COMPARATIVE EVALUATION OF DETECTION PERFORMANCES OF RADAR “COBALT - RLS" WITH FOREIGN RADIO LOCATION STATIONS (RLS) INTENDED FOR MONITORING THE MAN-CAUSED CONTAMINATION OF NEAR-EARTH SPACE

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Abstract. The use of ground radar-tracking facilities for space observations and monitoring the man-caused contamination of near-earth deep space is considered. Brief information about RLS "Haystack" (USA) and "FGAN" (Germany) and a comparison of their performances with the parameters of "Cobalt" RLS (radar) on the basis of the radio telescope THA-1500 are presented. The comparison is carried out on the criterion of the minimum size of the discovered objects at fixed distances. As a threshold of detection the magnitude of the relative signal / noise equal to 10 dB is accepted.

INTRODUCTION

The intensive activity of the leading countries in space investigation makes necessary the observation of near-Earth space (NES) and known objects. By the beginning of the 90-s' years the number of the catalogued space objects exceeded 20 thousand [1], now about 7 thousand continue their active existence. Below we consider the use of ground facilities for space observations, that does not demand launching special space vehicles into Earth orbits and maintaining their operation.

The modern radar-tracking technologies with high energy potential allow one to realize near-Earth space monitoring for the purpose of detection of the objects, dangerous first for manned space stations and for other active space vehicles of various assignments. Besides, some space vehicles, if destroyed and reentering can represent a serious danger to the population and objects located in the reentry area. The countries leading in the sphere of aerospace investigation, including Russia, actively develop ground radar-tracking engineering facilities for near-Earth space (NES) monitoring, without dependence on weather conditions.

With the purpose of evaluation of possible risks, the objects of observation were described by models [2, 3, 4], which by statistical methods predict a stream of objects through observable volume. The radar-tracking data, for clarification and check of the models’ parameters, are received now mainly from RLS "Haystack" (USA) and "FGAN" (Germany). Brief information about those RL stations and a comparison of their performances with "Cobalt" radar, developed by OKB MEI [5, 6], are presented below.
"HAYSTACK" RLS

The radar-tracking station "Haystack" [7] (Milstone, USA) represents a monopulse locator with a parabolic antenna with a diameter of 37 m. The feature of "Haystack" radar is the use of one antenna for radar-tracking and radio astronomical purposes. When solving radar-tracking problems, the carrier frequency is equal to 10 GHz (wavelength 3 cm), the width of the directional diagram is 0.05°, and the amplification factor of an antenna is 67.2 dB.

"Haystack" radar provides radio pulses of power 400 kW with right circular polarization, while signals with both right and left circular polarization are accepted. For observation in the mode of radar monitoring, the sounding signal in the form of a rectangular radio pulse with a duration of 1 msec at the repetition frequency of 40 Hz was used.

In real time the data were registered only at the detection of an echo – signal that is fixed, if the amplitude of an accepted signal exceeds the noise threshold of the system. During prolong observations for many hours, the effective use of recording equipment resources is ensured.

The high power performances of RLS allows finding objects with a diameter of 1 cm at a distance of about 1000 km.

EXPERIMENTAL SYSTEM "FGAN"

The experimental system "FGAN" [8] (Wachtberg-Werthhoven, 20 km from Bonn, Germany), is the radar-tracking system TIRA (The Tracking and Imaging Radar system), which consists of a tracking radar in L-band and the RLS intended for radio imaging in Ku-band. In both radars the parabolic antenna with a diameter of 34 m is used.

The operational frequency of the tracking radar is 1.33 GHz, and the duration of the emitted pulse is 1 msec. The emitted signal has a circular polarization. The processing of accepted signals is carried out by modern correlation technology of pulse compression by binary phase coding.

The first works with the complex "FGAN" began in January 1978. Now "FGAN" is the unique radar in Europe, which can find objects of a diameter of 2 cm at a distance of 1000 km.

