"REVIEWED"

DENSITY OF HAIL SUPPRESSION ROCKET NETWORK

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Summary. An economic rocket-based hail suppression system requires a rational launcher network. The current network in Serbia is on a spacing distance of 3 km. Considerations of seeding methodology and rocket operational characteristics show that spacing should properly be between 3 and 7 km, depending on the terrain elevation. Introduction of rockets with longer ranges would not be economical. Long range rockets are not now suitable for use in high terrain elevations and there are operational problems in their use. The higher price of such rockets would offset savings due to network reduction. Instead, further network reduction can be made possible by redesigning the rockets in use to have lower minimum trajectory elevations.

1. INTRODUCTION

Hail suppression in Serbia (Yugoslavia) as an organized program was started in 1967, covering in the beginning some 1500 km^2. Since then it has expanded into a large system, protecting approximately 35,000 km^2 of cultivated land, or practically all of Serbia. The seeding principles are of Soviet origin (Bibilashvili et al., 1981). The seeding tactics are described by Horvat and Lipovšćak (1983). Technologically, the system is based on a network of rocket launchers under the control of twelve regional radar centers.

The density of the launcher network is based on consideration of rocket capabilities. So, in the beginning, for small rockets with a vertical range of 1200 m, one launcher covered approximately 5-10 km^2. In 1969, the SAKO-3 rocket with a vertical range of 3500 m was introduced. At that time it was somewhat arbitrarily determined that the operational rocket range was 3 km so a launcher network was constructed with one launcher covering about 30 km^2. As of 1988 there were 1159 rocket launchers in use.

In the last decade, however, new rockets with better performances and more active seeding reagents were introduced into operational use. Their characteristics are described by Horvat and Lipovšćak (1983) and Aleksić and Vuković (1988). The SAKO-3 rocket was abandoned, so that the density of the rocket launcher network became obsolete, producing an unnecessary overhead expense in the system upkeep.

The purpose of this study was to look into the possibility of reducing the network size. The first part of the paper discusses factors influencing the network density. The second part describes our solution to the problem and its results. Surprisingly, it shows that rocket performance, though most important, is not the only factor determining network density. In fact, technical specification of the rocket performance should also be subject to network density considerations. This we will discuss in the concluding section.

2. FACTORS INFLUENCING LAUNCHER NETWORK DENSITY

For given terrain and climatological conditions, the main factors influencing overall network density are seeding methodology and rocket operational characteristics.

2.1 Seeding Methodology

The essence of the Soviet hail suppression concept as operationally applied in Serbia, is rapid and massive seeding of the assumed hail embryo formation region (EFR). With some variations, depending on the type of cloud seeded,the general goal (Bibilashvili et al., 1981) is to directly inject the seeding agent into the layer of the cloud bounded by the (-8^{o}C to -12^{o}C) temperature isotherms. However, recent development of new reagents with higher temperature activation thresholds allowed a slight modification, so that for certain rockets the lower boundary of the target layer is now defined by the -5^{o}C isotherm. In any case, seeding is conducted so that the top of the rocket trajectory is approximately in the middle of the target layer.

Thus, the height above the ground of the seeding layer and its depth influence the way rockets are used. As a first approximation this height is determined by the difference between mean sea level (MSL) heights of the two corresponding isotherms and ground elevation.

Figure 1 shows the mean monthly isotherm heights for 1200 GMT (1 p, local time) Belgrade soundings for the period 1972-1986. Depths of the (-8^{o}C to -12^{o})

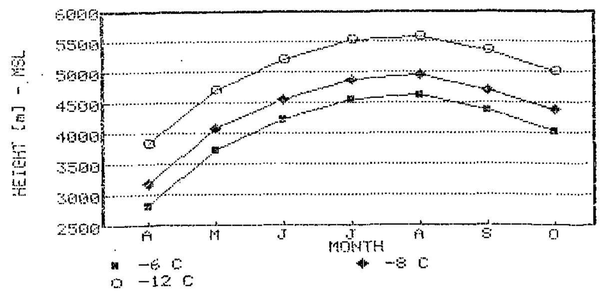

Fig.1 Mean monthly isotherm heights for Belgrade, 1200 GMT.

and (-6° to -12°C) layers appear to be rather constant, about 630 m and 970 m respectively. Isotherm heights, however, show strong seasonal change, with the highest values in August.

