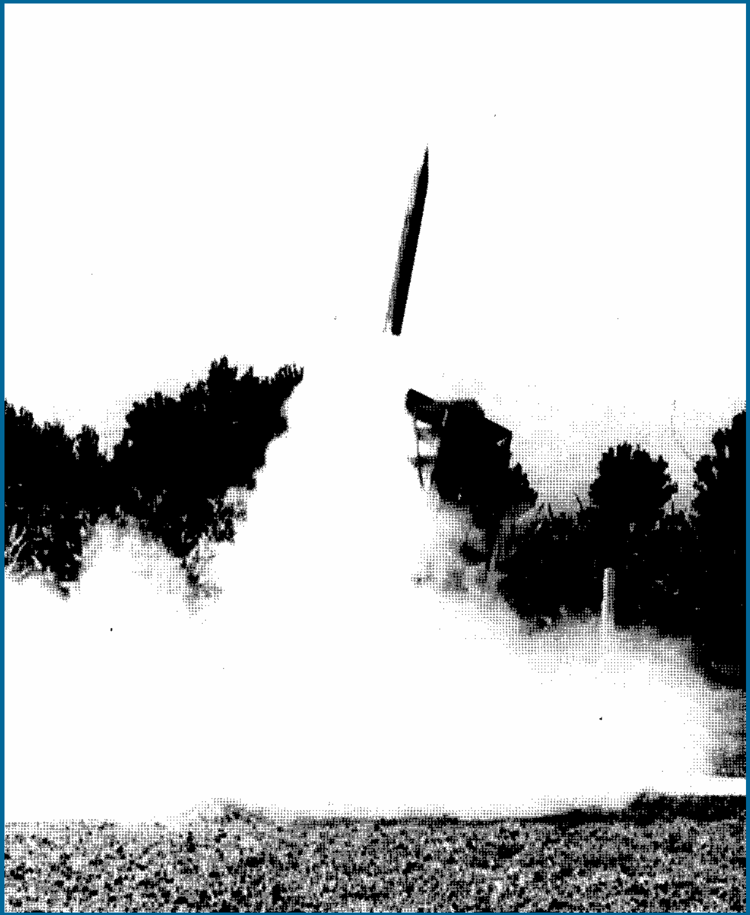

REPUBLIC OF BILGARIA
MINISTRY OF AGRICULTURE AND FOOD
AGENCY HAIL SUPPRESSION
17 Hristo Botev blvd., Sofia 1606
Tel.: +359 2 9152 952   Fax: +359 2 951 65 97
E-mail: hail_bg@yahoo.com

History

The hail suppression activity in Bulgaria as state politics begins in 1968 by building the first operative anti-hail unit at Saedinenie town, district Plovdiv.

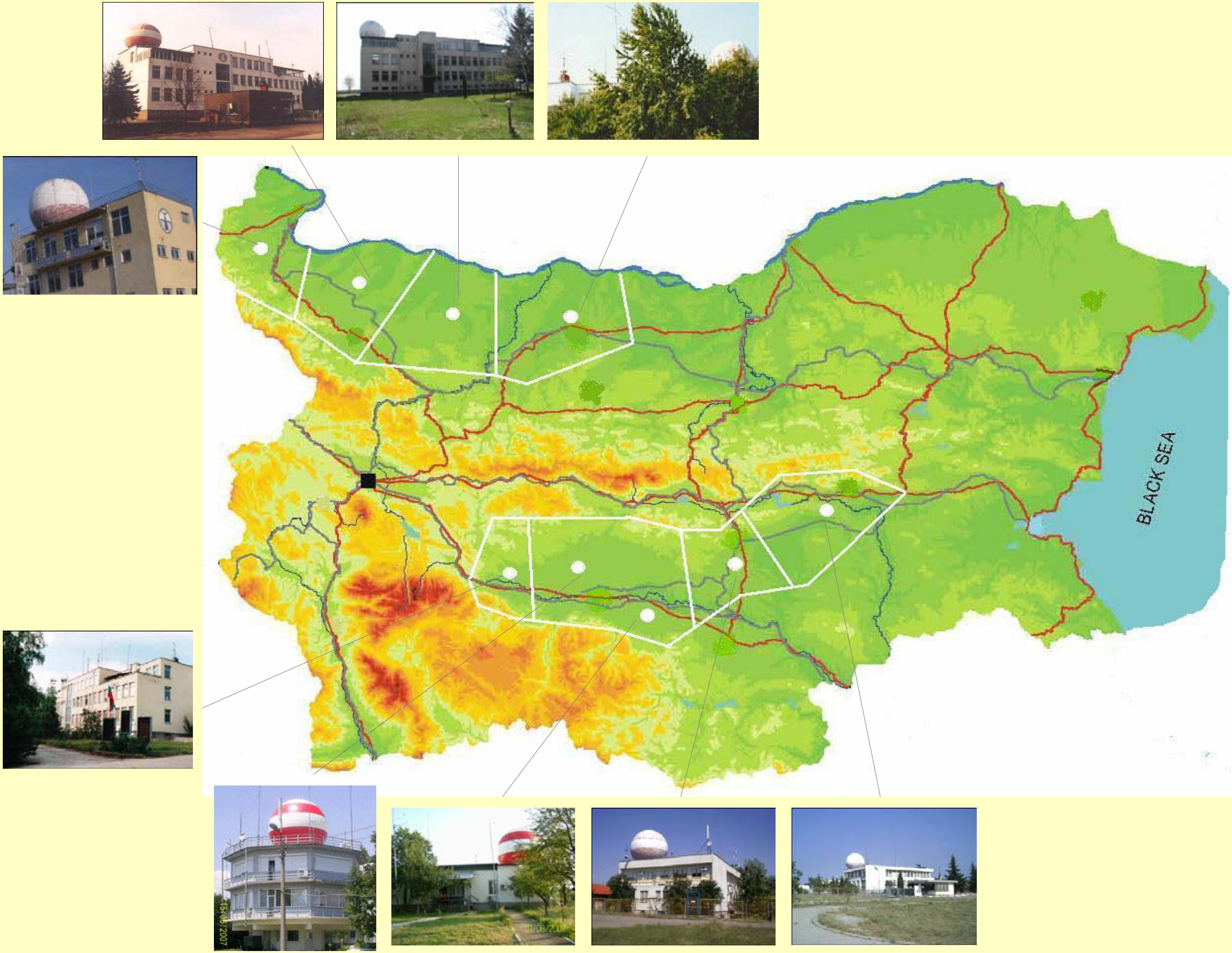


Russian rockets PGI-M, Oblako, Alazan-1M, Alazan-2M are used in Bulgaria until 2001.
From 1994 Alazans over-supplied with agent based on AgJ are used.

The Hail suppression activity in the Republic of Bulgaria is financed entirely from the state budget.

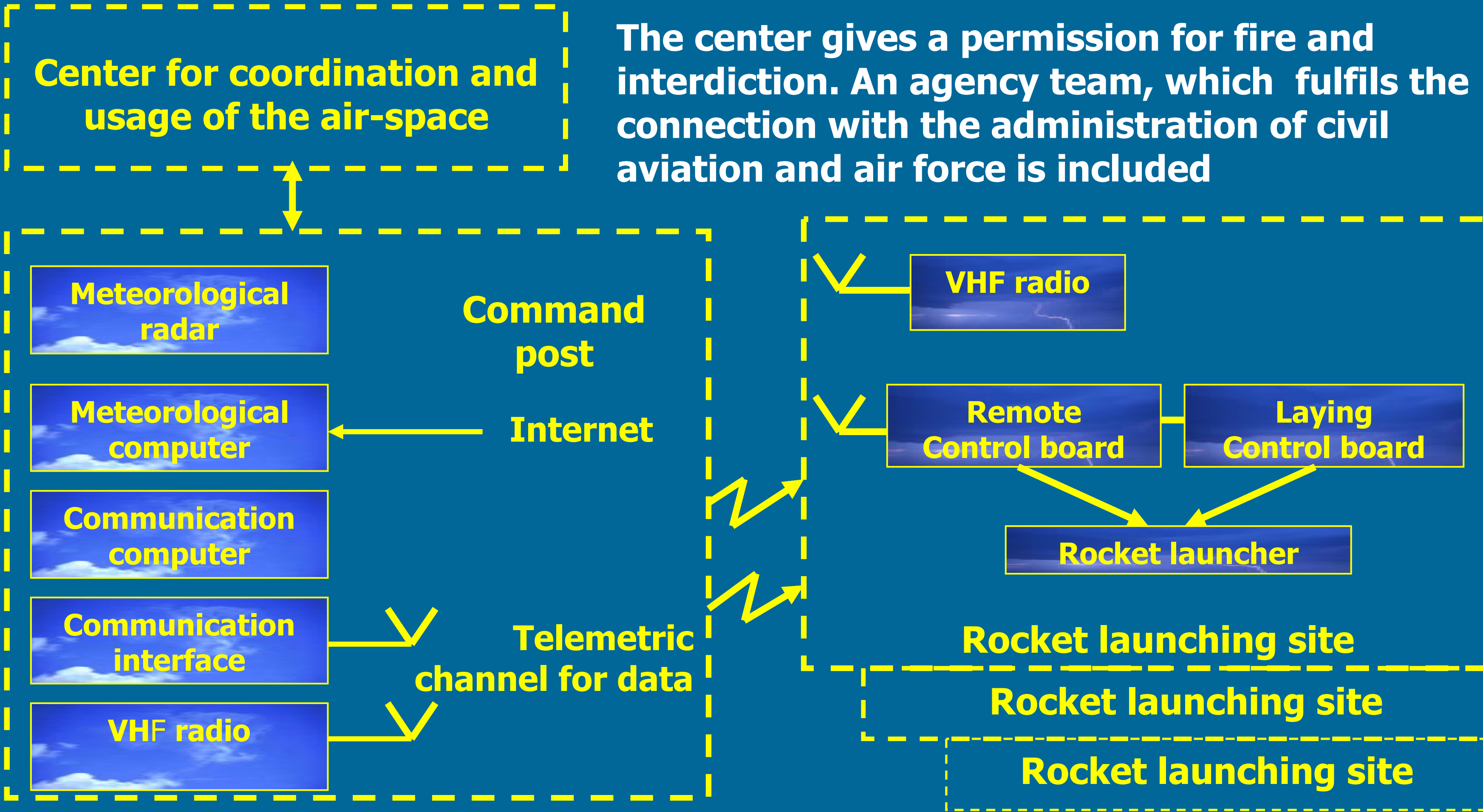
The hail suppression activity is realized by rockets, launched from Rocket launching sites, distributed around 9 Command posts. Every Command post with its respective Rocket launching sites is differentiated in a Regional Directorate. Regional Directorate Plovdiv includes two Command posts.