"COBALT" RLS

A radar-tracking complex "Cobalt - RLS" is deployed in OKB MEI, on the basis of two acting radio telescopes THA-1500 with a diameter of 64 meters and transmitter in cm-band (5 GHz) with power of 4 kW. This complex contains one-position "Cobalt" radar of the radio telescope THA-1500, located near Moscow – at "Bear's Lakes" site, and a reception station of a similar radio telescope THA-1500, located near Kalyazin town. The basic element of that complex is a one-position "Cobalt" radar, whose performances are compared here to the parameters of the radars "Haystack" and "FGAN". By use of RLS, "Cobalt" can monitor near-Earth
space (NES) using the pulse mode. As a sounding signal in this radar, there are "smooth" (without inter-pulse modulation) and pulses of linear FM, with variable duration and frequency deviation:
- In a mode « rough » - 1 MHz,
- In a mode « fine » - 10 MHz,

Polarization during the radiation is the right circular, during reception – the right and left circular.

**CRITERION OF AN EVALUATION**

The prime purpose of RLS monitoring is the detection of space vehicles, or their fragments, in various orbits. The possibilities of radar usage for this purpose depend on the energy potential, the effective cross-section of back scattering (BSCS) of inspected objects, and on the conditions of observation. In the present case the comparison of radars was conducted over a minimum size of the discovered objects at the fixed distance. As a criterion for detection, the magnitude of the threshold relation Signal/Noise for a single pulse of an accepted echo - signal (S/N=10 dB) was accepted. According to the main equation of a radar-location [9] the relation of a received signal to an average potency of noise is equal to:

\[
\frac{S}{N} = \frac{P \cdot A_1 \cdot \sigma \cdot A_2 \cdot T_{\text{acc}}}{4 \cdot k \cdot T_{\text{nu}} \cdot \pi \cdot R^4 \cdot \lambda^2}
\]

(1)

where \(S/N\) - relation of signal power to power of noise, \(P\) – transmitter power, \(A_{1,2}\) - effective areas of transmitting and receiving antennas, \(\sigma\) - effective area of the object back scattering (BSCS), \(T_{\text{acc}}\) - time of a coherent accumulation of a signal (in this case \(T_{\text{acc}} = \tau_{\text{pulse}}\), where \(\tau_{\text{pulse}}\) - pulse duration), \(k\) – Boltzmann constant (1.38x10^{-23} W / Hz.degree), \(T_n\) - noise temperature of antenna and receiver, \(R\) - distance up to the object of observation, and \(\lambda\) - wavelength.

Unlike "Haystack" and "FGAN" radars, the duration of the sounding pulse for optimal use of the transmitter power in RLS "Cobalt" varies depending on a distance to the object:

\[
\tau_{\text{pulse}} = \frac{R}{c},
\]

(2)

where \(c\) - velocity of radio waves distribution.

In this case the ratio (1) becomes:

\[
\frac{S}{N} = \frac{P \cdot A_1 \cdot \sigma \cdot A_2}{4 \cdot k \cdot T_{\text{nu}} \cdot \pi \cdot R^3 \cdot c \cdot \lambda^2}
\]

(3)

Therefore, the magnitude of the energy, reflected from the object, is proportional, not to \(1/R^4\), but to \(1/R^3\), that gives an essential advantage at a given transmitter power.

Space objects of man-caused origin, especially fragments of such objects after their destruction, have, as a rule, a complicated configuration. BSCS of these objects
depends on the observation conditions and the carrier frequency of a sounding signal. The comparison of radar performances was carried out for objects of spherical shape (like metallic balls).

During the evaluation of the dimensions of the discovered space objects the following ratio was used [10]:

\[
\sigma = \begin{cases} 
\frac{\lambda^2 \cdot \pi \cdot \left(\frac{L}{\lambda}\right)^2}{4} & \text{при } \frac{L}{\lambda} \geq 0.2 \\
2.25 \cdot \lambda^2 \cdot \pi^5 \cdot \left(\frac{L}{\lambda}\right)^6 & \text{при } \frac{L}{\lambda} \leq 0.2 
\end{cases}
\]  

(4)

here \( L \) - cross size (diameter of a sphere).