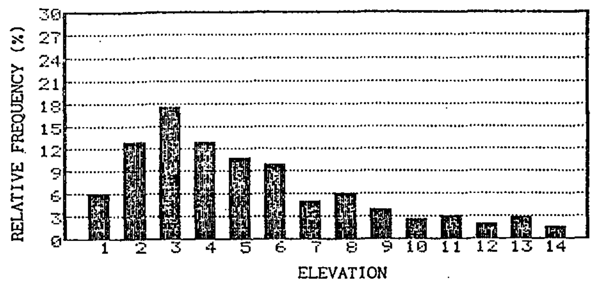

Fig.2 Distribution of firing point elevations (elevation in hundreds of meters)

The distribution of the firing point elevations is shown in the Fig.2. The most frequent heights are between 100 and 500 m MSL, and only about 10% of the stations have heights above 1000 m. It should be noted, however, that high altitude launchers are concentrated in the mountainous region of SW Serbia where they are approximately two thirds of the total.

2.2 Ballistic Considerations

To define the rocket network density, we need to know the values characterizing operational ranges of the rockets in use.

Figure 3 shows schematically characteristic horizontal ranges. In this figure, R_1 is the beginning of the rocket seeding path. It characterizes the radius of the unprotected area around the launcher for the given rocket type and trajectory elevation. R is the projection of the top of the trajectory. This distance is arbitrarily defined as the operational radius of the launcher. R_2 is the position of the end of the seeding path. At the same time, it should be the maximum distance between two launchers. All three characteristic distances vary with the rocket type, and trajectory elevation (e.g. elevation of the target layer).

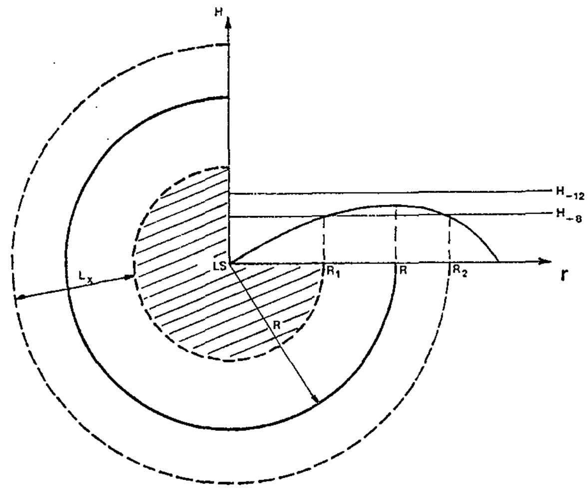

Fig.3 Characteristic rocket ranges. R_1 and R_2 are begining and end of the seeding path, R is the position of trajectory top.

2.3 Other Considerations

The factors described above are the main controls of launcher spacing. Choice of the particular launcher site, however, is subject to a number of other constraints. Some of the most important are that the site should be accessible and relatively close to operator living quarters, but for safety reasons at least 1-2 km from the nearest towns or depots of explosive and inflammable materials. Radio communication with the radar centre should be good, and if the site is in the real backwoods, it should be determined if the potential operators have electricity at home to recharge radio batteries.

Since our goal was to determine an overall network density, the factors just described were not taken into account.

3. DETERMINATION OF THE LAUNCHER SPACING

For the definition of the network density, we use a characteristic distance R_2 (maximum operational radius), because it allows overlapping of ranges of firing points. Thus, a"dead angle" area above a launcher could be seeded from neighboring firing points.

TABLE 1. Rocket Ranges

TYPE	TG-10	TG-5	SAKO-6	PP-6
Horizontal range (m)	10000	4000	4000	4000
Elevation range (deg)	45-85	45-85	45-85	55-85
Vertical range (m)	8500	5000	5200	5200

For each month of the season and given MSL heights of the launcher sites (which are varied in fixed height steps of 100 m) we determine the optimum trajectory elevations for each type of rocket, e.g. we choose ballistic trajectories with tops which are closest to the middle of the target layers. Rocket characteristics by type are given in the Table 1. For all calculations we have used interpolated values from the empirical rocket trajectories given by Jeftić (1986). From these trajectories we determine horizontal characteristic values of interest.

TABLE 2. Mean values of the maximum operational radius for the (-8°C, -12°C) layer. R is the operational radius and H the altitude range (MSL elevations).

	Small rockets		Large rocket(TG-10)	
	Spring	summer/fall	Spring	summer/fall
R(km)	3-4	2-3	7	7
H(m)	0-1100	300-1500	0-300	0-1100

TABLE 3. Similar to Table 2, but for the (-6°C, -12°C) layer.