The total protected area is 17 263 sq. km in the regions of the country with strongest hail damages.
In the Danube plane the protected districts are Vidin, Montana, Vratsa and Pleven.
In Upper Thracian lowland the protected districts are Pazardjik, Plovdiv, Stara Zagora and Sliven.


BLACK SEA

Work organization

The center gives a permission for fire and interdiction. An agency team, which fulfils the connection with the administration of civil aviation and air force is included



The Command post fulfils observation, command and control of the hail suppression activity

The fire is carried out from the rocket launching sites

Severe storm formation

Convective instability and high humidity as well as moderate wind shear in the atmosphere are necessary for hail storm formation.

Conditions, responsible for hail precipitation:

- Enough supercooled liquid water content
- Arising hail embryos (graupel or frozen drops)
- Strong updrafts

HAIL SUPPRESSION CONCEPTS

Beneficial competition

Artificial creation of additional hail embryos, which will be sharing the available liquid water content (LWC) limiting the size of growing hailstones.

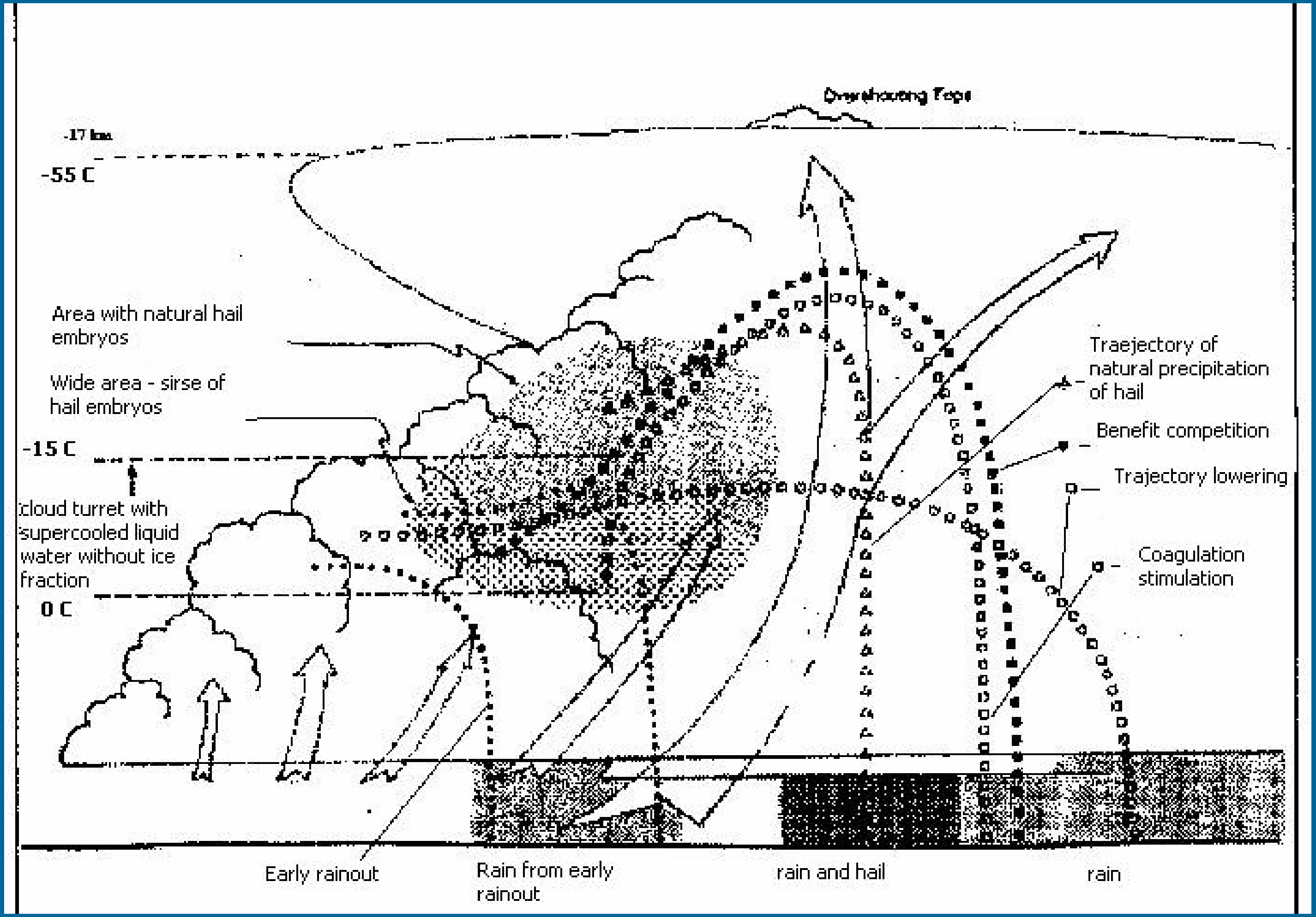
Early rainout

Rain stimulation in early growth phase of supercooled convective cloud which has not yet developed strong updrafts. The cloud's supercooled water content is reduced, which leads to reducing the number of hailstones with large size.

Trajectory lowering

Creation of conditions, under which the hailstones grow on lower height in the cloud, where the reduced LWC and shorter residence time restrict hailstones growth.

Hail suppression concepts – Technical documentation of WMO /1996



Multicell storm with developing cells in the flange with weak updrafts – in the left part of the figure and the mature cell – in the right part.

SYNOPTIC AND AEROLOGICAL ANALYSIS OF ATMOSPHERIC STATE

Synoptic analysis – based on maps with surface and level 850, 700 and 500hPa analysis, forecast models, meteograms, satellite information

Aerological analysis – Aerological soundings data is processed by one-dimensional model of a convective cloud

One-dimensional model with c microphysics parameterization

Made in Department of meteorology and geophysics
Faculty of Physics – Sofia University

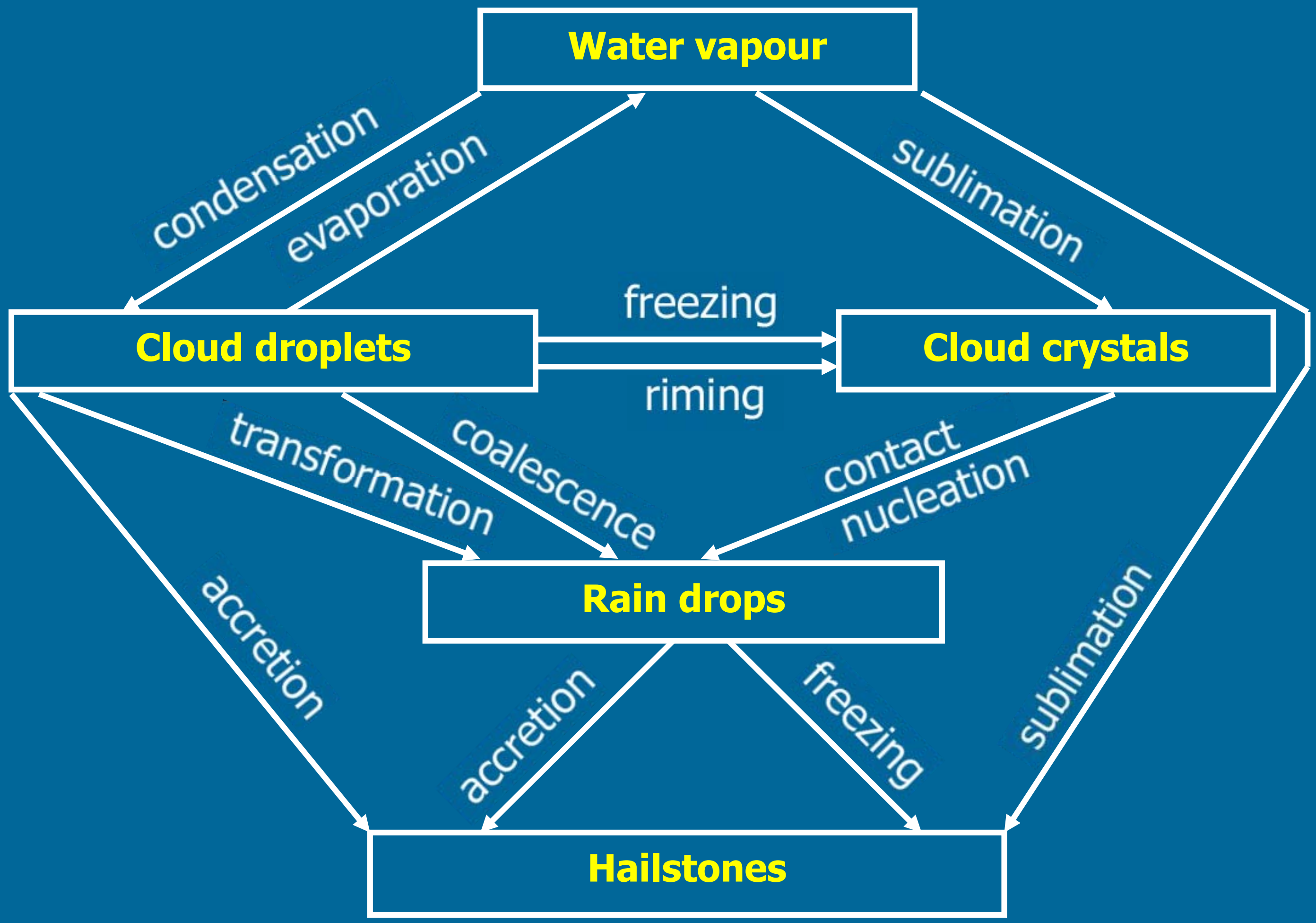
The application of the model for forecasting the type of precipitation is included as a report at the European Conference on severe storms in September 2007 in Trieste

The model is designed for determining of the thermodynamics characteristics of the atmosphere and the cloud characteristics, necessary for forecasting the type of precipitation and calculating of the diffusion cloud of the agent

- **The model is with relationship between the microphysics and dynamics**
- **The microphysics in the model is with “bulk water” parameterizations**
- **The cloud characteristics are a function of height**

Classification functions for forecasting the precipitation type (hail or rain) are obtained by stepwise discriminant analysis.

