INDEPENDENT RADAR MONITORING OF THE EARTH SATELLITES IN EMERGENCY (THE RORSAT CASE)

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Introduction

Space accidents and mishaps are inevitable. Some 10% of all launches ever carried out have appeared to be unsuccessful. About 30% of all launched satellites stopped their functioning prematurely, in the most cases the communication with them having been broken, and the only way to operatively monitor them was using the ground based radars. The last ones can be tasked with not only detecting and tracking spacecraft in orbit but also determining their non-coordinate characteristics – the attitude dynamics parameters, the spacecraft shape and dimension and so on. Solution of the last problem appeared possible after creation of the radar signature analysis methods in the US and the USSR in 60-ies. The possibilities of applying these methods are shown here, using the example of RORSAT ("Cosmos-469", "Cosmos-954", "Cosmos-1402", and "Cosmos-1900").

Brief Survey of the RORSAT Program

In 1970, within the confines of the "Cosmos" program, the development of Soviet satellites of ocean surveillance RORSAT started. The on-board radar power supply was provided by the on-board nuclear power set (NPS), first in the world practice.

Employment of this NPS meets the principles of using the nuclear power sources in space approved by the UN General Assembly [1].

In particular, after the end of its functional lifetime the deorbiting of NPS to the special graveyard orbit at the altitude of 900 – 1000 km was envisioned. The general view of RORSAT and its dimensions [2] are given at Fig. 1.

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Since 1970 till 1988 31 RORSATs ("Cosmos-367" ... "Cosmos-1932") were deployed in orbit. At present, the number of RORSATs in Earth (disposal) orbit is 29. Two of them ("Cosmos-469" and "Cosmos-1900") have made a wrecking deorbiting of their NPS caused by inadmissible growth of the stabilization errors.

"Cosmos-954" and "Cosmos-1402" failed to conduct the deorbiting maneuver and re-entered, which caused significant alarm in media the proper time.

After the mishap of "Cosmos-954" the programmed separation of the active zone (the bunch of uranium rods) was accepted. But after the accident with "Cosmos-1900" the launches of this series were ceased.

Before proceeding to detailed analysis of emergency situations with "Cosmos-469, 954, 1402, and 1900", let's give a general characteristic of the RORSAT's behavior in its disposal orbit [3].

In terms of the radar signature analysis, RORSAT has a classic electro-magnetic wave dispersion diagram with evident peaks of reflection from cylindrical and conic surfaces. This fact can help determine the attitude dynamics parameters in emergency situations with great accuracy and reliability.

The typical radar signature of RORSAT after its deployment into the disposal orbit is shown at Fig. 2. One can see periodical alternation of reflections from cylindrical (A) and conic (B) surfaces. Similar signatures were published earlier by American, German and Russian experts [3, 4, 5]. The periodicities of these reflections allows to estimate the precession period $T$. 

![Fig. 1. General view of RORSAT](image)

1- nuclear active zone;
2- NPS with the cooling circuit.

![Fig. 2. RORSAT typical signature](image)
Repetition of the cylindrical surface reflections strictly in a half precession period witnesses that the nutation angle is 90°, and the space object (SO) is tumbling, i.e. rotating around the maximum inertia momentum axis.

Within the interval [150 ... 170s], when one can see only reflections from cylindrical surfaces, the location vector \( d \) (SO \( \rightarrow \) radar) practically coincides with the kinetic moment vector \( L \). At the time \( t = 160s \) both vectors are practically co-linear (with the accuracy up to 3°). This fact underlies the direct method for the rotation axis determination (of course, assuming the properly preliminarily planning the observations needed).

By the way, more accurate methods exist, allowing determination of the attitude of the angular velocity vector \( \omega \) (or \( L \)) with accuracy up to some portions of a degree and of its modulo (or the precession period) up to some portions of one per cent.

