Global Advanced Research Journal of Agricultural Science (ISSN: 2315-5094) Vol. 7(12) pp. 366-376, December, 2018 Special Anniversary Review Issue.
Available online http://garj.org/garjas/home

Review

Flaws and advantages of current and prospective anti-hail protection methods, stations and networks (Review)

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Accepted 15 December, 2018

This review article shows flaws of current anti-hail protection methods and networks for hail prevention and suppression controlled by weather radars, which are unable to detect hail generative clouds and predict hail for timely start-up available anti-hail protection facilities. It is discussed as well advantages of new approaches in hail generative clouds high probable detection and classification based on radiometric observation of the sky and measuring changes of sky intrinsic emission in radiofrequencies, which allow implementing hail early detection and timely alerting anti-hail protection facilities and creating fully autonomous and automatically operating global networks of anti-hail protection applicable for hail prevention, hail sufficient suppression and hail trapping.

Keywords: Hail; Hail Detection and Alerting; Anti-Hail Protection; Hail Prevention, Hail Suppression; Hail Trapping; Supersonic Cannon; Weather Radar; Sky Brightness Temperature; Microwave Radiometer

1. INTRODUCTION

Recent weather events in Italy on October 21, 2018 (Samenow, 2018; Weston, 2018; The Local, 2018), when severe storms unload knee-deep hail in Rome and leaving residents were trapped in cars and escalators flooded, showed that hail is and remains an unresolved problem for all countries suffering of hail, from early spring to late autumn. And at global climate change many countries that are not currently affected by hail may be face to face with this problem soon, like Saudi Arabia in 2018 (Sharif 2018). The existing difference between the growth rates of the world population and food production, the uninterrupted increase in the pollution of nature and the deterioration of the ecology of the environment require solving the problem of lossless preservation of the crop in order to partially overcome the inevitable famine on the Planet. However, one of the main obstacles to solving the problem of lossless crop preservation is hail and heavy rain which every year cause great and severe damage to agriculture and human properties, as well as injure people, livestock and wild animals (World of Facts, 2015; Harland, 2018). In (Steiner, 1988) the details of some hail events that took place in the last quarter of the last century are presented. Some non-professional, but realistic pictures, footages and videos mostly shot by eyewitnesses and victims during sever hail events of last decade and their comments are shared on social media, for instance (Euronews, 2018; TreerootCO, 2017; Bowie, 2017; The Canadian Arcade, 2016; Jeff, 2012; Romero, 2015; Bezants, 2014: Unwetter, 2013; Dottyriver, 2013; Athanaiadis 2012, and others). Mentioned references show that the size of the damage may consist billions and billions USD all over the World. Therefore, to minimize material damage in size or to prevent economic disruption and downturn in agriculture it is necessary to develop and to use new approaches in anti-hail protection.

2. Current Status of the Art

At present the anti-hail protection is implemented by the following three methods: hail prevention method, which hinders in advance hail formation or interrupts the further growth of small ice particles in clouds, hail suppression method, which hinders the growth of already formed small and moderate hailstones into large ones, and plants overlapping method, which complete hinders or reduces the physical-mechanical impact of hail on the plant.

The overlapping method of plants by the anti-hail net of course is an efficient technique for protection. However, this technique is widely employed to protect some important farms only, and never for wheat and corn fields, for forage and herbaceous vegetation fields, since, the expenses of the anti-hail net's installation and handling are high enough and in a case of large-area farms the overlapping will cost very expensive. Really, in various countries (in Armenia, for Instance) the cost is about 18,000-20,000 USD per hectare for installation and is about 1,200-1,500 USD/hectare/year for both mandatory required handling operations (unroll nets in springtime and roll up in winter). In addition, its use is limited, and after a few years the net must be fully renovated and repaired. And therefore, to use the net throughout the warranty period, and not replace the net with a new one before that period, in some countries with a continental climate, when winter temperature is $-20^0 \div -25^0C$, and the summer temperature under the sun can reach $50^0 \div 60^0C$, it is necessary to collect and store the net in warehouses in winter. It should also be borne in mind that the likelihood that the same garden, orchard or vineyard will be damaged by hail every year is very small. Most likely, hail can damage the crop of the same area only once every 3 or 4 years.

Unfortunately, in spite of its high cost the anti hail net is not efficient in the event of severe hail storms. Consequences are potentially even worse than for a completely unprotected farm, because if the net's structure collapses on the crops the grower will often be forced to replant the entire afflicted areas (Anti-Hail News). Really, in a case of the severe hail with a thickness of 10cm the weight of the ice on each square meter of the net's area will be about 80-90 Kg. Therefore, it is more reasonable to protect such areas as well additionally by cheaper cost methods and means of hail suppression and to prevent initially the severe hail using supersonic cannons (gas-generators), for instance, which may operate autonomous and automatically.

Two other techniques for hail prevention and suppression is widely employed in the world: seeding of clouds with silver iodide or other substances, which induce freezing to occur at warmer temperatures than otherwise, and the use of sonic cannons or other kinds of explosive devices.

