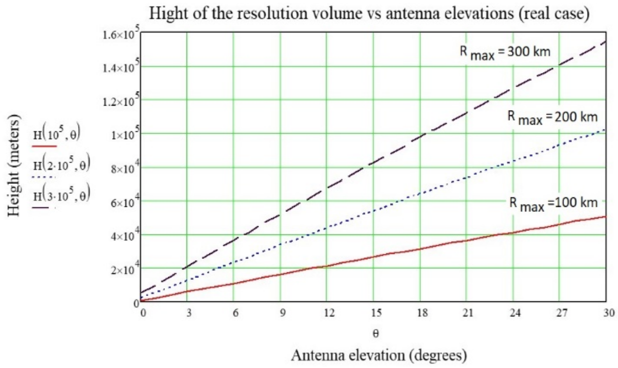

Fig. 6. Minimum height of the observed resolution volume vs antenna elevation at three values of range: 100, 200, and 300 km

The analysis and calculations performed show that the high energy potential of modern meteorological radars, combined in a network with average distances between radars of the order of hundreds of kilometers, cannot be effectively used to observe the surface layers of the troposphere, say, at least below three kilometers. In cases where radars are deployed in a complex terrain relief, especially in mountainous areas, powerful systems with a long range do not provide the necessary view at all due to obstruction shading.

Today's meteorological networks need significant refinement to obtain more accurate, high-resolution weather data. Taking into account the disadvantages of modern weather radar systems, namely: very high price (from US $ 1,000,000), high radiating power (from 250 kW) that is dangerous, difficulties with mounting and subsequent maintenance (large antenna, powerful motor, etc.), poor coverage due to Earth's curvature and topography, we can say about the contradiction between the needs existed and real characteristics of the weather radar networks.

How to solve this problem? It is possible to achieve coverage of the territory of a country, e.g., Ukraine with its geographical and topographic diversity on the basis of radar network of low-power, environmentally friendly, small-sized multifunctional meteorological surveillance radars.

In this case, we can achieve a situation, when the sanitary protection zone will not exceed 10 m (in the worst case). The smaller range and environmental cleanliness will allow to place components of the network, that is, weather radars, being guided only by the requirements of providing the necessary coverage of the territory. Instead of one powerful WRS, there will be several low power ones, but we will have significant savings both the cost of the radars themself and the costs of construction, installation and maintenance. But the most important result of such network modernization is radical improvement of the meteorological information quality because of much better coverage of necessary zones of atmosphere observation especially at comparatively low heights and in mountain regions.

Such approach can be considered as useful direction to further development of meteorological radar network that does not preclude the use of existent high-power WRS and installing new ones to cover difficult to reach areas with more or less flat relief.

IV. PLACES OF INSTALLING LOW-POWER RADARS WITH LIMITED RANGE OF OPERATION

The places of installing small radar systems as the sensors of meteorological network should fit the definite requirements. These requirements in many aspects are similar to those which are characteristic to mobile telecommunications base station. From this we can assert that a mobile base station is an ideal place for a high-resolution low-power radar install. There is a dense network of mobile carrier base stations around the world. About 1.5 million base stations operate now in the world, more that 25 300 stations work in Ukraine. These stations are already equipped with appropriate communications, power supply etc. The map of base stations in Europe by OpenCellID [8] is shown in Fig. 7. In the circles, the number of base stations for each region is indicated.

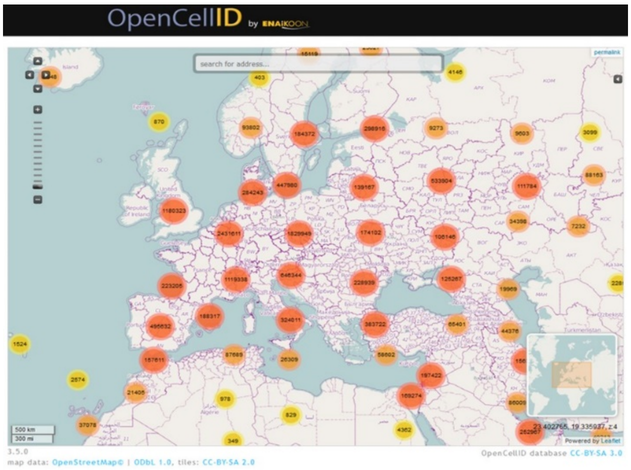

Fig. 7. The map of base stations (Europe) by OpenCellID [8]

Of course, radar network should not be as dense as mobile telecommunications network. So, we do not need to equip all base stations, but it is possible to select the most suitable ones from the point of view of providing necessary covering the zones of observation. It will be a small part of the whole number of base stations. Additional installing low-cost, low-power, high-resolution meteorological radars at some of such stations can solve the problem of high-precision, real-time weather monitoring.