Microphysics processes, taken into consideration in the model of cloud thermic



Distribution of the hydrometeors by size:

- For the drop sizes distribution is using Marshal – Palmer equation

$$N_D=N_0.exp(-XD)$$

- The model accepts a 21-element discretizational distribution of the cloud crystals depending on the temperature
The concentration of ice crystals at fixed supercooling is given by Fletcher

$$N(T_S)=N_S.exp(\beta_S.T_S)$$

To obtain the values, similar to the measurements in continental clouds, a correction given by Hobbs is made.

- The distribution function of the precipitation crystals is given by the equation

$$n_D=n_0.exp(-\Lambda.D)$$

- The calculations in the model begin from condensation level
- The active convective element is considered a sphere with radius

$$R(z) = R_0 + Z.tg\beta$$

where R_0 is the initial radius of the thermic

- For quantitative description of the process of interaction between the thermic and environment we use the quantity α(z), characterizing the mass alteration of the air in the thermic. We use the equation:

$$\alpha(z) = \frac{1}{M}\frac{dM}{dz} = \frac{0,6}{R(z)}$$

- To calculate the alteration of temperature in the raised cloud thermic we take into account the adiabatic cooling at the vertical motion, the emitted heat during condensation and sublimation of water vapor and freezing of cloud droplets, as well as the influence of mixing of dry and moist air masses

Runge-Kutta method is used to solve the system of equations as a 5m step for the calculation is used

In advance it is given:

- **Radius Ro=5 km and initial updraft velocity Wo=5m/sec of thermic at the cloud base, obtained based on studies in Bulgaria**
- **Experimentally determined constants, initial and threshold values connected with microphysics**

INPUT DATA

- **Data from aerological sounding**
- **Surface meteorological data** – temperature and relative humidity in a time close to sounding time and maximum daily temperature
- **Type of process**: frontal (convergence) or free convection determined by synoptic analysis

OUTPUT DATA

Basic characteristics of the environmental conditions

- Condensation level
- Distribution of air temperature and humidity in height in the environment, necessary for the calculations with the numerical model
- Height of isotherms 0, -5, -10, -12, -15, -20
- Temperature gradient between basic isobar levels
- $\Sigma(T-Td)850-700-500hPa$
- Instability index CAPE, Lifted index, K Index
- Wind hodograph

Cloud characteristics, obtained by calculations with the model

- DTMAX – (Ti – Te)max and the respective height
- WMAX – maximum updraft and the respective height
- LWCmax – maximum liquid water content and the respective height and temperature
- Imax – maximum ice content and the respective height and temperature
- Depth of the layers with updraft more than 20, 25, 30m/s
- Distribution of the cloud temperature in height, necessary for calculation of the diffusion cloud of the agent
- Forecasting the type of precipitation (hail or rain)

DIFFUSSION MODEL OF AGENT

Inside the clouds the agent is diffused through turbulent diffusion

During the transformation time of ice-forming nuclei into ice embryos, a fixed concentration of ice embryos is created at a fixed distance from the source.

Because of their small sizes the agent particles are carried away by the convective motions, which are observed in seeding area, and they begin to diffuse according to the laws of turbulent diffusion

According to Fik's law, the diffusion of aerosol particles from a momentary linear source (cylindrical symmetry) in homogenous and isotropic atmosphere is given by:

$$(1/K)(dc/dt)=d_2c/dr_2 +(1/r)(dc/dr)$$

Initial and border conditions:

at **r** = ∞	**c(t,** ∞) = 0
at τ = 0	**c(0,** 0) = ∞
at **t**=0 и **r** > 0	**c**(0, r) = 0

Law of conservation of the mass per unit length of source

$$2p\int_{0}^{\infty} crdr = Q^{l} = const$$

where:

τ – the time of diffusion

c – given concentration of an area with radius **r**

$Q^{l}=Q_0*\kappa$, Q_0 – number ice-forming nuclei per unit length of source

κ – coefficient of effectiveness of the agent

K – coefficient of turbulent diffusion

The field of given concentration is described by the equation

$$c = (4pKt)^{-1} Q^{|} \exp(r^2 (4Kt)^{-1})$$

from where the radius r in the direction of the respective axis of an area with a given concentration **C** is:

$$r = (((\lg Q^{|} - \lg c - \lg(4pKt)) * 4Kt)/\lg e)^{1/2}$$

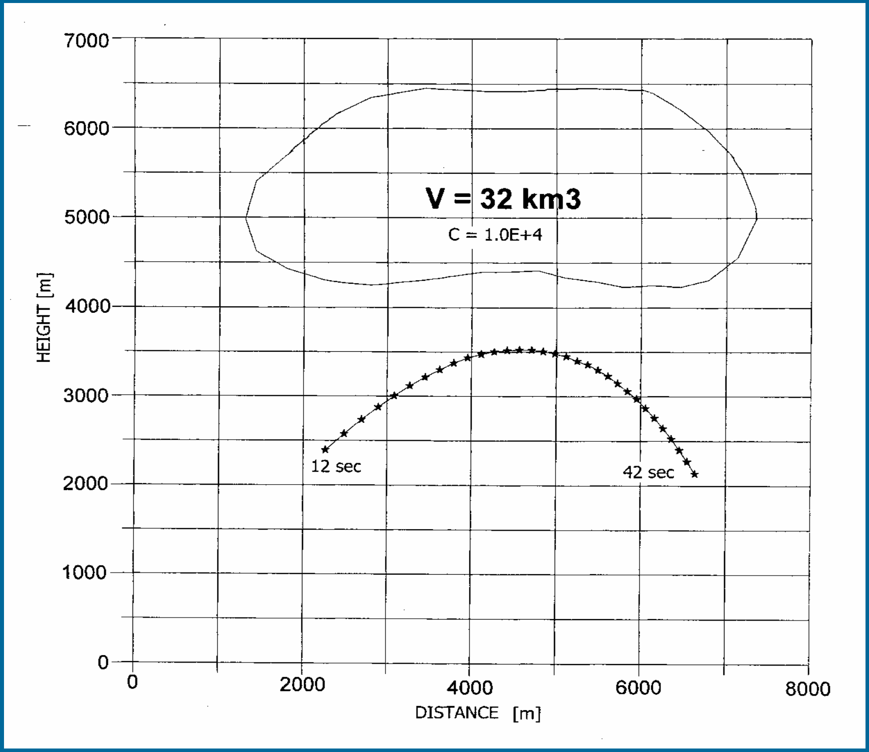
INPUT DATA OF THE MODEL

- The active part of the trajectories of the rockets
- The production of ice-forming nuclei by the generator in flight
- Coefficient of effectiveness of the rocket
- Distribution of cloud temperature in height
- Updraft in the seeding area
- Diffusion time
- Scale of diffusion
- Ice-forming nuclei concentration at the boundary of the diffusion cloud
- Vertical velocity of dissipation of turbulent energy
- Horizontal velocity of dissipation of turbulent energy

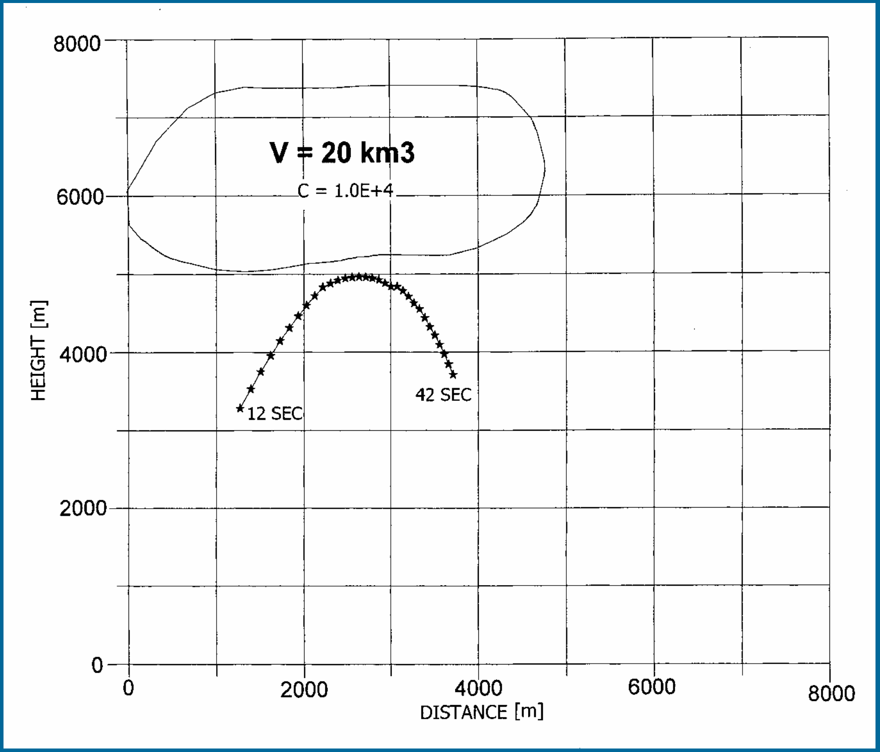
THE DIFFUSION MODEL CALCULATES:

- Volume of the diffusion area with a given concentration of ice-forming nuclei
- The elevation of the rocket sites for different altitudes

Elevation 60°, Updraft 10 m/sec



Elevation 75°, Updraft 8 m/sec



Categories of hail-dangerous cells and hailstorms. Criteria

	Zmax dBz	ΔH dBz	Development of cells	Seeding
I	$45 \leq Z \leq 50$	ΔH45 ≥1.5км	Slowly growing, with Zmax 15-25dBZ, reaching slowly Zmax 35-40dBZ, $H_{15dBz} \geq H_{-10°C}$. Small gradient of radar reflectivity Zmax 45dBz arises at a height $\leq H_{-10°C}$ and grows slowly in height	Continuous observation If ΔH45dBz grows more than 2 км, the cells are seeded
II	$40 \leq Z < 45$	ΔH40 ≥3км	Rapidly growing, with Zmax 15-25dBZ. Zmax reaching 35-40dBZ for 1-2 minutes. High gradient of radar reflectivity and growth of the cell in all directions. $H_{15dBz} \geq H_{-20°C}$	The cells are seeded with the purpose of early rainout
III	$45 \leq Z < 50$	ΔH45 ≥2км	High formation of an area with 45dBz $H_{45dBz} \geq H_{-10°C}$	The cells are seeded when 45dBz shows
IV	$50 \leq Z \leq 55$	ΔH45 ≥3км	Hailstorms	The seeding starts immediately
V	$Z \geq 55$	ΔH45 ≥4км	Hailstorms	The seeding starts immediately

STRATEGY OF THE SEEDING

I. The conceptions of hail suppression define seeding areas, which have high supercooled liquid water content and weak updraft. The introduction of ice-forming nuclei is continuous, at regular intervals during the whole period of hail danger.