There are two ways in which seeding is postulated to reduce hail severity. Seeding is intended to cause a vast increase in hail embryos, none of which grows to large hail because of competition for the available liquid water. Another approach, premature rainout, involves seeding of cloud elements at an early stage, so that particles which might otherwise become hail embryos fall out of the cloud as rain from lower levels rather than ascend to the higher levels where hail formation takes place. Seeding of clouds, which is implemented by shells or rockets, is an expensive and ecologically harmful one, since each shell or rocket (Alazan-5, for instance) contains 12.6g silver iodide (Antigrad) and costs 20-30USD at least, and for seeding of appeared hail or hail generative cloud a volley of 12-24 rockets is needed. It means that all quantity of silver of launched rockets and their debris (~4.7kg each (Antigrad)) will fall to the ground. Besides, as mentioned in (Steiner, 1988), carefully designed scientific experiments have not demonstrated any reduction of hail resulting from cloud seeding, however there is evidence that many hail suppression operations in various parts of the world appear to have reduced hail damage. There is another problem with rockets and shells application for anti-hail protection of near boundary areas, since the flight range of shells and rockets is about 2-6 km, and at the slightest mistake a shell or rocket can cross the border of a neighboring state and thereby cause undesirable conflicts or tensions in interstate relations.

The use of supersonic cannons, which are cheap and ecologically harmless in application, involves supersonic and significant shock waves generation by sequential detonating an explosive mixture of combustible gas (fuel) and air in a combustion chamber of the gas-generator and their direction upwardly to the sky. It is believed that the succession of shock waves transports positive ions from ground level to cloud level which disrupt formation of hail nuclei. It is assumed as well that due to the shockwaves which emanate from the gas-generators, the super cooling water situated on the external layer of hailstone is transformed from liquid state to solid state. Therefore the hail nuclei do not melt anymore and remain at small sizes which thus prevent them from inflicting damage when they hit the ground. By selecting material and quantity of the combustible fuel, number and duration of detonations it is possible to provide significant shock waves and to effect on the hail clouds up to 10km of altitude (Ollivier, 1995), changing hail cloud structure, preventing further development of hail and transforming hail into rain or wet snow or small ice drops.

Both described techniques of hail prevention and suppression are not efficient against already formed hailstones and severe hail, so the most important requirement in their application remains their timely startup. Shells or rockets must be fired or launched at least in cumulonimbus before large hailstones forming. Of course, it is more reasonable to fire shells or to launch rockets in nimbus (hail generative cloud), in order to prevent the formation of hail at once, but it will become very expensive way for anti-hail protection and will require the development of new types of devices for hail generative clouds' detection with high probability. The hail preventing supersonic cannon's (gas-generator's) operation must be approximately initiated 15-20 minutes before hail storm forming or storm arrival. The efficiency of both techniques decreases in proportion to startup delay. If the anti-hail device is activated when the storm is directly above, its efficiency will be very low. Therefore, for both techniques of protection it is strongly recommended to use them in conjunction with hail and hail generative clouds detectors.

Despite the fact that in some countries anti-hail launchers are manually controlled and their positioning along both azimuth and elevation directions are regulated on the basis of commands coming from human operators, in most countries for hail detection and clouds accurate and timely seeding usually powerful Weather Doppler radar is used, operating at short centimeter band of waves.

The control of separately operating cannon or a small group of cannons is carried out by the staff operator, manually or remotely by means of cellular or radio communications, in accordance with their visual observations, which is not acceptable for effective prevention or suppression of the hail, since include human factor. Usually, the anti-hail protection network, including a plurality of spatially distributed supersonic gas-generators and coordinating by the State, also controlled by the radar.

3. Flaws of Radar in Hail Prediction

Although these radars cost several hundred thousand (Weather Radar) or millions (Antigrad) USD, in dependence of the power and service facilities, however, they have serious disadvantages and cannot solve the problem totally. The Weather radar can detect and classify with high probability already formed hail clouds, but cannot classify hail generative (hail bearing) clouds which may be transformed in hailstorms. In addition, the meteorological radar consumes relatively high power 0.2kW (Weather Radar) and 14kW+14kW (Antigrad) and requires certain installation and operating conditions, which should provide the necessary condition for direct observation.

Really, the reflection coefficient of the smooth surface by power under zero incident angle of sensing is defined as;

$$R^2 = \left| \frac{1-\sqrt{\tilde{\varepsilon}(\omega)}}{1+\sqrt{\tilde{\varepsilon}(\omega)}} \right|^2 ,$$

where, $\tilde{\varepsilon}(\omega)$ - is a complex dielectric permittivity, $\omega = 2\pi f$ - is a circular frequency and f -is a signal frequency.

The complex dielectric permittivity of pure water and ice is defined by the following equation (Petrenko, 1993; Artemov, Volkov);

$$\tilde{\varepsilon}(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1+\omega^2\tau_D^2} + \iota \frac{\varepsilon_s - \varepsilon_\infty}{1+\omega^2\tau_D^2}\omega\tau_D ,$$

where ε_s is a static dielectric permittivity $(\omega << \omega_D)$, ε_∞ is a high-frequency dielectric permittivity $(\omega >> \omega_D)$, $\tau_D = \omega_D^{-1}$ is the Debye relaxation time, $\omega_D = 2\pi f_D$ - is the Debye circular frequency, f_D is the Debye frequency, and $\iota = \sqrt{-1}$.

The value of ε_s is about 90 for both water and ice at 0^0C, and increases at low temperatures (Artemov, Volkov). The value of ε_∞ is about 5 and 3 for water and ice, and the value of ω_D is about 20GHz and 5 kHz for water and ice, respectively (Artemov, Volkov). Then the value of R^2 is about 0.61 or 0.59 from the smooth water surface and is about 0.08 from the smooth ice surface at 9.6GHz and 3GHz of radiofrequencies, respectively. Thus, ice surface absorbs more and reflects less than water surface. It means that ice pellets will absorb more than water droplets. The above performed calculations serve only to illustrate the problem and nothing more.

