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Functional Restrictions on the Orientation of Onboard and Ground Methods in the RadioAstron Project

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Abstract—In this paper, functional restrictions on the orientation of the onboard systems of the space radio telescope, stations of scientific data receiving and ground radio telescopes in the RadioAstron project are considered. Restrictions important for practical problems of scheduling observations with ground-space radio interferometer are discussed in detail. An algorithm for calculating the angles of the narrow-beam antenna drive, which takes into account technological restrictions on the capability of its spatial orientation, is presented.

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1. INTRODUCTION

The RadioAstron radio interferometer of the *Spektr-R* project was created for astronomical observations of Galactic and extragalactic radio sources. The interferometer consists of ground and space segments. The ground segment is represented by ground radio telescopes as single instruments, and as a part of global radio interferometric networks. The space segment consists of a space radio telescope onboard the satellite and ground stations of scientific data receiving. In addition to both segments, ground-control methods and laser ranging stations for refining ballistic calculations are involved in the interferometer operation.

For the correct and effective operation of all elements of the interferometric system, it is necessary that, during observations, a certain set of conditions on the orientation of the space telescope and other devices onboard the satellite, as well as ground-support methods associated with it, was implemented. These conditions are stated in detail in the "Protocol of the Functional Restrictions on the Orientation of Onboard and Ground Methods of the RadioAstron Project" (http://www.asc.rssi.ru/radioastron/documents/constr/prot6v_ru.pdf).

Taking into account restrictions when scheduling observations with the RadioAstron interferometer is the most important problem. The calculation results and selection of optimal orbit according to the efficiency criterion for scientific research obtained in 2011 before the launch of the space telescope is a good illustration of the specifics of the RadioAstron project defined by these restrictions.[1] According to the results of the analysis, favorable conditions for interferometric observations with the space telescope arise in September to May.

2. COORDINATE SYSTEMS OF THE SPACE TELESCOPE

The position of investigated source on the celestial sphere is uniquely given by the coordinates in the equatorial coordinate system, i.e., the right ascension α and the declination δ.

Restrictions on the orientation of the space telescope in space are formulated in protocol for the coordinate system associated with the spacecraft and various devices on its board, including a 10-m radio astronomy antenna directed at the studied source during observations and a 1.5-m antenna used to transmit scientific information on special ground stations. In scheduling problems, the geocentric coordinates of the studied source, the Sun, and the Moon are transformed to the coordinate system of the space telescope. Then, an analysis is performed to determine how the positions of the Sun and Moon on the celestial sphere at the time of the studied source observation satisfy the restrictions formulated in the protocol. An example is given for only one of the cases of many procedures that must be performed before deciding that the chosen radio source can be observed on the specified date.

By definition, the coordinate systems (CS) of the spacecraft for which restrictions are formulated in the protocol are orthogonal and right. The basic coordinate system XYZ is connected with the spacecraft and its origin is located in the plane of joint of the Navigator basic module with a transitional truss [1]. The X axis is directed perpendicular to the plane of joint with transitional truss. The positive direction of the

[1] V.E. Yakimov, M.V. Popov, I.D. Litovchenko, and A.I. Sheikhet: The selection of the optimal orbit according to the efficiency criterion for scientific research in accordance with the launching window. *Scientific and Technical Report.* Moscow, ASC LPI, 2011.

X axis is the direction of the electrical axis of the space radio telescope (SRT) antenna. The Y axis is parallel to the axis of the rotation of the solar panels and the positive direction is the direction of the right panel if oneis looking at the spacecraft from the location of star sensors of onboard control complex.

The sighting coordinate system $X_sY_sZ_s$ is implemented with control elements installed on the SRT antenna. Axes with the same name of basic and sighting CS in the nominal position are mutually parallel and coincide in direction.

Each star sensor of onboard control complex (OCC), as well as the narrow-beam antenna (NBA) drive, is connected with its own instrument coordinate system $X_iY_iZ_i$, which is implemented by its seat (see Fig. 1, where the position of the instrument CS of the orientation sensors and NBA drive relative to the sighting CS are shown).

On Earth, the measurements of the angular position of the instrument CS are performed relative to the position of the sighting CS. Matrices that correspond to the results of the measurements are introduced in OCC. SRT pointing to the studied sources is provided by the setting from the Earth of quaternion of orientation of the sighting CS relative to the inertial CS. When controlling illumination by the Sun, Earth, and Moon (see below), the deviations of the sighting CS from the nominal angular position relative to the basic CS can be neglected.