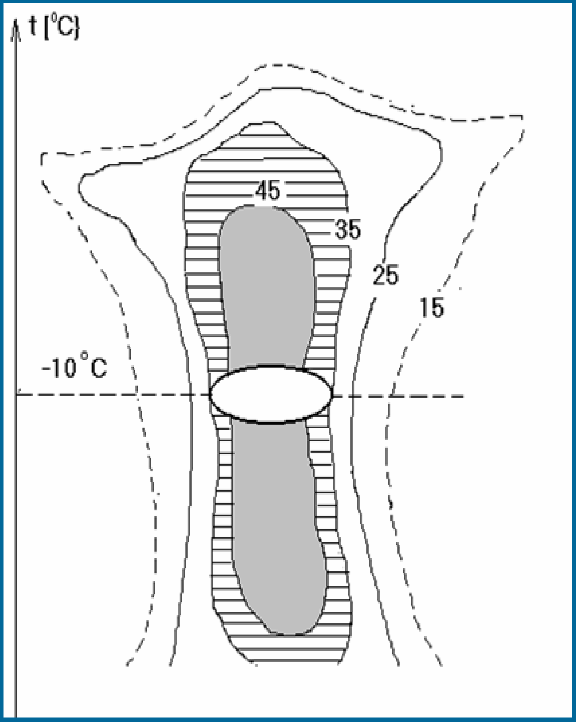
II. From the moment of dispersion of the agent until particles grow to rival sizes, a time of about 3 minutes is needed. Therefore the level of supplying of agent is chosen so that the horizontal section of the diffusion cloud will reach a level $-10^{\circ}C$ in the moment when the agent particles grow to rival sizes.

Types of hailstorms depending on the structure and the dynamics of development. Seeding areas

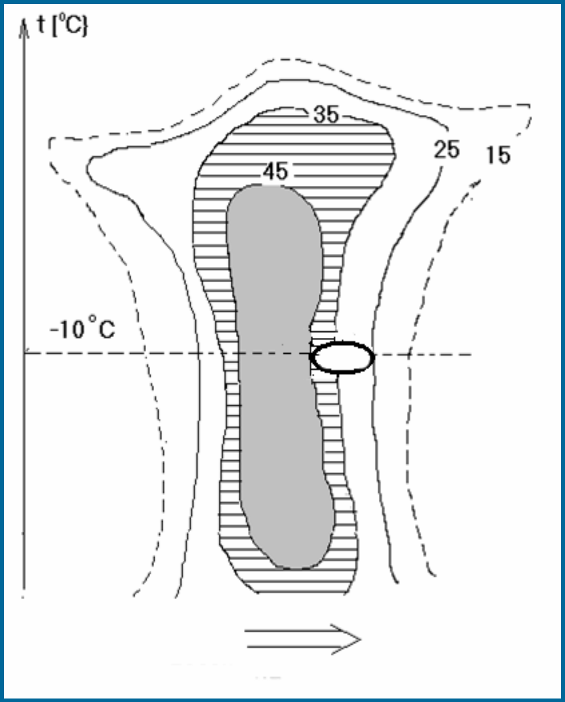
ISOLATED SINGLE-CELL **(free convection)**