The primary radar equation for average received power P_r is defined by the following equation (Dimova, Albats, Bonch-Bruevich, 1975).

$$\overline{P_r} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}$$

where P_t - is a transmitted power, G - is an antenna gain, λ - is a wavelength, R - is a range to the target, and σ - is a parameter called the Radar Cross-Section (RCS) of the target.

In general RCS is determined by projected area and by the directivity (both of which are dependent on the bulk geometry of the object) and the reflectivity (dependent on the material composition and/or small-scale surface geometry of the object).

The RCS of a sphere is in most cases especially simple. If the diameter is large compared to the operating wavelength ($\lambda << r$) then the RCS of a smooth reflective sphere with a radius r is just its projected geometrical area, or $\sigma = \pi r^2$, and this is constant with regard to wavelength and with regard to any linear polarization. But, when $2\pi r/\lambda$ falls below 1.0, which is appropriate to weather radar detection of raindrops and hail the RCS is strongly and linearly wavelength-dependent (like the 4th power).

Solid spheres made of nonconductive materials will generally have an RCS of approximately zero. Rain drops and spherical hail stones have small RCS. However, rain clouds and hail clouds may have enough RCS to be detected by weather radar if water quantity in clouds is enough for that.

Water droplets in clouds in rare case can grow in size up to 10mm in diameter. Opposite, hail pellets can grow their size up to 10cm and more in diameter (Jeff, 2012; World of Facts, 2015; Bowie, 2016) and mostly with a ruffle non spherical shape RCS of which is higher than RCS of spherical pellets of the same diameter.

To show flaws of weather radar for the task of hail generative clouds detection and recognizing (classification) let's assume that a cloud (a cumulonimbus) appears on the horizon with a mixed composition of water droplets and hail pellets of small size. Moreover, let's suppose that water droplets and hailstones have the same sizes and spherically shaped. Then RCS of cumulonimbus will be less than RCS of pure rain cloud (a nimbus) with the same quantity and sizes of droplets, since hail pellets in cumulonimbus will absorb part of the radar signal energy (power) and will decrease the power of the backscattered radar signal. And, since, detection and classification of hail or hail generative clouds is performed on the background of cloudy sky for high probable detection of hail generative clouds it will be necessary to set detection threshold of the cumulonimbus below the detection threshold of nimbus. But then there will be a high level for false alarm, which will lead to huge expenses in anti-hail protection and in undesirable pollution of agricultural lands, since it will be necessary to fire shells or to launch rockets in any nimbus is appearing in the horizon. And probably, thereat, in all advertisements of weather radars and in their technical circulars there is not any information about probabilities of detection and false alarm which are very significant parameters for radars and their application.

With a further increase of hail pellets' sizes and distortions of their shapes RCS of the cloud will grow and it will be possible then to clearly argue the appearance of hail on the screen of the monitor of radar. But then it will be too late, because the moment to prevent or to suppress hail will be missed, and the only thing that can be done in this case it is to try to interrupt further growth of hail pellets and to force the hail to fall down in that state in which it was detected. However, this is not always possible, and it is not the best solution to ensure the effective protection of rural and urban areas from hail.

Thus, despite the existing advantages of the weather radar, such as the width and range of observation, relatively small spatial resolution of sensing, polarization capabilities, possibilities of estimating wind speeds and clouds velocities, the weather radar still cannot be used for hail and hail generative clouds early prediction, high probable detection and classification with high probability, which are very significant for hail timely prevention and suppression. Therefore, a need in development and application of a new type of detector-classifier is appeared for hail timely prevention and suppression which will cost cheap and will have additional advantages relatively the weather radar in hail and hail generative clouds detection and hail timely prediction.

4. Application of Microwave Radiometry for Hail Early Detection and Prediction

It is known that all objects greater absolute zero radiate a little microwave energy as well as visible and infrared because of thermal radiation. This radiation is called thermal radiation because it mainly depends on temperature and emissivity. Thermal radiation can be expressed in terms of black body theory.

A black body is matter which absorbs all electromagnetic energy incident upon it and does not reflect nor transmit any energy. According to Kirchhoff's law the ratio of the radiated energy from an object in thermal static equilibrium, to the absorbed energy is constant and only dependent on the wavelength and the physical temperature T_o. A black body shows the maximum radiation as compared with other matter. Therefore a black body is called a perfect radiator.

Real objects, the so called gray bodies are not identical to a black body but have constant emissivity which is less than a blackbody. Therefore, for real objects a correction for emissivity should be made because normal observed objects are not black bodies.

The emissivity χ can be defined by the following formula (Dimova, Albats, Bonch-Bruevich, 1975).

$$\chi = g_1(\lambda, T_o) / g(\lambda, T_o),$$

where $g_1(\lambda, T_o)$ – is a spectral density of thermal radiation (radiant energy) of an object, $g(\lambda, T_o)$ – is a spectral density of thermal radiation of blackbody at the same temperature as the object. For microwave range of electromagnetic waves $g(\lambda, T_o) = \frac{2\pi}{\lambda^2} k_b T_o$, where $k_b = 1.37 \cdot 10^{-23} [J/K]$ - is Boltzmann constant.