	Small rockets		Large rocket(TG-10)	
	Spring	summer/fall	Spring	summer/fall
R(km)	3-4	2-3.5	7	7
H(m)	0-1100	300-1300	0-300	0-1300

A summary of results is shown in Table 2 (for the -8°C to -12°C layer) and Table 3 (for -6°C to -12°C layer). Results show that the rocket network densities depend on the rocket types, terrain heights and the season. With regard to the requirements for the standardization and fixing of the network density, the following general conclusion can be made:

1) Network density does not change significantly if the (-6°C to -12°C) layer is seeded instead of (-8°C to -12°C) layer.

2) Density of the network based on the medium range rockets should be 3 km; for the stations with elevation above 900 m MSL it should be 4 km.

Density of the network based on the large rockets should be 7 km.

3) In the beginning of the season, due to the low level of the target layer, long range rockets (TG-10) should be used only for stations with elevation below 300 m MSL. These rockets should not be installed on the stations with elevation above 900 m MSL. It appears that long-range rockets like the TG-10 should be installed only with the medium range rockets. Use of the medium range rockets has fewer limitations with regard to the station elevation as well as the season they can be used. Only in the spring they are not optimal for use in the stations with elevations above 1100 m MSL due to the limitations of the minimum admissible trajectory elevation.

4. CONCLUSIONS

The density of the hail suppression rocket network depends both on the seeding methodology and technical limitations.

From a purely methodological point of view, it is shown that network density does not have to be uniform over the protected area, but depends on the type of the rocket used, the season and elevation above sea level of the launching station. The minimum density is from 3 to 7 km, depending on the type of the rocket used. In the beginning of the season, seeding should be performed, preferably, with the medium range rockets. The reason for this relatively low height above the ground of the target layer. In this situation, long range rockets would have trajectories that are to high and so release most of the seeding reagent above the target layer.

For identical reason, an important limitation on the network configuration is the variation in elevation of the firing points. Medium range rockets should not be used on the low level stations (trajectories too low for efficient seeding), and long range rockets should not be used on the stations with high elevation. With regard to this, it would probably help to have rockets with lower minimum trajectory elevations.

It appears that extending the range of rockets does not necessarily open the possibility of network reduction. In fact, it may be that even rockets now in use have overspecified ranges. Although it is not usually discussed, all rocket launches must have a clearance from the Federal Flight Control Authority. A request is granted only if the air corridors are free or if not, aircraft must be above the some safety level. Otherwise, the request is put on hold status. We have briefly checked the logbook of the Kruševac hail suppression centre (commanding about 150 launchers). During the period from April to August 1989 its seeding operations lasted for the total of 3819 minutes. However, it was on hold status for 5377 minutes. It appears that they are frequently unable to shoot when they need to. The reason for this are the very high safety levels for the rockets in use - 28,000 ft for the medium range PP-6 rocket and 33,000 ft for the long-range TG-10. These are almost exactly the usual heights of airliner corridors,and it would be worthwhile to check what the scores would be if the safety levels were one or two thousand feet lower.Possibly, slightly lower maximum trajectory tops seeding activities could be performed without hindrances.

Anyway, from the purely economic point of view it does not seem reasonable to reduce the network density by extending the rockets range. Introduction of the current long range rockets was necessary to have the ability to reach the target layer at all times. Going for even longer ranges is, however, subject to "catch-22" constraints. We cannot have an economic system with two thousand full--time paid rocket operators. And, if we engage as rocket operators just symbolically paid farmers, as we do, rocket expenditure is by far the largest item in the suppression bill. Although, due to the Yugoslav hyperinflation, it is impossible to get any meaningful numbers, we can get an estimate by noting that seasonal engagement of one rocket operator is equivalent to the price of about two rockets. With some 25,000 rockets fired annually it is obvious that operators for the current network cost just a small percentage of the money used for the rockets. It does not seem reasonable to reduce this cost by introducing new, more expensive rockets.

Our final conclusion regarding the Serbian hail suppression rocket network is that it is too dense for the rockets in use. We have stated general guidelines for its reduction. Introduction of new of new rockets with longer range, however, would not pay off. Rather, further network reduction could be attained by redesigning rockets to have a lower minimum trajectory elevations, which would enable long range rockets to be used on the high elevation stations and throughout the season.

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