The sample measurements of some RORSATs ("Cosmos-469", "Cosmos-861", … "Cosmos-1900", "Cosmos-1932") conducted at different times after their launch to the higher orbit allowed establishing the following appropriateness:

1. In one or two days after the deployment the character of the RORSAT attitude dynamics absolutely changes. The unstable fast rotation around the long axis almost thoroughly transits into "tumbling", that is rotation around the maximum inertia momentum axis, the kinetic moment \( L \) (both as to its magnitude and direction) being saved.

The starting precession speed \( \omega_0 \) equals approximately 3 revolutions per minute for the most of RORSATs.

2. Further, due to the action of magnetic dissipative moment, the gradual deceleration of rotation by the exponential law occurs:

\[
\omega = \omega_0 \left( \exp(-\beta \delta d) \right),
\]

where \( \beta \) is the attenuation coefficient, and \( \delta d = d - d_0 \) is the time interval between the current and initial meanings of \( \omega \).

Most of RORSATs have constant \( \beta \) during 15 and more years, which is equal to 0.20 1/year. Respectively, the time interval of redoubling the period is

\[
D_{2T} = \ln 2 \beta^{-1} = 0.7 \beta^{-1}
\]

and equals 3.5 years (Fig. 3).
3. The effect of gravitational forces causes the slow evolution of vector $L$ which seeks to take a stable position along axis $Y$ of the orbital coordinate set where axis $X$ is parallel to that pointed from the Earth center to ascending node and axis $Z$ normal to the orbit plane, axis $Y$ complementing them to the right three [5]. Namely around axis $Y$ there occurs the nutation swing of vector $L$ with declination of $\pm 20^\circ$ in the plane and $\pm 10^\circ$ out of plane. All the RORSATs had the same nutation period of $L$ (about 40 days) with small tendency to diminution (to 30 days in 10 years), which is corroborated by modeling in the frame of Beletsky's theory [6, 3], "Cosmos-1900" being an exception to the rule again (see lower).

Next consider some emergency situations.

"Cosmos-469"

It was launched 25 December 1971. A week later, its NPS was deorbited to the disposal orbit. As the radar signature analysis showed later, the cause was the intolerable declination of the spacecraft from its normal course. In a day after its deorbiting, the RORSAT (NPS) changed the rotation character of its motion around its long axis to just tumbling with the period 20.2 s.. The signal structure analysis showed the deviation of the visual precession period $T_{vis}$ (Fig. 4), its maximum meaning ($T_{vis} = 25$ s) having been reached by the 125$^{th}$ s.. This allows to determine the minimum angle between the location vector and the kinetic moment vector by the formula following from the law of summation of angular velocities ($\omega_{vis} = \omega_0 - \omega_d$):
\[ \delta_{\text{min}} = \pm \arcsin \frac{\omega_d}{\omega_{\text{vis}}^m - \omega_0}, \]

where \(\omega_d\) is angular velocity of the satellite transfer motion along the orbit, \(\omega_0 = \frac{2\pi}{T_0}\) is the real rotation velocity, \(\omega_{\text{vis}}^m = \frac{2\pi}{T_{\text{vis}}^m}\) is the maximum value of the visual rotation velocity.

Knowing the location vector position at time \(t_m\), its angular velocity, and angle \(\delta_{\text{min}}\), one can easily find angles \(\rho\) and \(\sigma\), characterizing the position of vector \(L\) in the orbital coordinate system.

Assuming that vector \(L\) "has remembered" the position of the satellite long axis at time of the spinning up (stabilization by fast rotation), its declination from the orbit plane (declination of \(\rho\) from 90°) can be treated as the "track declination" (the row). In this case ("Cosmos-469") it coincides with the accuracy of 0.5° with the declination limit predetermining the emergency withdrawal of the NPS.

Then, assuming that at the spinning up time the spacecraft had the zero pitch declination, one can approximately calculate the argument of latitude of the withdrawal point:

\[ U_w \approx \sigma - 90°, \]

And then its geographic latitude (in this case it was about the latitude of Madagascar island).

Fig. 4. Deviation of the visual precession period for «Cosmos-469»

The emergency situation at "Cosmos-469" passed unnoticed, but in different circumstances it repeated at "Cosmos-1900".