3. RESTRICTIONS ON THE SPACECRAFT ORIENTATION

Full list of restrictions is given in Protocol. Some of them, although belong to different onboard devices, duplicate each other. Below, we only discuss the restrictions that define the conditions of availability for observations of the studied source by the RadioAstron interferometer on the given date.

Restrictions on Spacecraft Service Systems

3.1. Thermal Regulation System

The angle between the $+X$ axis and the direction to the center of the solar disk should be in the range of 90°–165° in the $X0Z$ ($+Z$) half-plane, and the output vector of the center of the solar disk from the $X0Z$ plane should not exceed ±10°. The values of the presented angles can be updated during flight tests.

3.2. Power Supply System (Solar Panel)

The angle between the direction from the spacecraft to the center of the solar disk and the normal to the plane of the solar panels should not exceed 10°. The condition of the implementation of this restriction is that the output vector of spacecraft–solar disk center of the $X0Z$ plane should not exceed ±10°.

Note. Solar panels can be rotated around the Y axis, which minimizes the angle between the direction from the spacecraft to the center of the solar disk and the normal to the plane of the solar panels.

3.3. Star Sensor AD-1 (1, 0, 2)

The onboard control complex includes three star sensors, i.e., AD-1-1, AD-1-0, and AD-1-2. At the nominal position, the axes of the two star sensors AD-1-1 and AD-1-2 are positioned in the half-plane rotated from the $Y0Z$ ($-Z$) half-plane by the angle of 15° around the Y axis to the direction of the $-X$ axis, by the angle of 45° to the $-Y$ and Y axes, respectively, counting toward the direction of the $-Z$ axis. The axis of the third star sensor AD-1-0 is in the $X0Z$ plane and rotated from the $-X$ axis by 30° to the direction of the $-Z$ axis. In the standard mode, two star sensors are used. The angle between the axis of each of the two working star sensors and shaded celestial body should exceed 40° for the Sun (to the center), 13° for Moon (to the nearest edge), and 25° for the Earth (to the nearest edge).

Note. When forming the research program during the flight, the choice of working star sensors should be implemented of approved for use and in view of the above restrictions presented in this protocol of restrictions.

3.4. Board–Earth Narrow-Beam Antenna (NBA)

In the NBA drive, the instrument (ICS) and the moving (MCS) right coordinate systems are implemented. The drive ICS ($X_iY_iZ_i$) is implemented by the landing plane, through which the drive is installed on the spacecraft and the system of class holes of the drive construction. The ICS nominal angular position of the NBA drive relative to the basic CS is determined by the angles F_X, F_Y, F_Z, which are counted as follows: after combining the ICS axes of the drive with the axes of the same name of the basic CS, sequential turns of ICS by the angles F_X, F_Y, F_Z around the axes X_i, Y_i, Z_i are performed, respectively. The positive angle corresponds to counterclockwise rotation when observed from the positive direction of the corresponding ICS axis. The values of angles for the nominal angular position of ICS of the NBA drive are as follows: $F_X = 0°$, $F_Y = -162.5°$, $F_Z = 0°$. The drive MCS ($X_mY_mZ_m$) is connected with the output flange of the NBA drive. The drive provides the MCS turns relative to ICS by the given angles as follows: ψ around the Y_i axis and θ around the Z_{m1} axis (Fig. 2). At the zero angle of the drive ($\psi = \theta = 0$), the axes of ICS and MCS with the same name in the nominal position are mutually parallel and coincide in direction.

The positive direction of the drive rotation around the Y_i and Z_{m1} axes is counterclockwise rotation if viewed from the positive direction of the Y_i and Z_{m1} axes, respectively. Permissible range of the drive turn