Mobile base stations are usually located at the elevated places, such as building roofs, towers, etc. Furthermore, typically these places are hard to reach by vandals are equipped with appropriate power supply have the high-speed Internet connection.

So, the low-power, low-size and low-cost high-resolution radars can be easily mounted at the existing base stations and integrated into the base station radars network.

V. NOVEL ACHIEVEMENTS OF SCIENCE AND TECHNOLOGY FOR PROSPECTIVE WEATHER RADAR

Among new technological achievements, which are important in the considered aspect, there are the following.

1) Creation of miniature radar systems based on microelectronics technology [9].

2) Application of millimeter wave radar for the remote sensing of the atmosphere [10].

3) Transformation to digital signal form as early as possible (maximally close to radio frequency head, at least on the intermediate frequency).

4) Implementation of software radar approach to provide agile radar technology [11].

Another group of achievements is related with new research results in the field of radar meteorology. Here we can mention the following results obtained during last years.

Spectral polarimetric radar approach [12] to the remote sounding of the atmosphere and deriving meteorological information about objects and phenomena in the troposphere. Such approach is implemented, for example, with Doppler-polarimetric radar [13], which is a source of rather sophisticated meteorological information, including information about dangerous for flight zones in the atmosphere.

First there were separately Doppler approach and polarimetric approach. Doppler approach provides information related with movements of scatterers in the resolution volume or/and relative average movements in different resolution volumes. Polarimetric approach is able to provide information related with the shapes and sizes of the scatterers in the resolution volume [14].

Spectral polarimetry is able to reply much more sophisticated question: what is the behavior of polarimetric parameters for different scatterers that are moving with different velocities inside a resolution volume. This approach leads to a kind of super-resolution [15].

In addition, traditional polarimetric parameters, like differential reflectivity [7], and novel measurables, like spectral polarimetric function [16], were studied, and new spectral-polarimetric parameters: slope of the spectral differential reflectivity and differential Doppler velocity [16] were introduced and researched.

The developed math models allow to model and simulate different parameters for different scenarios. Combining modeling and measuring opens new opportunities to retrieve more important information about meteorological objects and phenomena.

Tracking more parameters gives a possibility to apply, for example, neural classifier to recognize different objects [17].

Special algorithms of signal processing were developed to detect and estimate turbulence in the zone of observation, as well as hail hazard, icing-in-flight, and also to recognize even the nature and size of scatterers. Other problems that can be solved with coherent-polarimetric technique are electricity of the atmosphere (detection of lightnings and zones potentially dangerous to produce lightnings) and volcanic ash detection problem because a typical volcanic ash particle is a scatterer of irregular shape, that is, sensitive to polarization.

Finally, new ideas related with improving network quality [18], [19], [20] are very important and should be considered and used when implementing the proposed network.

VI. LAYOUT OF A LOW-COST WEATHER RADAR DESIGN FOR THE INNOVATIVE NETWORK RADAR

This section, just as an example, considers a possible design of X-band radar prototype for the proposed innovative network. This design is based on the application of passive slot antenna array, which was successfully used in the airborne weather radars by Research Institute “Buran” [21]. Actually, the size of the antenna determines the size of such a radar as a whole. All other components of the structure can be rigidly mounted on the back of the antenna that reduces losses from microwave rotating junctions. Digital primary processed signals can be transmitted wirelessly.

The size of this draft construction is 900x900x1130 mm as is indicated in Fig. 8.

Of course, in reality, based on modern technology of miniature radar, application of mm-wave band and software radar approach, the small weather radar system can be designed with much smaller sizes.

Basic parameters of such radar play important role to design and the size of the system. This will be considered in a separate paper.