In fig.1 the diagram of BSCS dependence on fragment sizes at operational frequencies for all 3 radars considered are indicated.

The inflection in the diagram corresponds to the boundary \( L = 0.2 \lambda \). From the analysis of the relations in fig.1, it was found that at the same conditions "Haystack" radar has the advantage during the detection of small sized fragments, because the sharp decreasing in BSCS at the operational frequency of "Haystack" (10 GHz) is exhibited only for sizes less than 5-6 mm. "FGAN" radar considerably concede to "Haystack" and "Cobalt" on the magnitude of BSCS for fragments less than 3-4 cm. "Cobalt" RLS takes an intermediate position between "FGAN" and "Haystack", because the BSCS at 5 GHz for fragments less than 1 cm (cross size) is only 10-12 dB, less than at the frequency 10 GHz.

The mode «beam park» is applied to deriving information about the degree of man-caused contamination of near-earth space (NES) by use of high-power locators [7], when the ray of an antenna is directed vertically up, or is fixed in a given direction. The locator accepts echo-s signals reflected from objects, flying through a ray. At fixed parameters of a sounding signal, the number of pulses irradiating an object during its flyover through a fixed ray, is determined by beam width, period of pulse repetitions, and the parameters of the moving object relatively to RLS. It is easy to be convinced that under condition (2), the number of pulses that irradiate the objects flying through a fixed vertically directed ray is determined by the beam width, and poorly depends on the circular orbital altitude of these objects. In this case, about 10 pulses can be accepted from each object intersecting a fixed ray of the radar. It creates data for the determination of an angular velocity and the orbital inclination of the observed objects, using the change of their angular coordinates during flyover through a ray.

**COMPARATIVE EVALUATION OF DETECTION PERFORMANCES**

In the table below the parameters of the radar and the results of its performance during detection of fragments at near-Earth space, monitoring in a range of distances from 0.3 up to 40 thousand km, are indicated.
Table RLS parameters during NES monitoring at the ranges from 0.3 to 40 thousand km.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>&quot;Haystack&quot;</th>
<th>&quot;FGAN&quot;</th>
<th>&quot;Cobalt&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 $f$, GHz</td>
<td>10</td>
<td>1.3</td>
<td>5</td>
</tr>
<tr>
<td>2 $P$, KW</td>
<td>400</td>
<td>*</td>
<td>4</td>
</tr>
<tr>
<td>3 $D_a$, M</td>
<td>37</td>
<td>34</td>
<td>64</td>
</tr>
<tr>
<td>4 $\tau_{\text{pulse}}$, Msec</td>
<td>1.023</td>
<td>1</td>
<td>$2R/C$</td>
</tr>
<tr>
<td>5 $T_n$, K</td>
<td>249</td>
<td>*</td>
<td>100</td>
</tr>
<tr>
<td>6 $P_{\text{min}}$, W</td>
<td>$3.4\times10^{-17}$ (S/N=10 dB)</td>
<td>*</td>
<td>$2.1\times10^{-18}/R$ (S/N=10 dB)</td>
</tr>
<tr>
<td>7 $L$, cm at $L&lt;0.2\lambda$</td>
<td>$0.475\times R^{2/3}$</td>
<td>$2.0\times R^{2/3}$</td>
<td>$0.845\times R^{1/2}$</td>
</tr>
<tr>
<td>at $L&gt;0.2\lambda$</td>
<td>$0.361\times R^2$</td>
<td>$0.95\times R^2$</td>
<td>$0.504\times R^{3/2}$</td>
</tr>
<tr>
<td>8 $R(L=0.2\lambda)$, thousand km</td>
<td>1.3</td>
<td>3.1</td>
<td>1.7</td>
</tr>
</tbody>
</table>

In the table the following designations were accepted: $f$ - frequency of radiation, $D_a$ - diameter of an antenna, $P_{\text{min}}$ - power of a signal accepted from a fragment with a minimum size, $L$ - minimum size of a discovered fragment, $R$ ($L=0.2\lambda$) - distance appropriate to detection of a fragment with a size $L=0.2\lambda$ when S/N = 10 dB.
Significant "FGAN" radar parameters, marked in the table by *, are absent in [8]. Besides in [8] there are no data on the accumulation of a signal and about the magnitude of S/N at the detection of a fragment of a size 2 cm for "FGAN" at the distance of 1000 km. Therefore, all accounts for this radar were executed in the supposition, that the fragment of a size 2 cm is detected at distance of 1000 km [8] for S/N = 10 dB (without accumulation).