Suppression of the hail formation process is realized by the seeding

Stationary cells

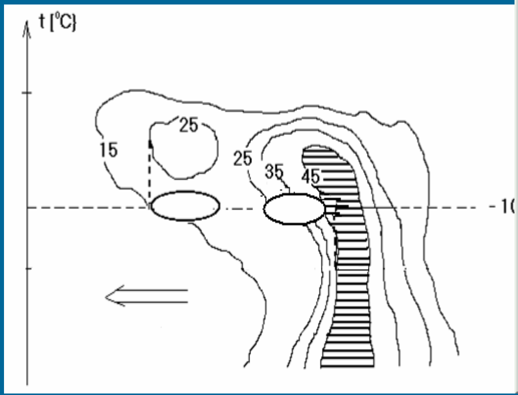


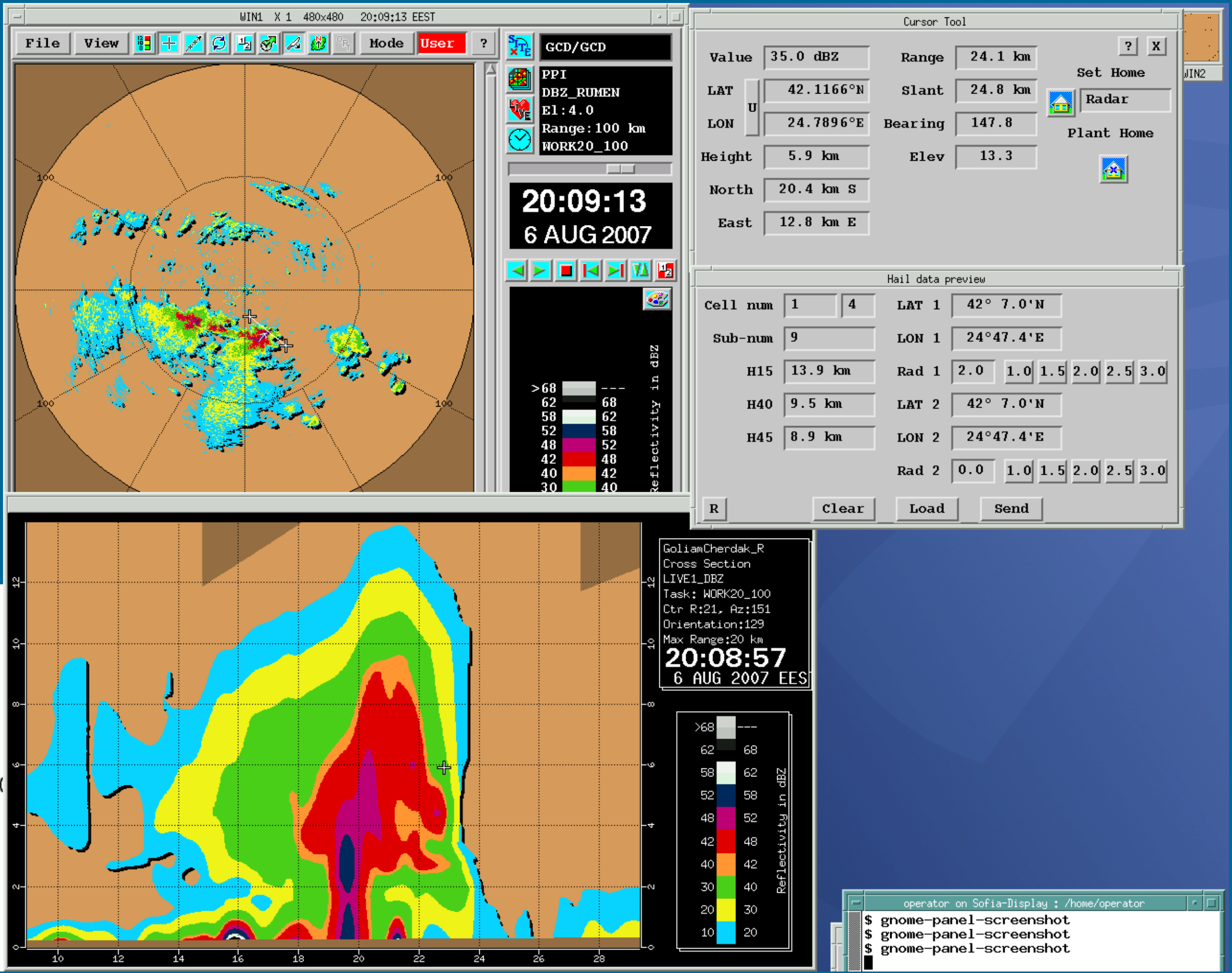
Moving cells



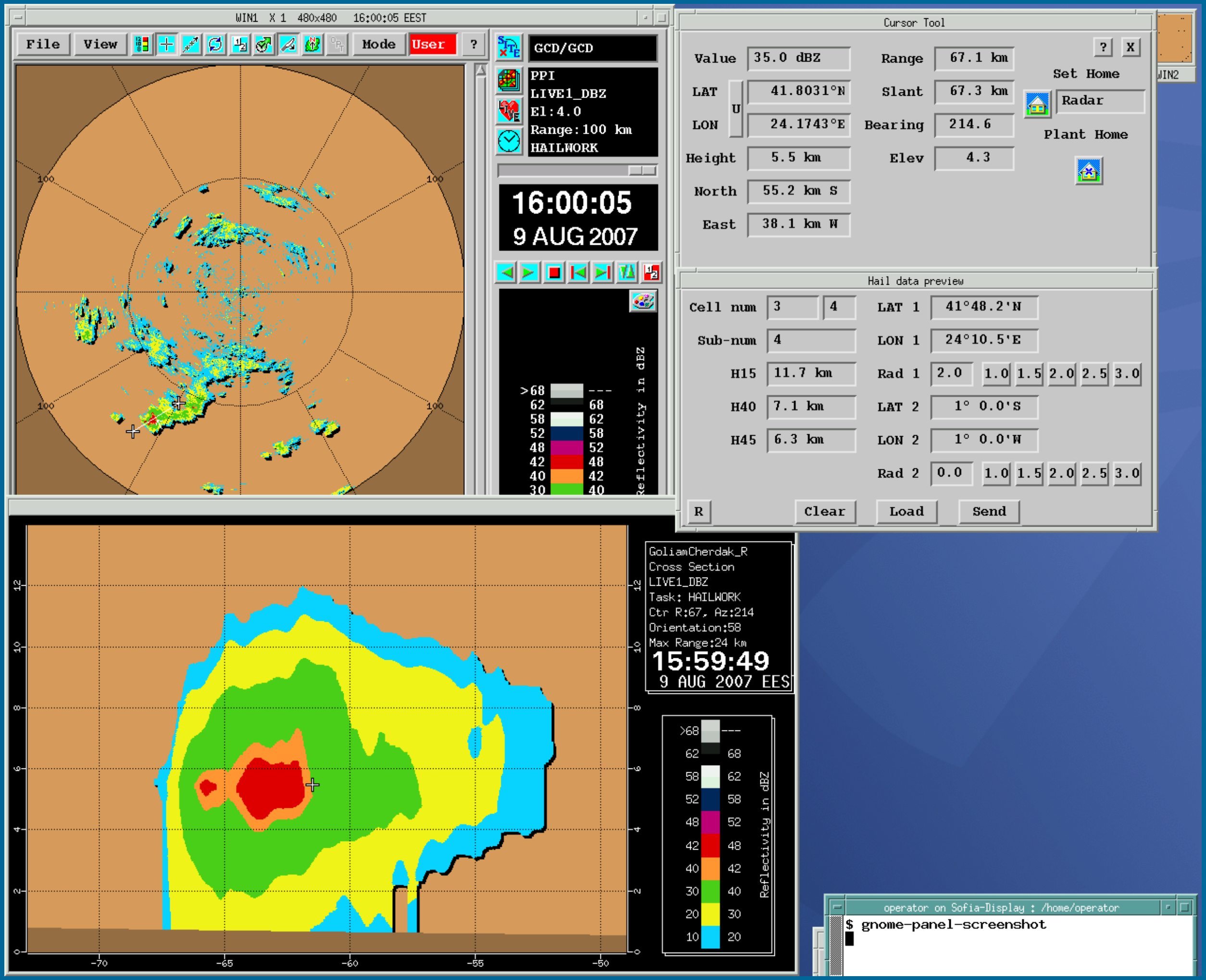
<u>MULTI-CELL STORM</u> (front or convergence)

The purpose is to disturb the process stability by early rainout of daughter cells and suppressing the hail formation process in the mature cell



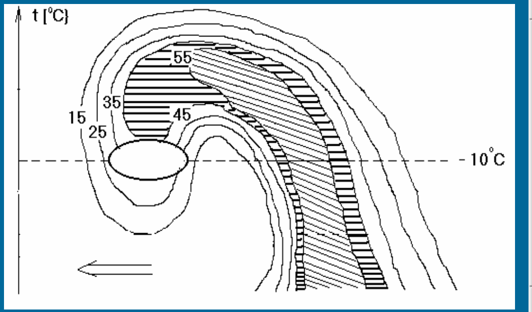


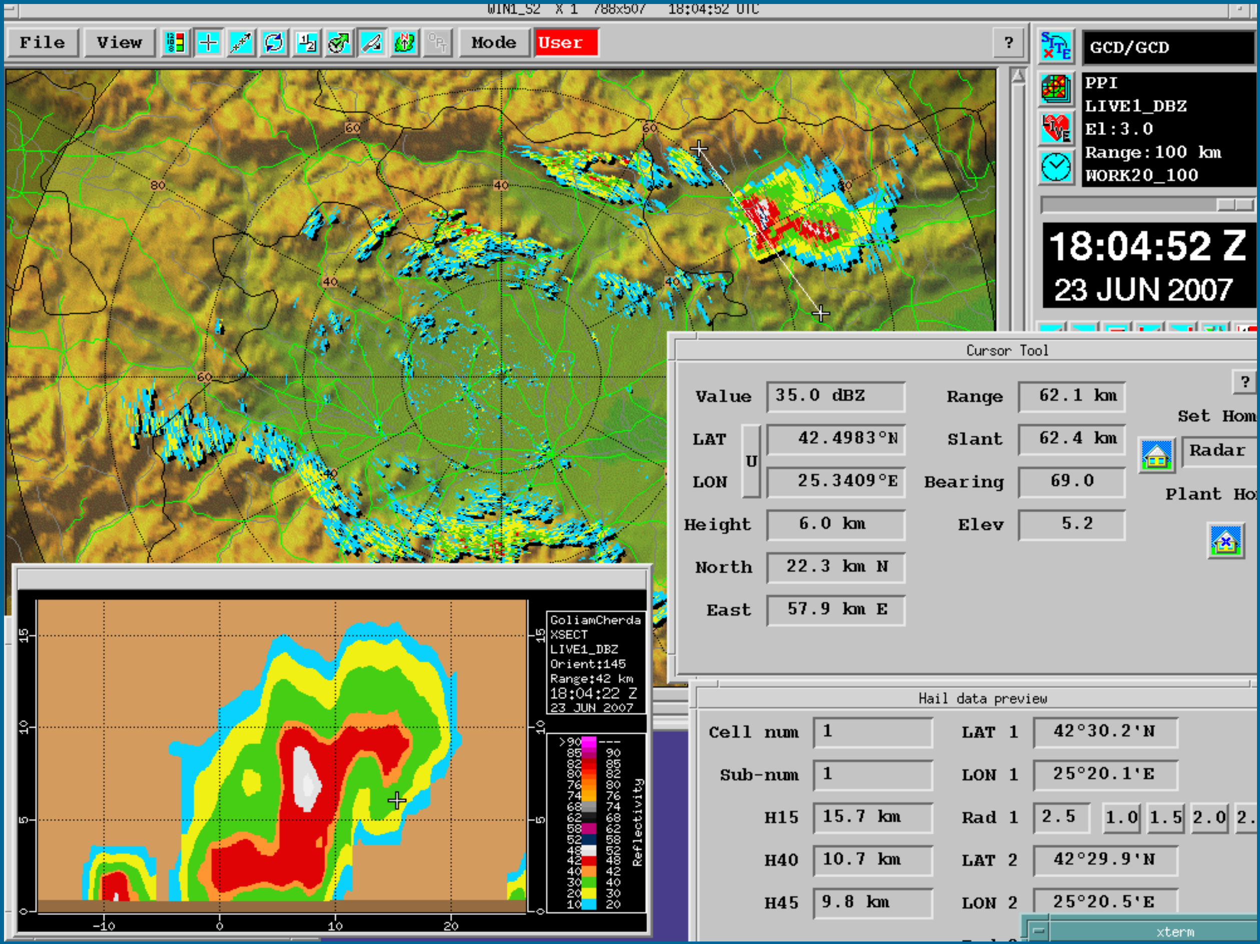
High formation of an area with 45dBz in multicell storm



<u>SUPERCELL STORM</u> (front or convergence)

The purpose is to disturb the quasi-steady state by disturbing the bounded weak-echo region (BWER) and interrupting of the process of renewal





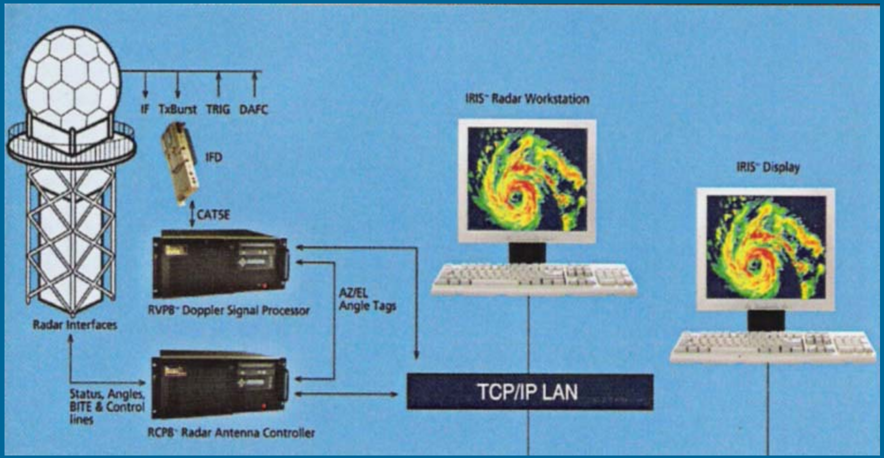
TECHNICAL MEANS AND SOFTWARE

RAPIRA

RADAR AND **A**EROLOGICAL **P**REVENTIVE **I**NFORMATION IN **R**EAL TIME, **A**NALYSIS

The system is designed to process and display the meteorological radar information from MRL5-IRIS, to process the aerological sounding data, to command and control the cloud seeding with the purpose of hail suppression and to command the anti-hail rockets' launching

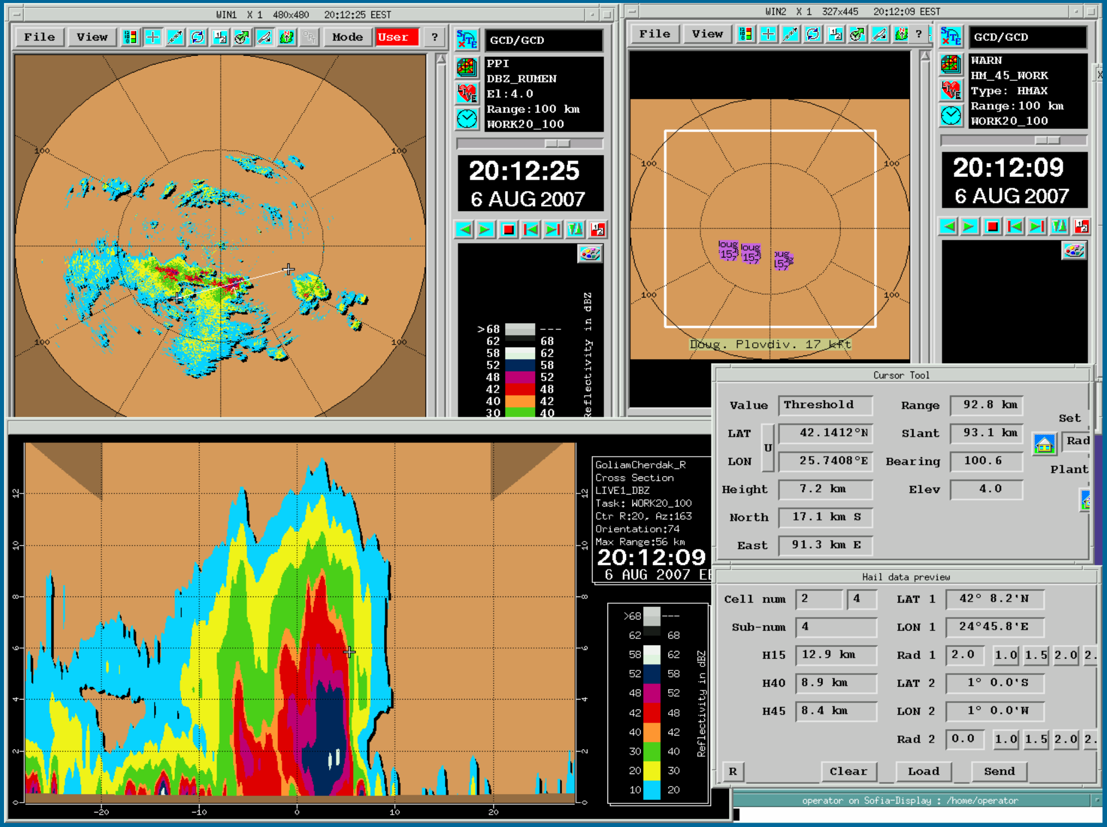
NETWORKED COMPONENTS OF THE SYSTEM



SIGMET'S IRIS together with the MRL-5 radar – powerful system for monitoring, tracing and forecasting of meteorological phenomena. It provides real time information.