Emissivity ranges between 0 and 1 depending on the dielectric constant (permittivity) of the object, surface roughness, temperature, wavelength, incidence (look) angle, azimuth, polarization, etc. The temperature of the black body which radiates the same radiant energy as an observed object is called the brightness temperature T_B of the object and is expressed as $T_B = \chi T_o$.

Besides absorptivity and emissivity gray objects possess as well reflectivity and reflect/scatter part of radiation incident upon them. Reflectivity G_r is defined by reflection (scattering) coefficient and ranges between 0 and 1 depending on the dielectric permittivity of the object, surface roughness, wavelength, incidence and azimuth angles, polarization, etc., and related to emissivity as $G_r = 1 - \chi$. Reflected energy from the object can be represented as well by brightness temperature $T_{Br} = G_r T_{Ba}$, where T_{Ba} is brightness temperature of ambient. Then, the total energy coming from the object can be described by the so-called apparent temperature $T_{ap} = T_B + T_{Br} = \chi T_o + G_r T_{Ba}$. The increase in apparent temperature is called thermal contrast.

For smooth surfaces, emissivity is defined by specular reflection coefficient as $\chi = 1 - R^2$. Consequently, according to the calculations of section 3, emissivity of water and ice smooth surfaces at zero incidence angles will be about 0.39 and 0.41 for water surface at 9.5GHz and 3GHz radio frequencies and about 0.92 for ice surface at both radio frequencies.

It means that open water surfaces are relatively poor emitters (and good reflectors) of microwave energy because of water's large dielectric permittivity. Ice on the other hand is a relatively good emitter (poor reflector) of microwave energy. Therefore, the difference in microwave emissions of water droplets and ice pellets allows for high probable detection and classification of cumulonimbus on the background of rain clouds and nimbuses in particular, since even if one water droplet will be transformed into ice pellet a thermal contrast will appear at once, which in the ideal case can be detected by super high sensitive passive microwave sensors. Passive microwave sensors are referred to as microwave radiometers. Microwave radiometers measure the emitted radiance from objects and ambient. This is often referred to as antenna temperature T_A which is related to the apparent temperature and antenna pattern characteristics as follows $T_A = \int_{\Omega_{ob}} T_{ap} G^2(\Omega) d\Omega \Big/ \int_{4\pi} G^2(\Omega) d\Omega$, where $G^2(\Omega)$ is a power antenna pattern (antenna gain) and Ω_{ob} is the solid angle corresponding to the object. The power of the recorded microwave radiation signal that is naturally emitted by objects and ambient at the output of the antenna-feeder path, or at the input of the radiometric receiver with a bandwidth Δf is defined as $P_s = g_s(f)\Delta f = k_b T_A \Delta f$.

Thus, microwave radiometers can be used for early detection and classification of hail and hail generative clouds. However, the main issue is to determine frequencies more preferable in terms of the cost and reliability of early detection and timely prediction of hail and hail generative clouds.

Measured and estimated results of observed sky (clear and cloudy) apparent temperatures T_{api} presented in **Figure 1** (Hambaryan, Arakelyan, Arakelyan, 2014; Artashes Arakelyan, Astghik Hambaryan, Arsen Arakelyan, 2016) shows that radiometric contrasts due to occasional appearance of a hail cloud on the clear sky may reach up to 20-80K or more in dependence of the frequency band. This means that microwave radiometers with usual sensitivities ~0.2K (C-band), ~0.5K (Ku-band) and ~1.0K (Ka- band) at 1s integration time may be successfully used for hail detection and hail generative clouds classification.

In **Figure 2** the results of unique field measurements are presented of increments ΔT_{api} of apparent (antenna) temperatures of smooth water surface of a swimming pool of 10x3m2 of size simultaneously at three microwave frequencies (5.6GHz, 15GHz and 37GHz), at vertical $i = "v"$ and horizontal $i = "h"$ polarizations, at 20^0 and 30^0 angles of incidence, under clear sky condition due to the occasional appearance in the sky the cumulonimbus that caused a heavy rain with rare hail of 0.5-0.8cm of sizes and perturbed the pool water surface (Arakelyan et al., 2010; Grigoryan et all, 2010; Arakelyan et all, 2011; Arakelyan, Hambaryan, Arakelyan, 2012; Arakelyan et all, 2012, Astghik Hambaryan, Artashes Arakelyan, Arsen Arakelyan, 2016).

According to the results presented in **Figure 1** (Hambaryan, Arakelyan, Arakelyan, 2014; Artashes Arakelyan, Astghik Hambaryan, Arsen Arakelyan, 2016) and in **Figure 2** (Arakelyan, Hambaryan, Arakelyan, 2012, Astghik Hambaryan, Artashes Arakelyan, Arsen Arakelyan, 2016), microwave frequencies from 10 to 37 GHz and above are more preferable for hail detection. In terms of cost, the preferred microwave frequencies are 10 GHz – 15 GHz. Microwave radiometers at these frequencies can cost 300-500 USD for mass production. Although for a frequency range of 37GHz, the cost of radiometers for mass production can be about 1000–1500 USD, however, the frequency band of 37 GHz is more preferable due to the high level of thermal contrasts from ice particles.