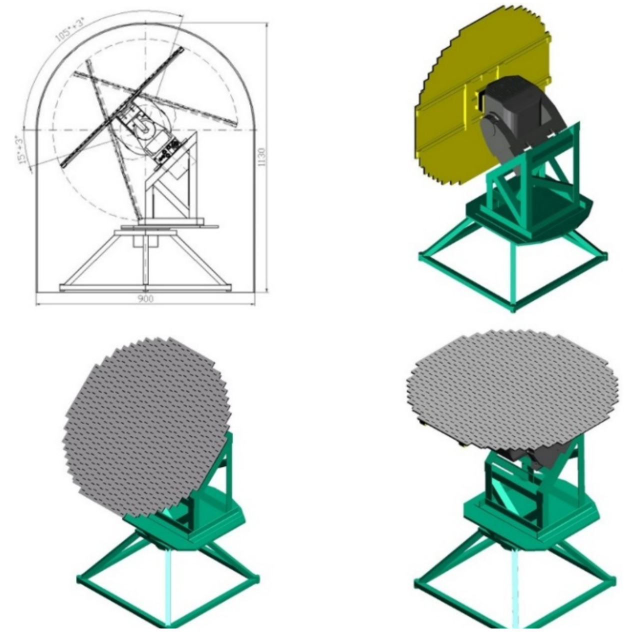

Fig. 8. Draft design of small WRS

VII. CONCLUSION

The nowadays weather radar networks need the substantial upgrade in order to provide the most accurate information in real-time with high resolution.

The disadvantages of modern dual-polarimetric weather radars are their substantial cost (from $1,000,000), high peak radiation power (from 250 kW) that is not safe enough, as well as some difficulties with mount and following maintenance.

Cheap and small radar with limited range of operation is much more suitable for such a network under the condition of enough minimum density of the network.

The dense network of mobile base stations already exists worldwide, at safety from vandals and elevated places, with appropriate power supply and broadband Internet access. It can be used partially as suitable places for installation of small weather radars. Of course, organizational questions should be coordinated with the owners of the stations.

Modern radar technology provides the opportunity to create small and even miniature radars with new possibilities to extract weather data and disseminate information using cloud and IoT technologies.

An installation of low-power, low-cost radars with limited range, but with high range resolution to the mobile base stations can solve the problem with high-accuracy real-time weather monitoring, as well as some others related problems.

The next work will be devoted to calculation and substantiation of minimum radar parameters for such a network.

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Ф. Й. Яновський, Чженбін Ху. Концепція вторинної автоматизованої мережі для моніторингу погодних умов з радарів і малопотужних датчиків

Статтю присвячено створенню вторинної мережі з використанням базових станцій операторів мобільного зв'язку. Обговорюються загальні переваги вторинних мереж. Пропонується побудувати нову мережу недорогих малих базових радарів, додавши малопотужні радари до наявного обладнання вибраних базових станцій. Це дає можливість отримувати метеорологічну інформацію високої роздільної здатності, зокрема, про небезпечні погодні явища в режимі реального часу та для будь-якого регіону покриття мобільної мережі. Застосування запропонованої мережі не обмежується метеорологією, але включає також деякі інші галузі, наприклад, моніторинг руху, спостереження за міграцією птахів і комах, тощо.

Ключові слова: вторинна мережа; метеорологічний радар; базова станція; недорогий радар; інформаційна радіолокаційна мережа.

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Направлення наукової діяльності: радіолокація, обробка сигналів, дистанційне зондування атмосфери, електронні системи, адаптивні вимірювання, електрика атмосфери.
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Ф. И. Яновский, Чжэнбин Ху. Концепция вторичной автоматизированной сети для мониторинга погодных условий с радаров и маломощных датчиков

Статья посвящена созданию вторичной сети с использованием базовых станций операторов мобильной связи. Обсуждаются общие преимущества вторичных сетей. Предлагается построить новую сеть недорогих малых базовых радаров, добавив маломощные радары к существующему оборудованию выбранных базовых станций. Это дает возможность получать метеорологическую информацию высокого разрешения, в частности об опасных погодных явлениях, в реальном времени и для любого региона покрытия мобильной сети. Приложения предлагаемой сети не ограничиваются метеорологией, но включают также некоторые другие области, например, мониторинг движения, наблюдения за миграцией птиц и насекомых и т. д.

Ключевые слова: вторичная сеть; метеорологический радар; базовая станция; недорогая РЛС; информационная радиолокационная сеть.

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