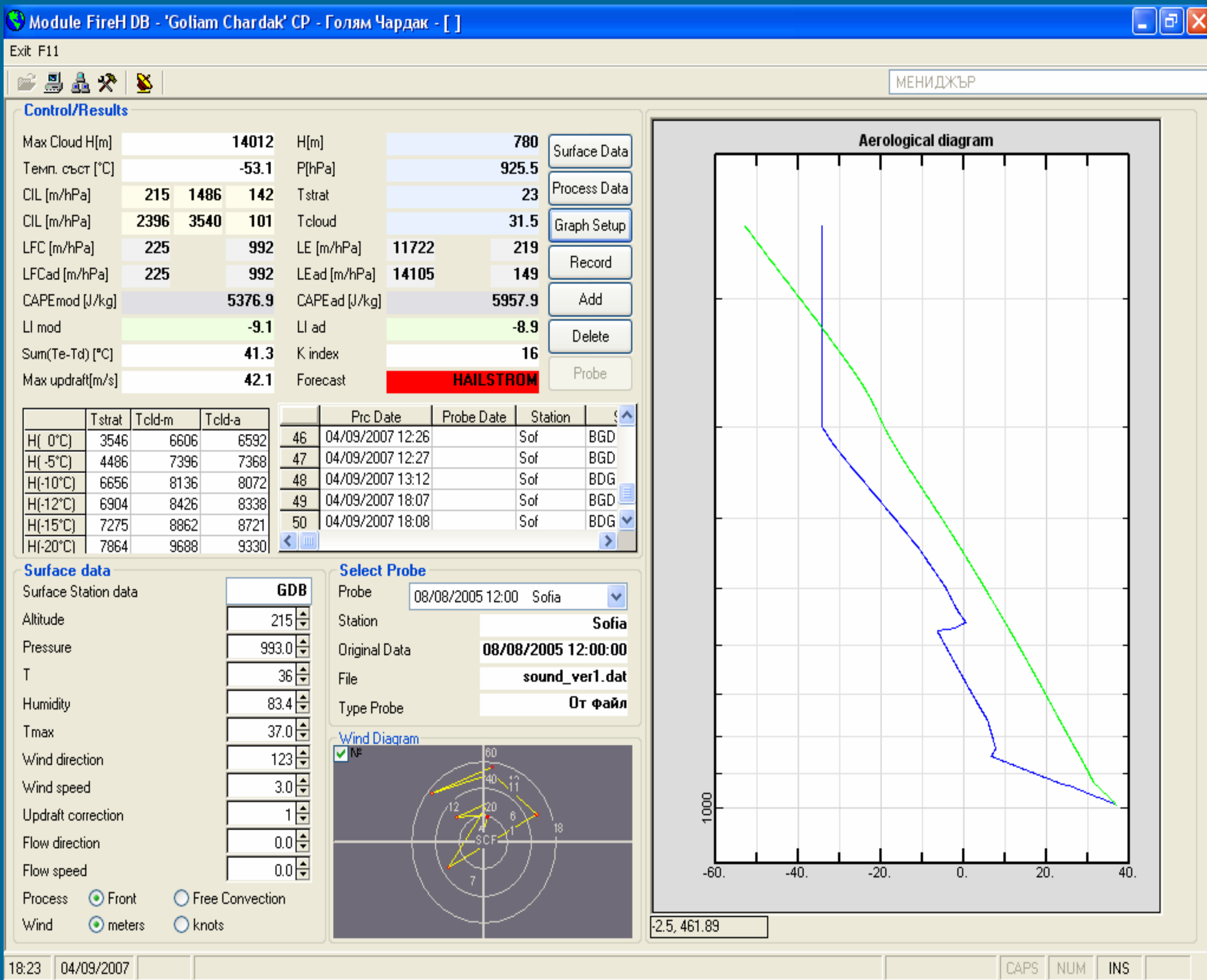
FIRE HAIL – software for preparing the data for cloud seeding. It makes recommendations for firing.

FIRE W – communication and information system with specialized software for control and firing anti-hail rockets.

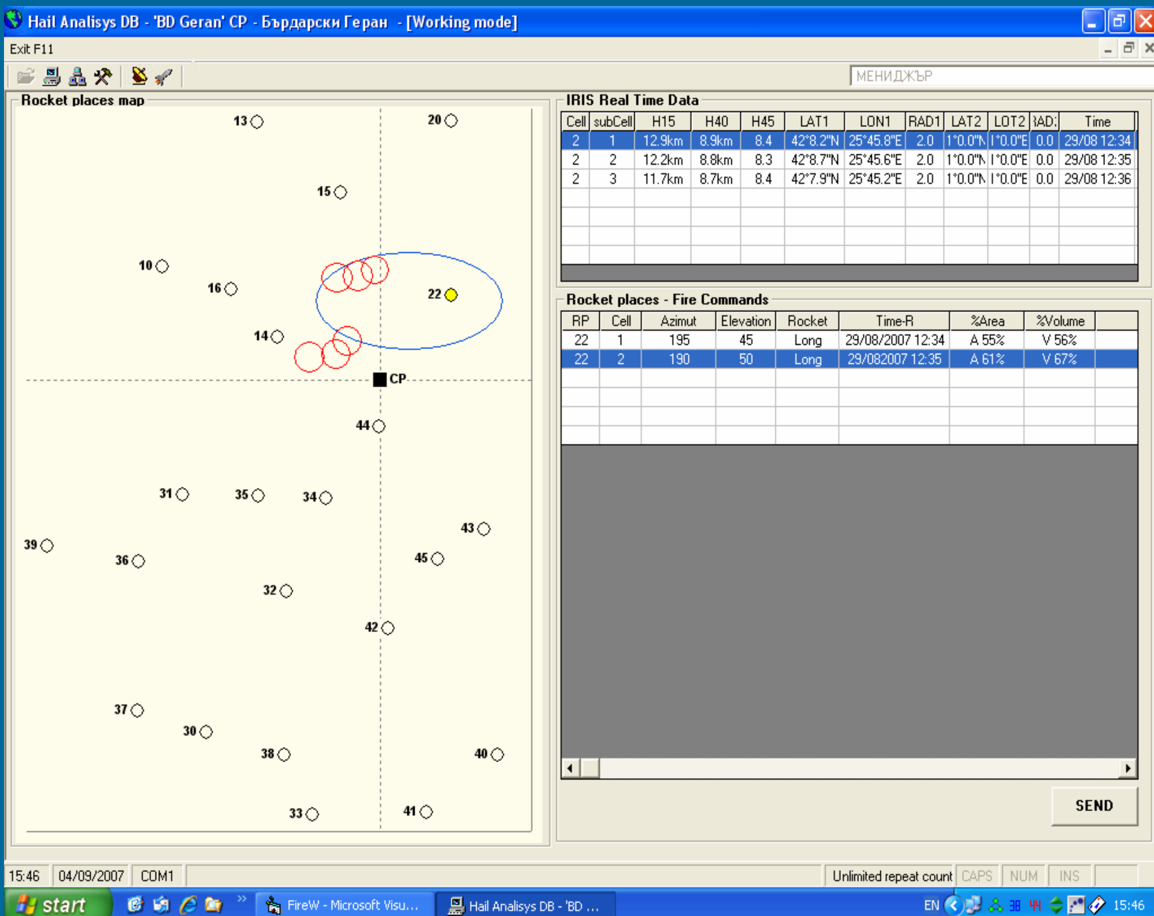


MRL5-IRIS – performs display of cloud systems and selection of hail-dangerous cells, which enables the accurate determination of the cloud's structure, seeding area location and its radius, the beginning and the end of hail suppression activity

The heights of the areas with different radar reflectivity, seeding area location and its radius are transferred to the FIRE HAIL module