5. A Method of a Restricted Areas' Anti-Hail Protection and Hail Trapping

The idea to use microwave radiometers for hail and hail generative clouds early detection, which is very significant for hail prevention and suppression by timely starting-up of sonic generators has been initially patented in Armenia as an invention (Arakelyan, 2013). After that the invention was patented in China (Arakelyan, 2016a), in the USA (Arakelyan, 2016b), in Canada (Arakelyan, 2017a), in the

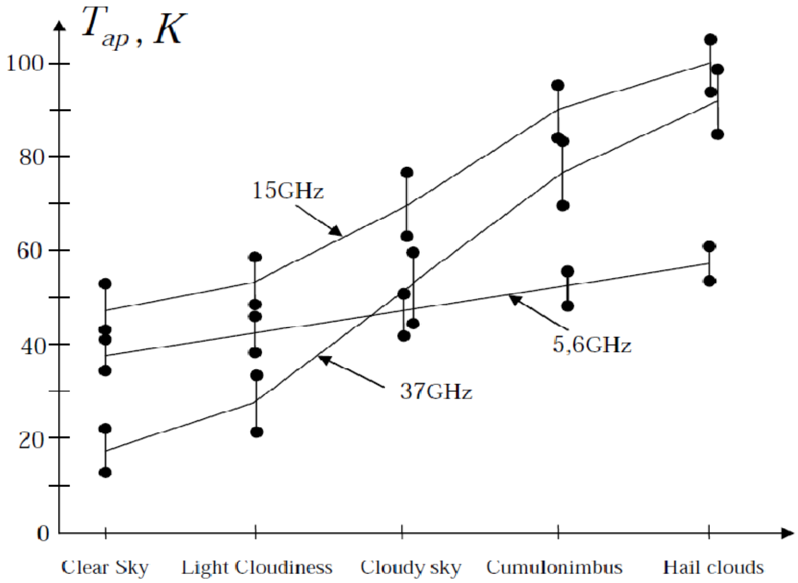

Figure 1 Clear sky and clouds brightness (apparent) temperatures at vertical polarization of radiometric sensing

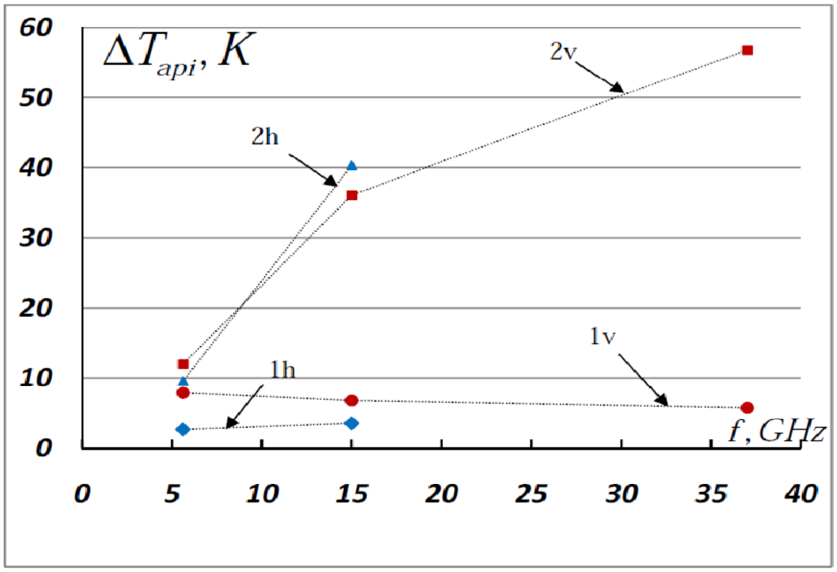

Figure 2 Frequency dependences of water surface radiometric (thermal) contrasts due to rain perturbation (1v and 1h) and appearance of nimbus at vertical (2v) and horizontal (2h) polarizations of radiometric sensing

EU (Arakelyan, 2017b), in the Russian Federation (Arakelyan, 2017c). On the basis of the obtained European Patent the invention is patented in France, in Germany, in Spain, in Italy, in Switzerland, in the UK and in Turkey. The invention is patenting also in India (Arakelyan, 2014).

The application of two microwave radiometers allows implement fully autonomous and automatically functioning anti-hail protection of an area of a minimum size of 50-70 hectare (circle space of a radius of ~500m) which is a maximum size of protecting area by one sonic cannon (gas-generator) (Ollivier, 1995).

In **Figure 3** an outline of a version of implementation of a local network of autonomous and automatically functioning anti-hail protection of the protected area (1) of a limited size is presented. The far-range detector-alerter (2) set on the scanner (4) is used to observe sky of the adjacent land all around the protected area and to warn the anti-hail protection system (3) by alert signals about the impending