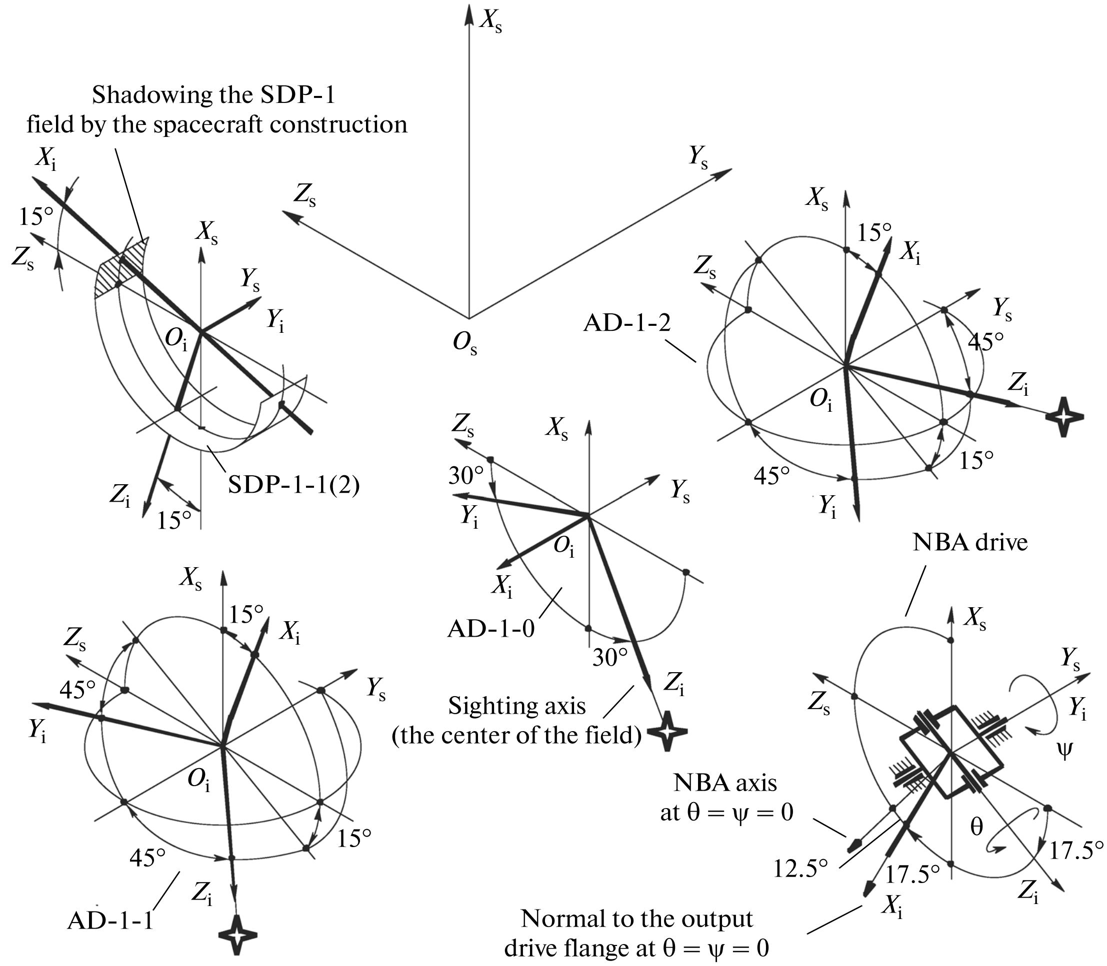

Fig. 1.

angles: from −73° to 90° for the ψ angle; from −90° to 90° for the θ angle.

NBA is rigidly installed on the output flange of the antenna drive in such a manner that its axis in nominal position at zero drive angles was deflected from the $+X_i$ axis of the instrument CS at the angle of 12.5° in the plane $X_i0_iZ_i$ to the direction of the $-Z_i$ axis of the instrument CS. During flight, the angular position of the NBA axis at output drive flange can be specified according to the results of performed operations of the NBA adjustment. The real angular position of the electrical axis is determined by two angles δ_{a1} and δ_{a2}.

These angles at $\psi = \theta = 0$ are counted as follows: δ_{a1} is angular deviation of the electrical axis of NBA from the plane $X_i0_iY_i$. The positive direction of counting is the direction to the direction of the $-Z_i$ axes, and δ_{a2} is angular deviation of the projection of the electrical axis of NBA on the $X_i0_iY_i$ plane from the $+X_i$ axis. The positive direction of counting is the direction to $+Y_i$. In the nominal position, $\delta_{a1} = 12.5°$, $\delta_{a2} = 0$. At present, according to the results of the NBA adjustment performed during the real SRT operation, $\delta_{a1} = 14.76°$. An algorithm for calculating the angles ψ and θ of the NBA drive for pointing the electrical NBA axis at the station of scientific information receiving, which is also a ground-tracking system (GTS), is presented in the Appendix.