In [7] the performances of the "Haystack" radar are indicated in a volume, sufficient for an evaluation of potential possibilities of "Haystack" during the detection of fragments in near-Earth space and a comparison with the parameters of the "Cobalt" locator. Let's notice, that for "Cobalt" RLS the evaluation was executed under the condition of the correspondence of pulse duration of a sounding signal to a distance to the object (see line 4 of the table). In line 7 of the table for each radar the dependence of a minimum size of a discovered fragment on the distance is indicated, using a criterion of fragment detection by one reflected impulse at S/N = 10 dB (i.e. not counting accumulation of a pack of impulses). The transition from one function to the other was made at distances of R (L=0.2λ), it’s the magnitude for each radar is indicated in the appropriate column of line 8.

On the basis of the data listed in the table, in fig. 2 for each RLS the diagram of the dependence of a minimum size of a discovered fragment on distance is constructed. Analysis of the results shows that "FGAN" concedes to "Haystack" at distances up to 3000 km, because of a higher operational frequency. At distances exceeding 3000 km, the performances of these radars, during detection of fragments, are close enough. However, it is necessary to notice, that the data for "FGAN" were obtained non-directly, instead of a direct account, as it was made for the two other RLS.

In the whole range of distances 400 - 40000 km, the potential performances of "Cobalt" RLS on sizes of discovered fragments is much better than "FGAN". Besides, in "Cobalt" RLS, due to a change of radiation pulse duration proportional to distance, the decrease of a fragment minimum size was achieved with the increase of distance (at constant S/N = 10 dB), unlike "Haystack" and "FGAN" radars, where the fixed pulse duration of radiation is used.

"Haystack" has the advantage, in comparison to "Cobalt", for detection of small sized fragments (less than 1 cm) on orbits with heights up to 1000 km. Counting the potential possibilities, "Cobalt" RLS concedes to "Haystack" at distances less than 1700-2000 km, and exceeds it at distances more than 2000 km.

It is necessary to notice, that the power of an accepted signal $P_{\text{min}}$, appropriate to a given criterion of detection for "Cobalt" RLS, is much less than for "Haystack". In fig. 2 the results of the power of a signal accepted from the fragment with minimum sizes during its detection, on a criterion S/N = 10 dB at given distance, were indicated in the diagrams as "Signal 1" and "Signal 2". The diagram "Signal 1" corresponds to "Haystack" and "FGAN", diagram "Signal 2" - "Cobalt" RLS, at the same conditions.
As a distinctive feature of "Cobalt" RLS, we should notice the dependence $P_{\text{min}}$ on the distance up to the object; from that dependence we can conclude, that for realization of above mentioned potential performances of "Cobalt" locator, a considerably higher sensitivity of receiving device relative to that realized in "Haystack" and "FGAN" radars, should be ensured. Therefore, the possibility to get the mentioned advantages of "Cobalt" RLS, mainly depends on the practical realization of the receiving device and noise conditions at the site "Bear’s Lakes".

CONCLUSIONS

1. The potential performances of the RLS complex "Cobalt" on detection of small sized fragments, on a criterion $S/N=10$ dB, practically do not concede to, and moreover, at distances more than 3000 - 4000 km, even exceed, the similar performances of "Haystack" radar.

2. In the whole range of distances 400 - 40000 km, the potential performances of "Cobalt", in relation to sizes of discovered fragments, are much better than for "FGAN".

3. The realization of the potential possibilities of the "Cobalt" complex, on detection of small sized fragments in the near-Earth space, mainly depends on the practical fulfillment of the receiving device, and the noise conditions at the site intended for reception of echo – signals.
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