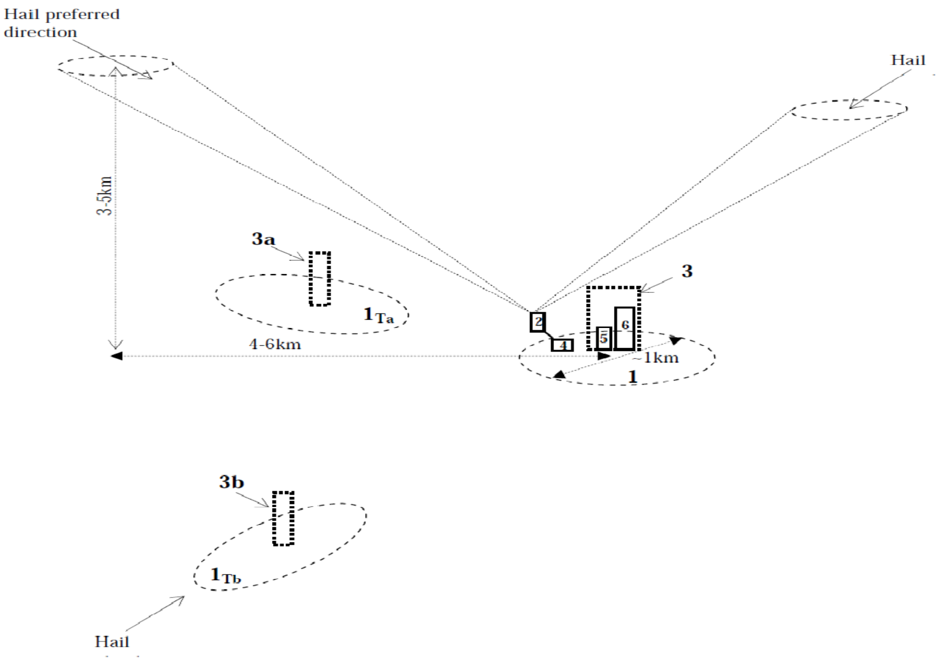

Figure 3 An outline of a version of a local area anti-hail protection and hail trapping 1 – a protected area of a limited size, 1_{Ta} and 1_{Tb} – hail trapping areas, 2 – a far-range detector-alerter, 3, 3a and 3b – hail prevention systems, 4 – a scanner, 5 – a local detector-alerter, 6 – a supersonic cannon (gas-generator)

hail danger when it detects hail generative clouds or cumulonimbus at distant approaches to the protected area, usually 4-6km far to the protected area.

Detailed descriptions of operational peculiarities of a local network of anti hail protection of **Figure 3** and block diagrams of the far-range detector-alerter (2) and the hail prevention system (3) are presented in any of above mentioned patents (Arakelyan, 2013; Arakelyan, 2016a; Arakelyan, 2016b; Arakelyan, 2016c; Arakelyan, 2017a; Arakelyan, 2017b; Arakelyan, 2017c) and in (Arakelyan, 2017d). The scanned far-range detector-alerter (2), set on the scanner (4), permanently observes and measures continuously the adjacent land's sky intrinsic microwave emission under specified elevation angle of observation (tilted observation). Approximately up-directed local detector-alerter (5) simultaneously measures the protected area's sky intrinsic microwave emission and compares measured values with the "minimum" threshold level and starts-up the supersonic cannon (gas-generator) (6) if the sky intrinsic microwave emission exceeds the "minimum" threshold level. The local detector-alerter uninterruptedly listens as well radio ether to receive warning signals about impending hail danger transmitted on the air by the far-range detector-alerter when the danger is appeared. If the local detector-alerter receives warning signals then it begins to compare sky intrinsic emission with the "alert" threshold level, which is 3-15K lower of the "minimum" threshold level, and if measured values of the intrinsic emission of the edge of the looming cloud exceed the "alert" threshold level, then the local detector-alerter starts-up the sonic cannon (gas-generator).

For some regions, hail or cumulonimbus has a preferred direction and usually comes approximately from the same direction, and sometimes near of the protected area one can find places where hail is allowed. These facts can be used to capture hail, to force hail to fall out on the territory where its damage can be relatively small. The method of hail early detection and prediction by microwave radiometers described above makes it possible to implement a completely autonomous and automatically functioning network of hail traps. Such a network of hail traps first described in (Arakelyan, 2017d) can be completely implemented separately or in combination with an implemented network of anti-hail protection, if there are places near or far of the protected area where hail may be allowed fall out.

In **Figure 3** an outline of a version of realization of autonomous and automatically functioning network for hail capture in hail traps is presented as well. When the far-range detector-alerter (2) detects hail cloud or cumulonimbus coming from the preferred or from another direction and warns the local detector-alerter (5a) or (5b) of the anti-hail protection system (3a) or (3b) of the trapping area (1_{Ta}) or (1_{Tb}), the detector-alerter (5a) or (5b) of the anti-hail protection system (3a) or (3b) starts-up the supersonic cannon (6a) or (6b) of the anti-hail protection system (3a) or (3b) by the above described way. In the absence of nearby located far-range detector-alerter the anti-hail protection system (3a) or (3b) works separately and uses “minimum” threshold level for starting-up the sonic generator (6a) or (6b). Simultaneously the anti-hail protection system (3a) or (3b) transmits on the air warning signals on impending hail danger from the trapping area (1_{Ta}) or (1_{Tb}) for protected areas located far away or for weather services.

When the far-range detector-alerter detects a cloud of severe hail which can approach to the trapping area (1_{Tb}) from the side of the protected area (1), crossing it, then the anti-hail protection system (3) alerted by the far-range detector-alerter turns-out the supersonic cannon (6) of the protected area and skips the hail cloud. Simultaneously, it warns the anti-hail protection system (3b) of the trapping area (1_{Tb}) by transmitting on the air warning signals about impending hail danger from that azimuth direction, which starts-up the supersonic cannon (6b) when the signals of sky intrinsic emission exceed the “alert” threshold level. By this particular way of a solution, fully described in (Arakelyan, 2013; Arakelyan, 16a; Arakelyan, 16b; Arakelyan, 16c; Arakelyan, 2017a; Arakelyan, 2017b; Arakelyan 17c; Arakelyan, 2017d) it is possible to implement a fully autonomous and automatically functioning network of spatially distributed hail traps.