When implementing radio communication through NBA by the spacecraft–GTS line: vector of sighting spacecraft–GTS line should be in the range of permissible angular positions of the NBA axis, and angular velocities for each drive axis should not exceed 0.1 deg/s at precision stabilization and at adjustment of scientific equipment. When reorienting the spacecraft from one source to another, there are no requirements for the pointing accuracy of the NBA, and the distance of the spacecraft from GTS should be more than 5000 km.

Restrictions for Onboard Scientific Equipment

3.5. Cooling System of Low-Noise Amplifiers, Microcryogenic System

The Sun should not shine on the surface of the cold plate radiator. The radiator is positioned on the surface of a truncated cone with a half-angle of 30° and with

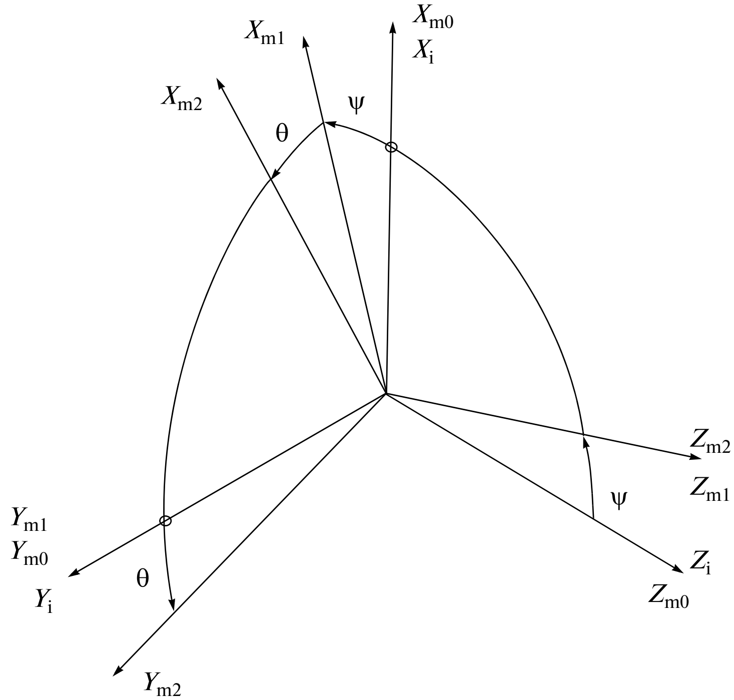

Fig. 2.

an axis that coincides with $+X$, which occupies a part of the lateral cone surface restricted by the dihedral angle of 60° (±30° relative to the $-Z$ axis). At geocentric distances of the spacecraft of less than 20000 km, the angle between the $-Z$ axis and the direction to the center of the Earth's disc should exceed 30°.

3.6. Radio Astronomy Onboard Receivers and SRT Antenna

The angle between the direction to the center of the Sun and the $+X$ axis should exceed 90°; the angle between the direction to the center of Moon and the $+X$ axis should exceed 5°; the angle between the direction to the nearest edge of the Earth's disk and the $+X$ axis should exceed 5°.

Restrictions when Reorienting the Spacecraft

The reorientation of the spacecraft is carried out by the final-turn method, which involves one rotation about the axis, the angular position of which relative to the sighting and inertial coordinate systems is constant when turning. After reorienting the electric axis of the SRT, the antenna should be oriented toward a new researched source.

In the case of the impossibility of performing restrictions for onboard service systems and scientific equipment, when reorienting by the final-turn method, it can be performed using two or more consistent turns, each of which provides performing restrictions.

Note. The required accuracy of orientation is achieved 150 s after the termination of reorientation. Reorientatino can be carried out both with continuous pointing of the NBA toward the working GTS and without pointing, the variant is defined when scheduling investigations. When searching for the Sun, which is performed after the spacecraft is launched into the working orbit and in emergency situations, it is acceptable to violate all restrictions indicated in this protocol.

4. RESTRICTIONS FOR GROUND METHODS OF CONTROL, RECEIVING SCIENTIFIC DATA, AND GROUND RADIO TELESCOPES

The angle between the ground station–spacecraft (or researched source) vector and the local horizon is taken as the elevation angle of the spacecraft (or researched source).