"Cosmos-954"

It was launched in 1977. At the end of its active existence all the on-board equipment suddenly failed (supposedly due to depressurization), the spacecraft became uncontrolled, and initially it was apparently in the state of slow residual rotation called forth by the last stabilization pulse. The angular velocity of such rotation was less than 0.1°/s.
A supposition was suggested on possible consequent gravitational stabilization of the elongated spacecraft (the length of "Cosmos-954" was 10 times its diameter). Revelation of gravitational stabilization with the help of the signature analysis is accomplished by measurement of the visible spacecraft size by the width of interferential petals of its dispersion diagram (Fig. 5):

\[ \Delta \theta = \frac{\lambda}{2l_{\text{vis}}} \]

where \( l_{\text{vis}} \) is the visible spacecraft size, \( \theta \) is the measurement foreshortening counted from transversal, and \( \lambda \) is the radar wavelength.

![Fig. 5. The visible spacecraft size depending on its foreshortening.](image)

After some consideration, this supposition did not find any persuasive corroboration, appeared to be rather weak, and was left. The mode of slow rotation could have been close to the gravitational stabilization by chance.

We run into another unexpected phenomenon – that of autorotation, when the angular velocity increased instead of diminution. The cause of this phenomenon appeared to be a lateral view gantry construction, which led to spinning up the re-entering spacecraft.

In three days after the accident, the radar signature showed the rotation period about 700 s. Then the angular velocity started to grow, and to the end of orbital existence of the spacecraft it grew 5 times (the rotation period decreased up to 150 s), the nutation angle gradually increasing from 30° at the outset to 90° ultimately.

At such values of rotation parameters it became possible to determine the kinetic moment vector attitude by comparing the conity angle \( \gamma \) in the dispersion diagram and that in the signature. Such a device allows determining the angle \( \delta \) between the kinetic moment vector \( L \) and the location vector \( d \) at time interval \( \Delta t_i \) when the reflections from cylindrical and conic surfaces were observed. Then the following equations system should be solved with respect to the direction cosines of vector \( L \):
where upper index $o$ means that vectors $L_i$ and $d_i$ unity sized.

By data obtained at the last three revolutions before reentry, it became clear that "Cosmos-954" seeks to run into the "propeller mode" when vector $L$ coincides with the vector of orbital velocity, when passing through the most dense layers of the higher atmosphere in the area of equatorial "swellings". With that, the ballistic factor increases up to its maximum value, which is $1.5$ times its average value and $7$ times its minimum value, the spacecraft being oriented with its long axis along the velocity vector.

Two calculations of the reentry time and place were carried out – one with the average value of ballistic factor and the other $1.5$ times as much. The first calculation gave the wrongfully earlier estimate (over Africa). The second one predicted the real reentry over Canada.

The fall of "Cosmos-954" radioactive fragments to the territory of Canada aroused the world community protests. Later, some additional measures were undertaken to prevent radioactive pollution of the incidence area in future in such emergency cases. In particular, separation of the active zone of NPS was envisioned, which appeared to be very efficient as it was demonstrated during the "Cosmos-1402" accident. The heavy compact bunch of uranium rods not only remains in the Earth orbit very long, but also when at last it reenters it melts and burns in higher atmosphere.

"Cosmos-1402"

Its launch took place in 1982 and was the $21$st one in succession. The accident with it occurred after the completion of the four-month flight program. The spacecraft executed the commands for separation of the gantry, for spinning up itself, and then, in a half revolution, for separation of the active zone of NPS. But it failed to commit the commands for separation of NPS from the instrument compartment and for its deorbiting to the disposal orbit.

Soon after that, three space objects were detected at the low working orbit: the gantry that was burnt very soon, the large payload, and a rather small active zone (approximately $60$cm×$20$cm).

The experts run into an unexpected situation when observing the large fast-rotating "Cosmos-1402" payload. At the first sight, the spacecraft seemed to be stabilized by three axes, but its radar signatures were very noisy. Those signatures were obtained with the help of short-wave radars (L-band) with the limited registration rate (several tens of Hz), which appeared insufficient for reproduction of "petalous" structure of the signature. But since the angular velocity of the location vector varied very largely during one track (from a portion of degree per second to several degrees per second), there existed short segments where some peculiar synchronism occurred. For several successive periods of rotation the measurements fell on the same phases of the dispersion diagram. At Fig. 6 the signature of
"Cosmos-1402" and the synchronism segment are shown where one can see the rotation period $\approx 0.6$ s (100 rev/min).