Described method of hail prediction and hail early detection by microwave radiometers allow as well enhance the efficiency of anti-hail protection and of hail trapping, in particular, by join application of two hail preventing techniques: by shock waves and by clouds seeding. However, by seeding clouds one needs to understand the enrichment of the lower layers of the atmosphere with reagent particles, by injecting during first few detonations a reagent into the combustion chamber of the supersonic cannon, which will be further transferred to the upper layers of the atmosphere by shock waves. Detailed block diagram of such a supersonic cannon (gas-generator) and the description of its application for hail prevention are fully described in (Arakelyan, 2013; Arakelyan, 16a; Arakelyan, 16b; Arakelyan, 16c; Arakelyan, 2017a; Arakelyan, 2017b; Arakelyan 17c).

6. Wide-Ranging Anti-Hail Protection of a Vast Area

As shown above and in (Arakelyan, 2017d) by two radiometers it is possible to implement fully autonomous and automatically functioning of the anti-hail protecting device, like a supersonic cannon, for instance, and to provide anti-hail protection of the area (circle space) of 50-70 hectare of a size. In accordance with (Artashes K. Arakelyan, 2017) by application hundreds, thousands radiometers it will be possible to perform a global anti-hail protection of a vast area functioned fully autonomous and automatically. But, if the cost of hundreds or thousands of radiometers can reach the cost of the meteorological radar, then, where is it the benefit to use radiometers? The benefit is obvious from the following. In addition to the flaws of the radars in detecting and classifying hail and hail generative clouds, let us assume as well that the meteorological radar and thousands of radiometers protect the area of the same size. Then, in the event of an accidental failure of the radar, the whole protected area remains unprotected for a long time, since, it is not always possible to repair the failed radar on site, and its replacement will require large financial and labor costs and the time which is the main decisive factor for successful implementation of the protected area's anti-hail protection.

And in a case of radiometers, at the simultaneous failure of even half of the number of radiometers, which is almost unbelievable, only half or lesser part of the protected area will remain unprotected. Moreover, replacing or repairing faulty radiometers is easier, cheaper and faster than in the case of the radar. In addition, radiometers has low power consumption, can be supplied by a power from a small solar panel, they do not require certain installation or operating conditions, and as mentioned above, radiometric observations cannot miss the stage of transformation of water vapor and drops of water to hail, and can detect and classify hail and hail generative clouds better than radar.

In **Figure 4** an option is presented for implementation of a fully autonomous and automatically functioning large-scale network of anti-hail protection to protect a vast area (1) comprising M>>1 spatially distributed protected sites (2) 50-70 hectares each and hail trapping areas (2_T). Each protected site (2) and hail trapping area (2_T) is equipped with an anti-hail protection system (3) comprising a powerful supersonic cannon and a local detector-alerter for early detection of impending hail or hail generative clouds, by measuring apparent temperature of the corresponding part of the sky just over the protected site or hail trapping area, and for timely starting-up the corresponding site’s and trapping area’s supersonic cannons. Detailed block diagrams of the corresponding site’s local detector-alerter and supersonic cannon (gas-generator) are presented in (Arakelyan, 2017d; Artashes K. Arakelyan, 2017).

The large-scale network of anti-hail protection of the protected area (1) of any size, which is a particular case of a general solution fully described in (Arakelyan, 2013; Arakelyan, 2016a; Arakelyan, 2016b; Arakelyan, 2016c; Arakelyan, 2017a; Arakelyan, 2017b; Arakelyan, 2017c), is implemented by the following way. After initial running of the wide-ranging anti-hail protection network, that is after initial starting of all M anti-hail protection systems (supersonic cannons and corresponding local detectors-alerter), each anti-hail protection system of the network and the whole anti-hail protection network continue their operation autonomous and automatically. Each local detector-alerter of any of M anti-hail protection systems (3) with its up-directed antenna observes uninterruptedly (continuously) corresponding part of the sky, measures the power of signals of sky intrinsic microwave emission (more