4.1. Restrictions for Orientation of Antennas of Ground Control Stations: The Elevation Angle of the Spacecraft Should Exceed 7°

The Sun–ground-control station and antenna–spacecraft angle should exceed 10°; the Moon–ground control and station antenna–spacecraft angle should exceed 5°. The geocentric coordinates and maximum angular velocities over azimuth and elevation angles of the ground-control station are shown in Table 1 of the Protocol of Functional Restrictions.

4.2. Restrictions for Orientation of Antennas of Ground-Tracking System : The Elevation Angle of the Spacecraft Should Exceed 10°

The Sun–GTS–spacecraft angle should exceed 10° and the Moon–GTS–spacecraft angle should exceed 5°. The GTS geocentric coordinates and maximum angular velocities over azimuth and elevation angle are shown in Table 2 of the Protocol of Functional Restrictions.

4.3. Restrictions for Ground Radio Telescopes: The Elevation Angle of the Researched Source Should Exceed 10°

The Sun–ground radio telescope–researched source angle should exceed 10°; the Moon–ground radio telescope–researched source angle should exceed 5°. Ground radio telescopes are conventionally categorized as large (diameter of 32–64 m) or small (diameter of 22–32 m) in accordance with the size of the antennas. The information on the ground radio telescope we used is taken from the file formed by ASC LPI.

5. OBSERVATION CONDITIONS

When observing, it is suggested that the formulated above restrictions are implemented.

5.1. Scientific Observations

When conducting scientific observations, it is necessary to ensure the following conditions: the visibility of researched source from the spacecraft, the visibility of researched source from at least three ground radio telescope simultaneously, (in this case, two of the ground radio telescopes should be large and the third should be small), and the visibility of the spacecraft from one of the tracking stations.

Note. Scientific observations can be interrupted to measure the trajectory, to transfer commands during the control session, to change the GTS; to unload control engines–flywheels using engine stabilization, and when passing through a shadow from the Earth or Moon. Times and instants of these operations are predefined when forming the scientific program.

5.2. The Mode of Adjustment and Calibration of Amplification Coefficient of the Srt Antenna

The adjustment operation in flight is used to determine the angular deviations in two planes of the electrical axis of the SRT antenna from the intended direction in the sighting CS and is performed by scanning the SRT antenna in the vicinity of the adjustment source (astronomical object) by programming the angular motion of the spacecraft from a given initial position with the simultaneous receipt of the signal of this source using SRT, as well as transferring data obtained using SRT to Earth, and telemetry information about of OCC on the spacecraft orientation.

As a result of processing on Earth, the angular deviations of the electrical axis of the SRT antenna are calculated as follows: $\Delta\alpha$ is the angle between the projection of the axis on the $X_s0_sZ_s$ plane and the $+X_s$ axis of the sighting CS, the positive counting direction is the direction towards the $+Z_s$ axis, $\Delta\beta$ is the angle between the axis and the $X_s0_sZ_s$ plane of the sighting CS, and the positive counting direction is the direction towards the $+Y_s$ axis.

Calculating the quaternion of the orientation of the sighting CS relative to the inertial CS for pointing SRT to researched sources should perform in view of the angular deviations found for the electrical axis of the SRT antenna.

Note. During processing, the ICS angular deviations of star sensors with respect to those measured in the Earth's position, as well as their systematic errors, are reduced to equivalent angular deviations of the electrical axis of the SRT antenna relative to the sighting CS. Simultaneously, the data on the ICS angular position of star sensors can be correlated by no more than 1 arcmin with corresponding changes in the onboard matrices of their ICS (chapter 3).

The SRT adjustment is mainly performed without transferring the data on the GTS, and onboard memory is used for recording. For the entire time of the SRT operation, the adjustment data were only transmitted via the NBA–GTS channel twice. When adjusting SRT, it is necessary to take into account the restrictions on the spacecraft orientation stated in this protocol. The list of adjusting sources and their coordinates are given in Tables 4 and 5 of the protocol.

5.3. Adjustment Mode for the Narrow-Beam Antenna of the Spacecraft

When adjusting the NBA, i.e., searching for the axis of the radiation pattern, OCC forms a program of turns of the NBA drive based on the ψ and θ angles relative to the calculated direction toward the GTS. When implementing these turns, the level of the signal obtained from the NBA is measured and recorded on the GTS. As a result of the joint processing on Earth of the data obtained during a series of operations of the NBA adjusted by different ψ and θ angles, five parameters are specified, i.e., three angles of the ICS drive position relative to the sighting CS and two angles δ_{a1}, δ_{a2} of the orientation of the electrical NBA axis relative to the output drive flange (MCS).