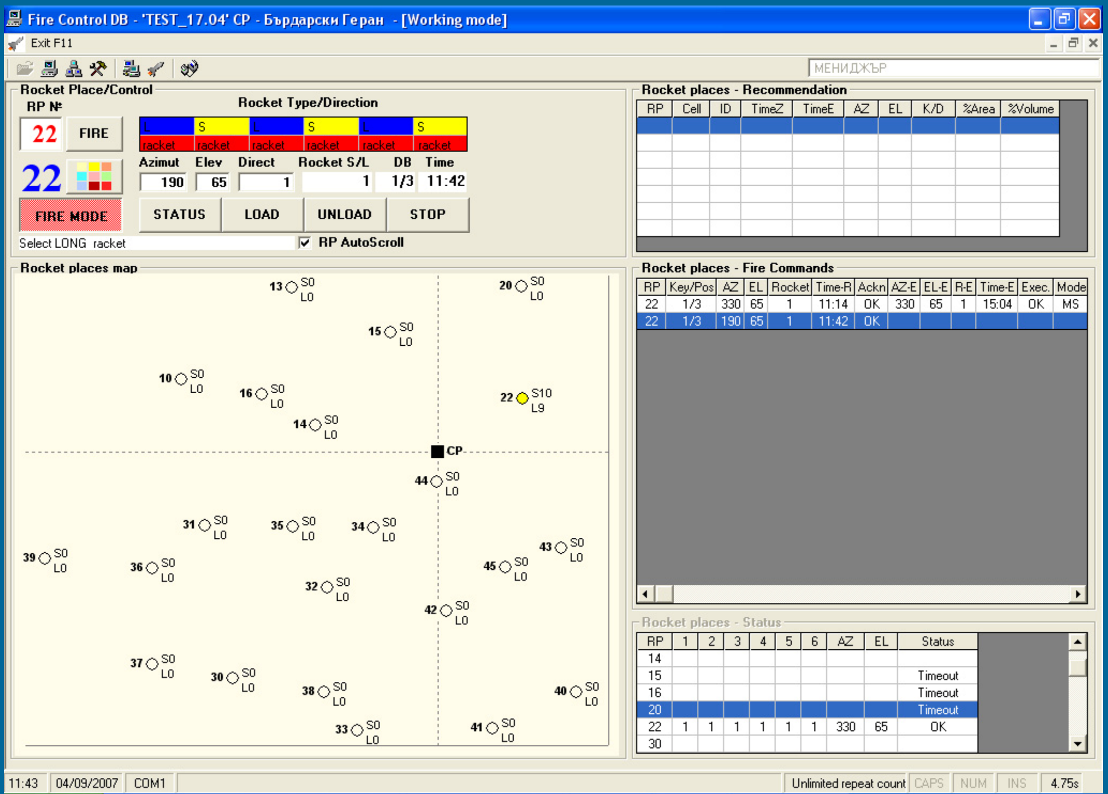
FIRE Hail - based on calculated thermodynamic characteristics of the atmosphere and the volumes of the diffusion agent specifies the fire data



According to the seeding areas defined by MRL5-IRIS the software specifies the rocket launching sites that can fire and the percent of volume seeding

It makes recommendations for firing, which are transferred to FIRE W.

COMMUNICATION AND INFORMATION SYSTEM FOR FIRE CONTROL FIRE



FIRE W – multifunctional software, which carries out many operations: from setting access rights to the system, through a procedure for loading rockets or rocket imitators for training to real work mode and reporting the status of launching sites.

Control board (at the Command post) – radio-interface to the specialized software; consists of radio-modem and FM radio for data; provides coded connection to the remote control board.

Remote control board – used for checking the launcher, for testing of rockets and firing them. It establishes communication by radio channel with the Control board at the Command post. It records all the gunner's actions during training and firing.

Automated Launching – by the command of the specialized software FIRE W and a single button, the launcher is automatically positioned from 0° up to 360° in azimuth and from 45° up to 85° in elevation and can fire up to 6 rockets. There is also a backup manual positioning mode.

Antenna Systems – include directional antennas with amplification 8dB and unidirectional antennas with amplification 7,8dB.

Voice communication system – based on mobile radios.

THE COMMUNICATION AND INFORMATION SYSTEM PROVIDES

- Control of the fire from the Command post through a coded telemetric connection
- Reliability of the transferred information
- Accurate and timely execution of the launch commands
- Test for connection with the rocket launchers and full real-time control of the condition of the equipment and execution of the commands.
- Training mode
- Archive of the conditions and execution of the commands with different sorting combinations
- Control of the consumption and the availability of rockets at the Command post and at the Rocket launching site – manual and automatic creation of documents for delivered and launched rockets
- Possibility for automatic collection and processing of meteorological data: temperature, relative humidity, pressure, wind speed and direction, accumulative rainfall and snowfall and rain rate

ANTI-HAIL ROCKET MTT-9M

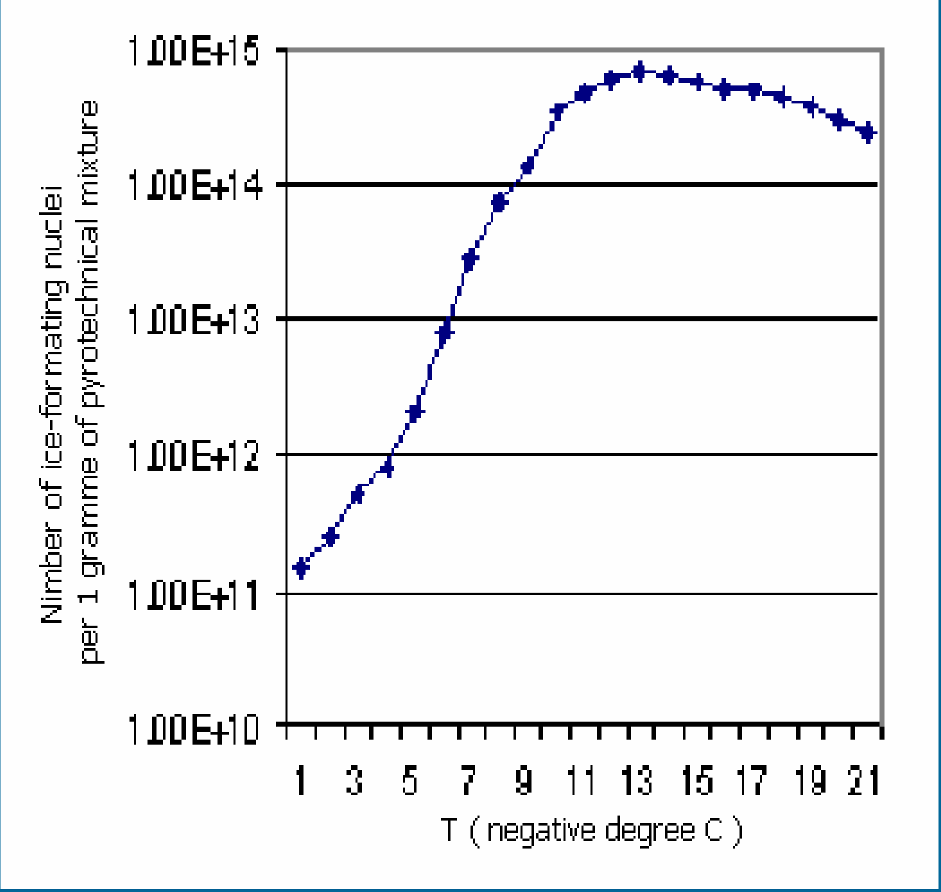
AVERAGE PRODUCTION OF ICE-FORMING NUCLEI FROM ONE GRAM AGENT OF «HEMOD 99» WITH 10% COMPOSITION AgJ

T°C	Measured by Paul J. DeMott – Colorado			Measured in Plovdiv		Measured in Zagreb	
	1991г	1994 г	1999 г	1998 г	2000 г	2006 г	2006 г
- 4°C	5.30E+10	3.20E+10	6.90E+10	3.20E+10		3.57E+10	
- 6°C	4.30E+12	5.40E+12	5.56E+12	5.40E+12	5.35E+12	2.06E+12	
- 8°C	9.12E+12	1.98E+13	7.10E+12	7.30E+12		8.63E+12	
- 10°C	3.10E+13	3.07E+13	3.20E+13	2.98E+13	3.10E+13	1.81E+13	3.48E+13
- 12°C	3.22E+12	3.45E+13	3.27E+13	3.10E+13		2.10E+13	

The researches in Colorado and Plovdiv are carried out in a CSU-type cloud chamber. The research in Zagreb is in an isothermal chamber type DNMZ RH, and only at -10°C in a CSU-type cloud chamber.

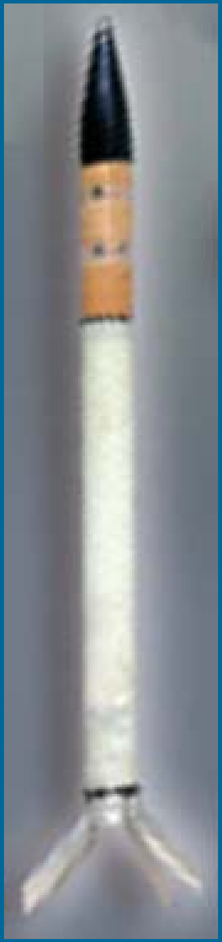
Production of ice-forming nuclei from the rocket's generator in flight

The work of the rocket's generator and production of ice-forming nuclei are modeled depending on the parameters of the flight and the surrounding temperature