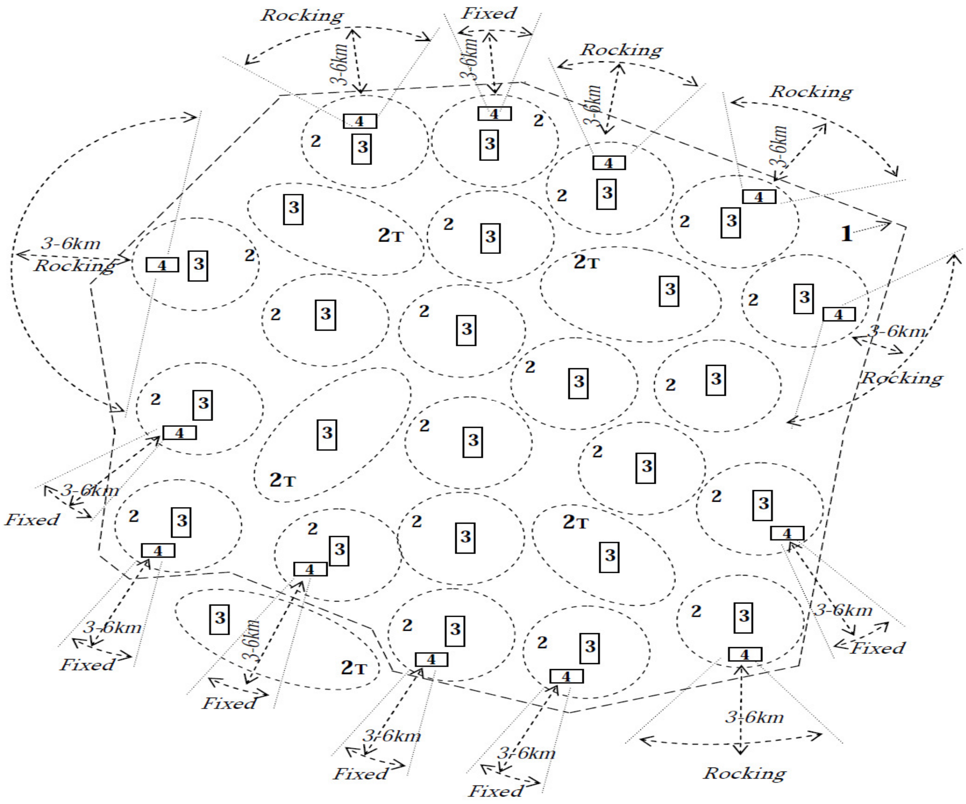

Figure 4 An outline of a version of large-scale anti-hail protection network 1 – a protected area, 2 – a protected site, 2T – a trapping area, 3 – an anti-hail protection system comprising a local detector alerter and a supersonic cannon (gas-generator), 4 – a far-range detector-alerter with a scanner if necessary

exactly external emission or antenna temperature) and compares measured values with the "minimum" threshold level. When the measured value of the power of external emission exceeds the "minimum" threshold level, then the local detector-alerter starts-up corresponding supersonic cannon and simultaneously warns other anti-hail protection systems (3) about impending hail danger. Warned about the hail danger near located anti-hail protection systems decrease its threshold levels down to the "alert" threshold level and wait for further developments and when the measured values of the intrinsic emission of the edge of the looming cloud exceed the "alert" threshold level, then the nearby located local detector-alerter starts-up its supersonic cannon and simultaneously warns others by chain. This chain action is interrupted only when the threat of hail disappears.

The above described network is an effective one when marginal sites (2) of the protected area (1) can be used as hail traps and as an alerter which will provide required time for in time running of the internal sites supersonic cannons that is 15-20 minutes before the hail storm arrival. However, such a situation with marginal sites is not common. Usually, the marginal sites are agricultural lands too and for their highly effective protection it is necessary to get advance information about the impending hail storm. This problem is solved by the following way. Marginal sites of the protected area (1) in addition are equipped with a remote sensing complex of K far-detection (far-ranging) systems (4) spatially distributed along the edges of the protected area. It is shown as well in **Figure 4**. The remote sensing complex which serves the whole protected area (1) of M sites is used for far-ranging detection of hail or hail generative clouds over an adjacent land all around the protected area at a horizontal distance 4-6km far from the edge (boundary) of the protected area (1) and at the altitude 3-5km, as well as for warning the anti-hail protection systems of the protected sites of the protected area (1) by transmitting on the air the warning signals on impending hail danger from a certain adjacent land of the protected area of M sites. The number K depends on the type of spatial distribution of M sites and it can have a value from the interval [1÷M], e.g. if M sites are spatially distributed around a common center it will be possible to use only one (K=1) far detection system. If all M sites are located far apart as a long chain then for entire serving the protected area of M sites it will be necessary to use K=M far detection systems. Depending on the terrain relief, any of the far detection systems can be installed individually, near or at a distance from the corresponding detector-alerter, inside or outside the corresponding protection site, etc. Further action of the chain is described above and in (Artashes K. Arakelyan, 2017) in detail.

Sometimes, some of marginal supersonic cannons of **Figure 4** and supersonic cannons of trapping areas can be equipped in addition by reagent injecting facilities, to make hail to fall off in trapping areas and to quickly neutralize hail threat.

In (Arakelyan, 2013; Arakelyan, 2016a; Arakelyan, 2016b; Arakelyan, 2016c; Arakelyan, 2017a; Arakelyan, 2017b; Arakelyan, 2017c) it is described as well a method how to control the global anti-hail protection network from the single center which can be a preferable version for countries where anti hail protection is under the government care. This solution supposes to create a main control center that will receive warning signals transmitted on the air by far-detection systems or by local detectors-alerter, will process and will warn about impending hail danger those local detectors-alerter, corresponding sites of which may be directly affected by hail. Despite the apparent advantage this method suffers by some flaws too. The first one is - additional expenses connected with the main control center's creation and its exploitation. The second one is - if something happens with the main control center (an accidental failure) the whole protected area remains unprotected for a certain time required for its repairing.

CONCLUSION

Independently of frequency band and polarization microwave radars cannot predict hail in its early stage of forming, since high absorption peculiarities of ice particles, relatively to water droplets of the same sizes, may prevent timely detecting and classifying of hail clouds incipience which is the most required parameter for hail prevention and suppression at the beginning of hail clouds formation. Radars can detect and classify hail with high detection probability when hailstons grow to the certain, already large sizes, when all efforts to prevent or to suppress hail can be in vain.

Microwave radiometers which are applicable for measuring sky and clouds intrinsic emission are very sensitive to ice particles incipience in clouds. Microwave radiometers with usual sensitivities may be successfully used for hail early detection and classification, for hail early prediction and alerting on impending hail danger are necessary for hail timely prevention and suppression. By application of radiometric detectors-alerter it is possible to implement an autonomous and automatically functioning anti-hail protection of a local area of a limited size. By application of radiometric detectors-alerter it is possible as well to create fully autonomous and automatically functioning network for implementation of anti-hail protection of a vast (unlimited) area, as well as to prevent and to suppress hail by capturing hail by fully autonomous and automatically functioning network of spatially distributed hail traps.

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