Safety system for space vehicles using integrated devices located outside of the satellite platform

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Abstract. The article presents a system for detecting space objects using integrated devices located outside the satellite platform, which can significantly expand the possibilities of creating micro-consuming small-sized high-temperature and radiation-resistant radar systems of autonomous small spacecraft as part of satellite groups to solve the tasks.

1. Introduction
Space debris is end of life satellites remaining in orbit, upper stages and booster rockets, dumped fuel tanks, fragments of destroyed objects, as well as springs, bolts, nuts, plugs etc.

Large debris, colliding with outdated spacecraft and destroying them, will generate new debris. If this happens, the density of space debris in the orbit will begin to grow by itself already without any human involvement.

Meanwhile it is here in the so-called sun-synchronous orbits many weather satellites and Earth remote sensing satellites are turning. An example of a collision between the US communications satellite Iridium-33 and early Russian military satellite Cosmos 2251 resulted in a density of more than 5 millimeters of space debris fragments increasing by another 30 percent. The number of large debris amenable to tracking from the Earth has also increased.

As a result, existing satellites now have to maneuver more often to avoid dangerous proximity with debris that is to dodge a collision. It happens at least once a year. As a result, fuel consumption increases which ultimately negatively affects the life of the apparatus.

The most intensive areas of modern space technology systems development is increasing their degree of autonomy and the implementation of the group small spacecraft functioning. The task of autonomous control in the spacecraft task force is solved at a high level and requires operational information about
the situation in the near space. Currently, the best results can be achieved by using the 5 mm wavelength range, taking into account complete damping of signals from the Earth, i.e. the presence of a clean underlying surface.

2. Control of space objects using a synthesized aperture antenna

Due to the fact that the introduction of small spacecraft into the working orbits for scientific purposes contributes to the research, study and conduct of space flight tests, each spacecraft can be equipped with a bearing (detection) system for space debris as additional equipment.

This equipment can be N radars with a synthesized aperture of the antenna (SAR), located on the satellite and having a sufficiently high frequency of sounding of outer space. The directional characteristics of the antennas of these locators should overlap in such a way as to provide a single-pulse measurement of the direction to the space object (figure 1).

![Figure 1. The location of the directivity characteristics of the antennas of the satellite locator.](image)

When considering this issue, we first introduce some restrictions that will be removed subsequently:

- flight radii and angular speeds of rotation of a satellite and a space object around the Earth provide rectilinear motion at a certain section of their flight;
- angular velocity of rotation of the satellite around its axis ensures the stationarity of the satellite throughout the entire section of its rectilinear motion;
- a rectilinear motion section should ensure the formation of the synthesized aperture of the antenna. That is during the flight in this area, it is necessary to obtain, without gaps, n echo signals from the space object;
- the space object has one element, the effective scattering surface of which exceeds similar surfaces of other elements, i.e. dominant brilliant point. In this case, the effective reflective surface of the remaining elements of the space object can be neglected.

Let the length of the true aperture of the antenna of one locator along the satellite path line be d. Given the operation of one of the antennas to transmit and receive directional characteristics formed by a true aperture with a single-channel output in the direction of a stationary object, we can attribute the equivalent width in radians

\[ \Delta \alpha \approx \frac{\lambda_0}{d} \sqrt{2} \sin|\alpha_0|, \]  

where \( \lambda_0 \) is emitted wave length; \( \alpha_0 \) is the angle between the direction of motion of the satellite and the direction of the space object located at a distance D from the satellite (figure 2).

As a result, each antenna from the space object will receive a packet of reflected radio pulses. Its maximum duration \( T_{\text{max}} \) with non-tracking reception depends on the value of the \( \Delta \alpha = 1 \) effective reflecting surface and the distance D of the space object to the satellite path line.
Taking into account (1)

\[ T_{\text{max}} = D \left| \cotg \left( \alpha_0 - \frac{\Delta \alpha}{2} \right) - \cotg \left( \alpha_0 + \frac{\Delta \alpha}{2} \right) / v \right| \approx (D \cos \varepsilon \cos \alpha_0) \Delta \alpha / v \approx D \lambda_0 / \sqrt{2} \cdot v \cdot |\sin \alpha_0| \cdot 3. \] (2)

During observation \(|t| = D |\cos \varepsilon \alpha_0| / v\) the radial distance to a fixed space object changes according to the law determined by the first three members of the Taylor series:

\[ D = \sqrt{D_0^2 + (D_0 \cotg \alpha_0 - vt)^2} \approx D_0 \cos \varepsilon \alpha_0 - vt \cos \alpha_0 + (v^2 t^2 \sin^3 \alpha_0) / 2D_0, \]

where \(D_0\) is a minimum distance between a satellite and a space object.