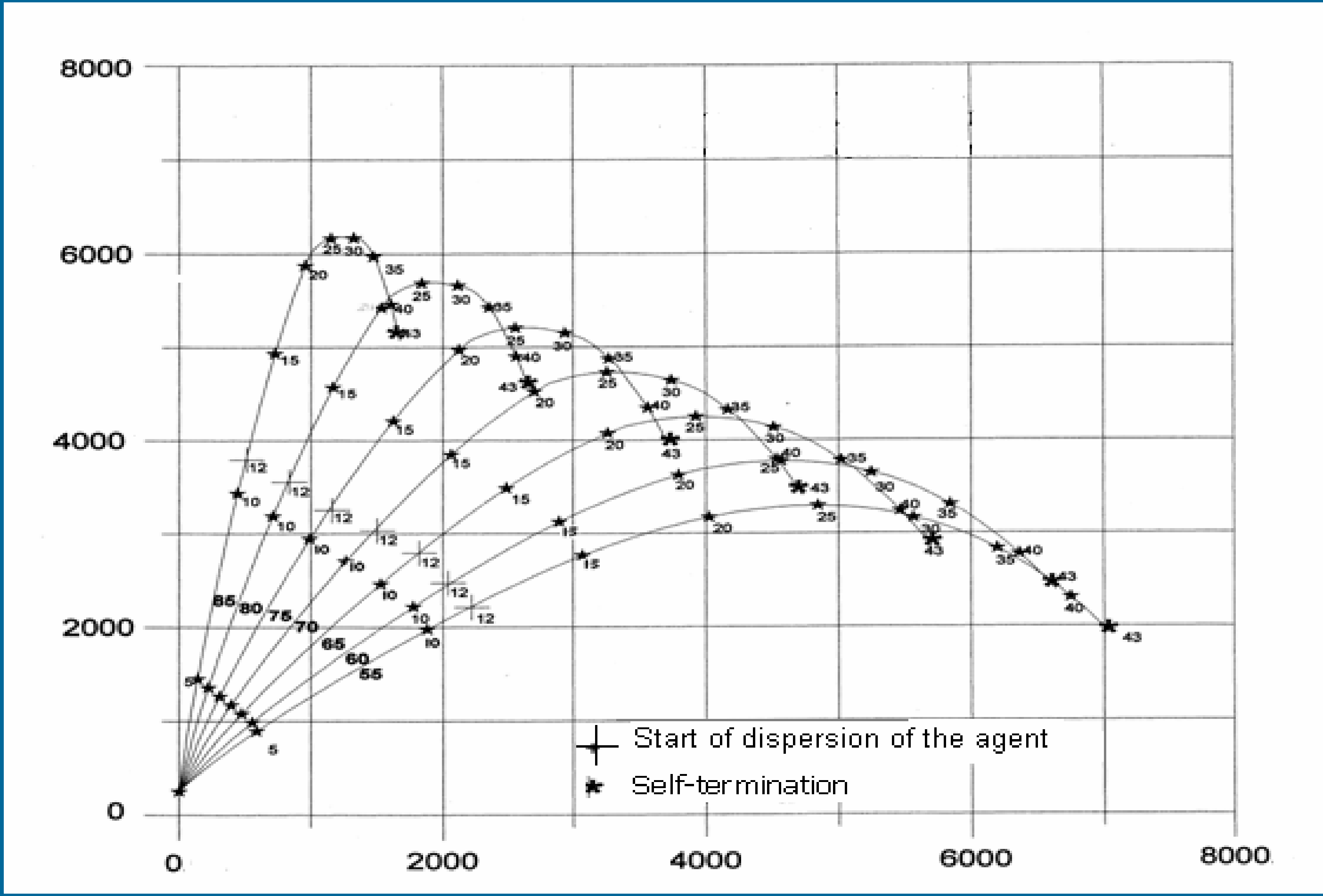
Technical parameters

Length of the container, mm	**1045**
Outside diameter of the container, mm	**60**
Length of the rocket, mm	**910**
Diameter of the rocket, mm	**55**
Weight of the rocket, kg	**2,8**
Total weight of the rocket with the container, kg	**3,85**
Weight of the agent, kg	**0,4**
Initial velocity, m/sec	**75**
Working time of the engine, sec	**8**
Time of dispersion, sec	**30**
Time of self-destruction, sec	**42**
Working temperature range, T°C	**from -5 to +50**
Temperature range for storage, T°C	**from -30 to +50**
Warranty, years	**3**



Trajectories of anti-hail rocket MTT-9M

Altitude of rocket launching site - 250m

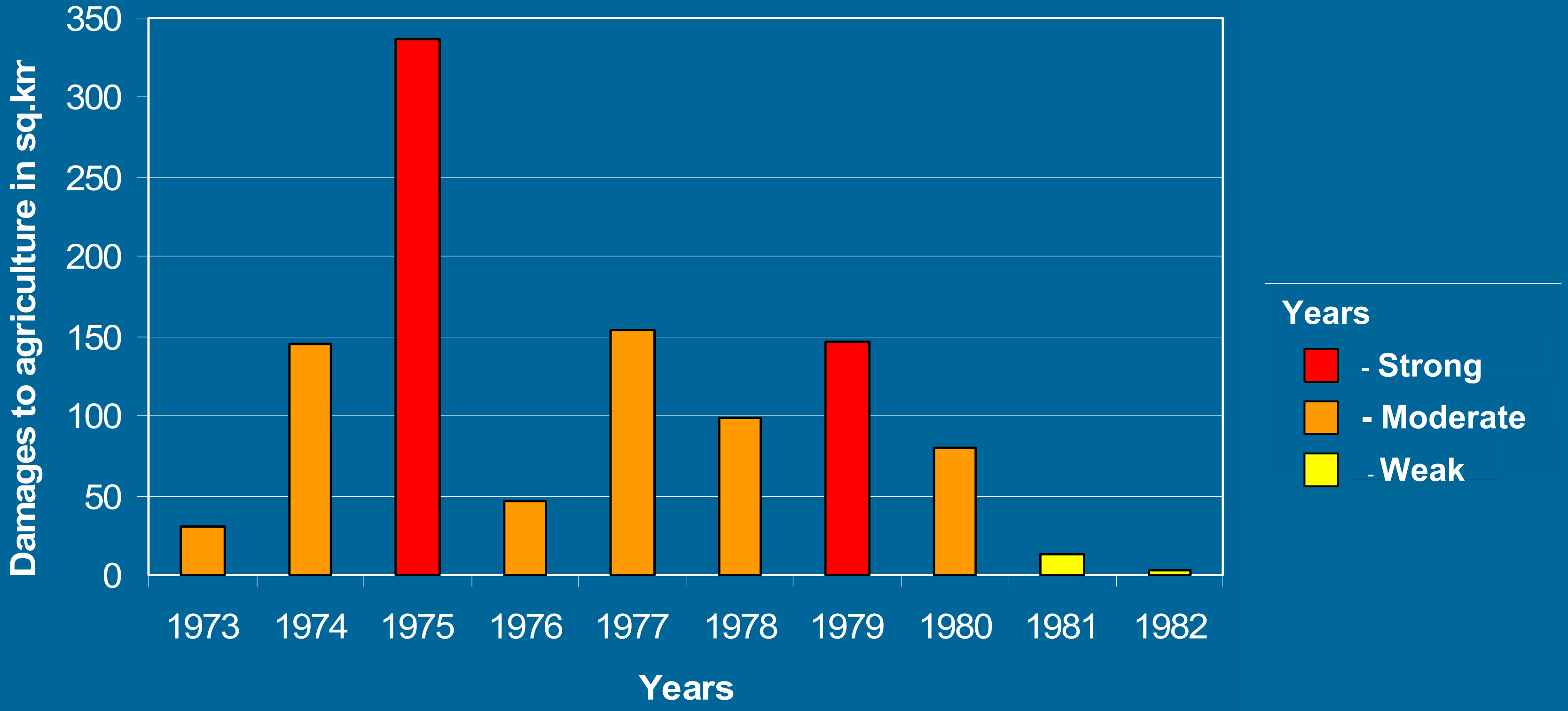


Altitude of rocket launching site - 500m

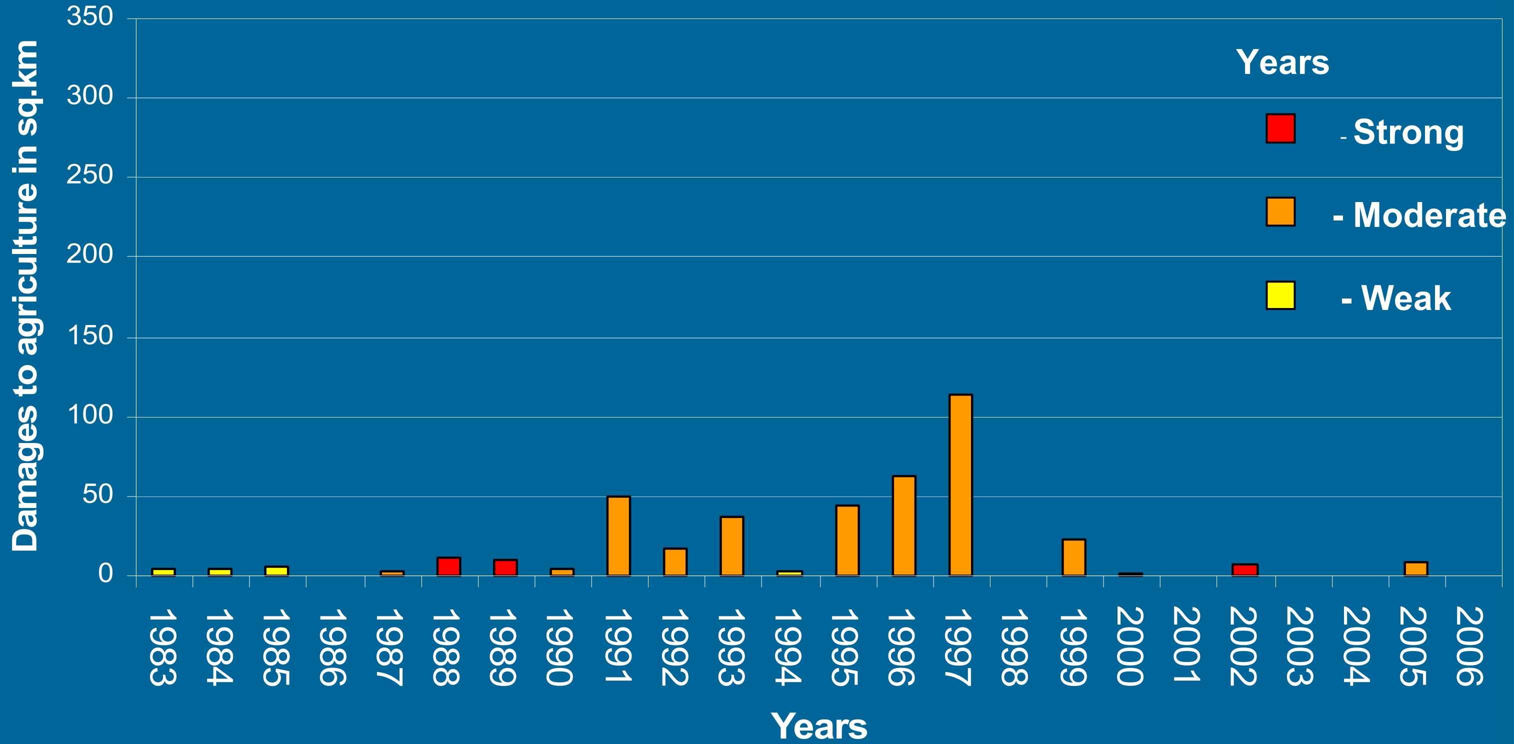
Hail suppression activity in Regional district Vratsa during the period 1973 – 1982, protected area - 1900 sq. km

Radar station SON λ=3.2 cm, anti-hail rocket Alazan with PbJ

A method of the Georgian Academy of Sciences



Hail suppression activity in Regional district Vratsa during the period 1983 – 1996, protected area - 1900 sq. km Radar station MRL-5, until 2001 – Alazan, from 2001- MTT-9M 1983 – 2001 Bulgarian method, from 2001 – refined method



1996 – no hail suppression activity

1995, 1997, 1999 – the hail suppression activity is carried out during a part of the hail dangerous season

1986, 1998,2001, 2003, 2004, 2006 – the damage area is less than 1 sq. km