The active zone behaved absolutely differently. Having the same initial rotation speed about the long axis as the payload, it had not turned into the "tumbling mode", the nutation angle having been less than $70^\circ$ and the precession period – about 3 s. Variations of precession periods for these two main fragments are shown at Fig. 7.

Prediction of reentry time for space objects having smooth evolution of their rotation parameters is not a very hard task because of relatively stable value of ballistic factor. The first fragment reentered, as it was predicted, over the Indian ocean and the second one did so over the Atlantic ocean in 12 days after.
"Cosmos-1900"

This satellite was placed to the working orbit at the end of 1987. At the beginning of 1988 its flight program was completed, and to replace the satellite another one namely "Cosmos-1932" was launched, which appeared to be the last one having NPS on-board. 21 May 1988 its NPS successfully was deployed to the disposal orbit.

At the same time, "Cosmos-1900" failed to execute the last operation and continued its lowering in atmosphere. As in case of "Cosmos-954", it threatened to collapse. However, unlike "Cosmos-954" having lost the attitude control, the orientation system of "Cosmos-1900" still continued to be in order. Analysis of the radar signatures showed that its attitude control errors were quite tolerable though increased as the spacecraft lowered (perhaps, due to destabilizing effect of the lateral survey gantry (Fig. 8)).

Declination $\Delta \theta$ of the maximum reflection foreshortening from $90^\circ$ is accounted for by the attitude control errors in pitch $\Delta \nu$ and row $\Delta \psi$:

$$\text{Max} \Delta \theta < \sqrt{2} \text{ Max} \{\Delta \nu; \Delta \psi\}.$$ 

30 September 1988, when "Cosmos-1900" reached the altitude 150 km, its attitude control errors run out the tolerable limit and, as in case of "Cosmos-469", the automatic deorbiting maneuver was executed. Though the disposal orbit appeared to be 200-250 km lower than with the rest RORSATs.

![Fig. 8. Typical signature of the stabilized «Cosmos-1900»](image)

![Fig. 9. «Cosmos-1900» vector L nutation (June 1997)](image)
The subsequent radar observations showed that "Cosmos-1900" differs from the rest RORSATs not only by the orbit altitude, but also by its own rotation parameters. If during first 7-8 years of its flight in the disposal orbit deceleration of its rotation and the nutation character of kinetic moment vector were the same as for the rest RORSATs, since November 1996 till July 1997 they significantly changed (see Fig. 9). The attenuation coefficient of rotation increased more than twice as much and became equal to 0.53 1/year ($D_{2T} \sim 1.3$ year). The nutation character of kinetic moment vector changed as well: the nutation variation period decreased from 40 to 12 days [7].

These phenomena can be accounted for by the growth of influence of aerodynamic dissipative and conservative moments [6].

So, long before the reentry, the influence of the atmosphere upon the own rotation parameters is much more than upon the orbit parameters

**Conclusion**

"Cosmos-1900" will be the first RORSAT to fall to the Earth approximately in 300-500 years. Its orbital behavior can be monitored with the help of radar signature analysis during several next years till its precession period remains less than the one-track observation duration (200-400 s). Then, another ways should be sought.

The examples of radar signature analysis given here do not transmit all the potential possibilities of the new tool for processing the non-coordinate radar information and, the more so, do not comprehend all the possible scopes of its applications. Sometimes we have no other ways for getting the necessary data on the defunct or silent spacecraft or those in contingency.

Not all the spacefaring nations dispose of the necessary technical facilities and appropriate software. So, it seems expedient to unite the capability in this sphere and to create the universal tool or tool kit that can be used by every nation for monitoring their own spacecraft, periodically estimating its state, and constant monitoring in emergency situations.

**References**

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