At the cost of the adjustment, the contribution of the drive is significantly reduced in the final error of NBA pointing. A considerable part of the random, unknown, but constant systematic errors of the drive when processing is reduced to the equivalent five above stated specified parameters.

The M_{adj} matrix corresponding to the three specified angles of the ICS position of the drive, as well as two angles δ_{a1} and δ_{a2} are introduced in OCC from the Earth and subsequently used in OCC when calculating the drive angles ψ and θ for pointing NBA (see Appendix). When making adjustments, it is necessary to take into account the restrictions for pointing NBA.

6. CONDITIONS FOR LASER RANGING SESSIONS

During ballistic calculations, the initial data consist of possible ground stations for laser ranging sessions, including the stations listed in Table 3 of the protocol.

When calculating the possible intervals of performing the laser ranging sessions, the following conditions of performing these sessions are accepted: an elevation angle of the spacecraft above the horizon for corresponding laser ranging station should be greater than 30°; the angle between the directions from the spacecraft to the Sun and to the laser ranging station should be more than 15°, and the elevation angle of the Sun above the horizon for the corresponding laser ranging station should be less than –10°. The duration of the laser ranging session should be no more than 1 h. In the middle of the laser ranging session, the $-X$ axis of the spacecraft is directed toward the Earth, in which case, during the laser ranging session, the angle between this axis and the vector of spacecraft–Earth should be not more than 3°. Restrictions on the orientation of the spacecraft stated in the protocol should be considered.

CONCLUSIONS

Scheduling the real observations of radio sources by the RadioAstron interferometer is not restricted to considering only the functional conditions on the orientation of the various elements of the ground-space radio interferometer in accordance with Protocol. At the final stage of preparation for observing researched sources from the given list, as well as their sequence and duration of observation sessions, the verification of compliance of thermal mode of the various parts of the transmission narrow-beam antenna and the spacecraft as a whole is performed.

APPENDIX

ALGORITHM FOR CALCULATING ANGLES ψ AND θ OF THE NARROW-BEAM-ANTENNA DRIVE

When calculating the angles ψ and θ of the NBA drive, to point the electrical axis toward the GTS, the matrix M_{adj} and the angles δ_{a1} and δ_{a2} of the real angular position of the electrical NBA axis at output flange of the NBA drive in MCS should be considered.

Let $\bar{r}_E$ be the unit radius vector of the GTS station in the ICS drive calculated using the matrix M_{adj}. The following algorithm is then implemented.

(1) Check the condition $|r_{Ey}| < \cos(\delta_{a1} + \delta_{th})$, where δ_{th} is value of security threshold. Initially, we adopt $\delta_{th} = 1°$. Hereinafter, it can be adjusted and corrected using the command and program information transmitted onboard from Earth.

(2) If condition (1) is not satisfied, then values of the angles ψ and θ calculated to this time are saved.

(3) If condition (1) is satisfied, the drive rotation angle ψ_0 is calculated assuming $\delta_{a1} = \delta_{a2} = 0$:

$$\psi_0 = \arctan 2\left(\frac{-r_{Ez}}{\sqrt{1 - r_{Ey}^2}}, \frac{r_{Ex}}{\sqrt{1 - r_{Ey}^2}}\right), \; -\pi < \psi_0 \le \pi.$$

(4) $\delta\psi = \arcsin\left(\dfrac{\sin\delta_{a1}}{\sqrt{1 - r_{Ey}^2}}\right)$;

(5) $\psi = \psi_0 - \delta\psi$;

(6) $\theta = \arcsin\left(\dfrac{r_{Ey}}{\cos\delta_{a1}}\right) - \delta_{a2}$.

(7) Check whether the calculated angles ψ and θ belong to the operating range

$$\psi_{min} \le \psi \le \psi_{max}, \; \theta_{min} \le \theta \le \theta_{max}.$$

If the calculated angles ψ and θ are outside the range, the fulfillment of the flight mission for pointing NBA is finished. Values ψ_{min}, ψ_{max}, θ_{min}, and θ_{max} are shown in the Protocol of Functional Restrictions.

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