From here is the relative radial velocity \(v_r = dD / dt\) and Doppler frequency of an element of a stationary space object

\[ F_D = \frac{2v_r}{\lambda} \approx -\frac{2v}{\lambda} \cos \alpha_0 + \left( \frac{2v^2}{D_0 \lambda} \sin^3 \alpha_0 \right) t. \]

**Figure 2.** Formation of the synthesized aperture of the antenna, detection of a relatively stationary object.

The linear frequency change \(F_D\) during the observation time \(T \leq T_{\text{max}}\) corresponds to a quadratic phase change and leads to frequency modulation of the received signal with a frequency deviation

\[ \Delta f = 2v^2 T |\sin \alpha_0|^2 / D_0 \lambda. \] (3)

To reproduce the spectrum of Doppler frequencies, the pulse repetition rate \(F_{\text{P}}\) must exceed the frequency deviation \(\Delta f\).

Thus in order to detect a relatively immovable space object (space debris), to measure the distance to it and also to determine the composition, it is necessary that each of the satellite locators operate in the synthesized aperture of the antenna.

However, the probability of finding stationary space debris in the orbits of artificial Earth satellites is insignificant as according to the laws of physics, debris will eventually approach the Earth, and therefore will have some speed and acceleration.

In this regard the detection of moving objects will be the most probable (figure 3). The speed of these space objects in this case will be approximately equal in amplitude to the speed of the spacecraft. The direction of flight of debris can be either oncoming or intersecting with respect to the flight path of the
satellite. For this reason to detect space objects and measure their parameters and coordinates, it is necessary to use satellite locators with combined synthesis of the antenna aperture, combining direct and inverse methods.

![Figure 3. Formation of the synthesized aperture of the antenna, the detection of an object moving at a speed approximately equal to the speed of flight of the satellite.](image)

A space object detected by one locator will be observed in the same way by another (neighboring) locator. As a result the difference in the amplitudes of the signals received by various locators can determine the direction to a given object

\[
\alpha = 2 \text{Re}(\frac{-jZ_\Sigma Z_\Delta^*}{|Z_\Sigma|^2}),
\]

where \(Z_\Sigma\) and \(Z_\Delta\) is correspondently the result of the total and difference processing of the signals received by neighboring locators.

As a result of the foregoing the task of determining the angular direction of a space object relative to the satellite’s flight axis is reduced to choosing two neighboring locators whose orientation is determined by one of the known navigation methods, for example differential-ranging, determining the position of the satellite relative to beacons located on satellites with a geostationary orbit.

Information about the detected object, its range relative to the satellite’s location and direction relative to the tangent to the satellite’s orbit can be transmitted to automated spacecraft control centers for decision-making.

Based on the results of observations on the stationary interval (the indicated restrictions), a decision is made on the course of the space object and its threat to the flight of each specific satellite.

In order to determine the location of a space object with a synthesized aperture of the antenna of one locator accurately, it is desirable to use a LFM signal of short duration. This will additionally make it possible to obtain an increase in the detection range of a space object due to the coordinated filtering of received signals, which in turn is a prerequisite for a high satellite speed.

Since the effective reflective surface (ERS) of satellites varies significantly \((\bar{\sigma} = 10^{-3} \div 10^2)\), the detection range of these objects will also be different.

The required minimum detection range for unambiguous measurement of the range of an object with a minimum image intensifier is approximately 100 km. In this case, the detection of satellites with a large ERS will occur at ranges of approximately 10 ÷ 15 times exceeding the minimum requirements. When using the pulsed radar method, the average power of the emitted signal by one locator of such a satellite will be approximately 100 W, and the energy consumption for ensuring the operability of other elements is usually an order of magnitude lower than the energy consumption of the transmitting device [1-12].
3. Conclusion
Thus radar detectors system of space objects creation, even on all satellites, will make it possible to control outer space close to the Earth and make corrections to flights of spacecraft. Minor energy costs show that, if necessary, it is possible to install these locators even on small spacecraft.

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