Lebedev Physical Institute, Russian Academy of Sciences

Astro Space Center

Laboratory Of Ballistic-Navigation Support For Space Projects

“SOAP: Spacecraft Orbit and Attitude Prediction tool” Input and Output Parameters

Fraerman A. V.

Zapevalin P.R.

Moscow 2025

Contents

Chapter 1

Output files

1.1 Ephemeris

Ephemeris document consists of

1. time stamp — with interval equal to output step(2.2.4)
2. position vector in geocentric celestial reference frame GCRF (units: km)
3. velocity vector in GCRF (units: km/s)
4. attitude quaternion — quaternion transforming coordinates of the local coordinate system (rigidly connected to the device) to the GCRF axes in the format (w, x, y, z)

1.2 Telemetry

Telemetry document consists of

1. time stamp — with interval equal to integration step
2. torques, applied to the spacecraft in local coordinate system (units: N * m)
3. control systems momentum, depending on whether they are installed on the spacecraft

a) reaction wheels — angular momentum of each reaction wheel and 3 components of its total momentum (units: N*m*s)

OR (see 2.5.1)

b) gyrostats — angular momentum of each gyrostat (units: N*m*s);

c) magnetorquers — magnetic momentum components (units: A*m^2)

4. torque of stabilization engine (units: N*m)

5. angular momentum of the spacecraft (units: N*m*s)

Chapter 2

Input parameters

This chapter provides a complete list of input parameters.

2.1 General structure of an input JSON

In general JSON-file has structure as follows:

```
"block 1": {
    "key 1": value,
    "key 2": [value 1, value 2],
    "key 3": [
        {
            "element 1": value,
            "element 2": value
        },
        {
            "element 1": other value,
            "element 2": other value
        }
    ]
},
"block 2" : {
    ...
}
```

JSON can contain the following blocks:

- simulation(2.2) – parameters of numerical integration
- spacecraft(2.3) – least required parameters of a spacecraft
- geometry(2.4) – surface of the spacecraft divided into polygons and solar panels
- control_systems(2.5) – attitude control systems, its quantity and parameters
- attitude_modes(2.6) – scan and constant attitude regimes
- forces(2.7) – switches to forces and torques included into simulation
- filenames(2.8) – paths to dependency and ephemeris and telemetry files.

All block names are specified with a lowercase letter in the format in which they are listed in this list.

The order of the blocks, as well as the parameters within each of them, is logical from the author's point of view, but is not mandatory — the program will correctly read the file regardless of the order of the structural blocks.

The following chapters examine each block separately with a full description of the parameters and their types. An example of an input file with all parameters is given in the chapter 3.

2.2 Simulation

In the *simulation* block, the following parameters are mandatory: interval, step, start_time. Optional parameters include: output_step, orbit_file.

2.2.1 interval

The integration interval, a floating-point number in seconds.

2.2.2 step

The integration step, a floating-point number in seconds. To select an automatic integration step, set the step parameter to a negative number or zero.

2.2.3 start_time

The initial epoch, specified in the format YYYY-MM-DDTHH:MM:SS.S Any character can be used instead of the 'T' separator.

2.2.4 output_step

The output step for data in the ephemeris file, a floating-point number in seconds. By default, it is equal to the integration step when using a constant step and to the interval when using an automatic step.

2.2.5 orbit_file

The path to the orbit file. If this parameter is specified, the orbit calculation will not be performed, and the values from the specified file will be used instead. By default, the orbit file is absent.

2.3 Spacecraft

In the *spacecraft* block, the following parameter is mandatory: state_vector. Optional parameters include mass, quaternion, angular_velocity, inertia_tensor.

2.3.1 state_vector

The spacecraft state vector in the inertial coordinate system (km and km/s), 6 floating-point numbers.

2.3.2 mass

The spacecraft mass in kg, a single floating-point number. The default is 10 kg.

2.3.3 quaternion

The orientation quaternion in the format w x y z, 4 floating-point numbers. The default is (1, 0, 0, 0), which corresponds to the alignment of the local and celestial coordinate system axes.

2.3.4 angular_velocity

The initial angular velocity of the spacecraft in rad/s, 3 floating-point numbers. The default is zero.

2.3.5 inertia_tensor

The spacecraft inertia tensor, excluding the inertial orientation system (gyrostats, reaction wheels), in kg*m^2 in its principal axes. A vector of 3 floating-point numbers (diagonal elements of the inertia tensor). The default is (10, 10, 10).

2.4 Geometry

In the *geometry* block, the following parameters can be specified: polygons, solar_panels, vtk_file, vtk_koeffs.

2.4.1 polygons

Specifies the number of *count* polygons and a list of *parameters*. The description of each polygon must include its position vector, unit vector of the outward normal, area, albedo (reflection coefficients), and specularity.

These polygons do not include solar panels.

2.4.2 solar_panels

The description of solar panels is the same as the description of polygons but also has an additional parameter *rai* — Rotation Axis Index. It is assumed that the solar panel can rotate relative to one of the main axes of the spacecraft, presenting the largest area to the Sun. The rai parameter can take the values 0 for the Ox axis, 1 for the Oy axis, 2 for the Oz axis, and -1 if the solar panel cannot rotate.

2.4.3 vtk_file

If there is a file describing the spacecraft surfaces in VTK Polygons format, it is sufficient to specify the path to this file instead of describing the polygons.

2.4.4 vtk_koeffs

If a vtk file with polygons is specified, you can specify the path to the corresponding file to set their albedo and specularity coefficients. This file has a text format and must contain 2 columns of floating-point numbers - albedo and specularity coefficients (in that order).

If there are N rows in this file and less than the number of polygons P, then for the last P-N polygons, the albedo is set to 0.54 and the specularity coefficient to 1.0.

If the coefficient file is not specified, the values 0.54 and 1.0 are set for all polygons.

2.5 Control systems

In the *control_systems* block, attitude control systems are specified: gyrostats, reaction_wheels, magnetorquers, pulse_engines, as well as the control_order parameter.

2.5.1 gyrostats VS reaction wheels

Although both systems are "flywheels" in a nutshell, for historical reasons, they exist separately in the program. Moreover, they are mutually exclusive – a spacecraft can be equipped with either gyrostats or reaction wheels. This is logical in the sense that a specific spacecraft is equipped with only one type of flywheel system.

The difference between these systems is as follows: gyrostats are mounted so that they rotate independently along the spacecraft's principal axes, so their quantity must be a multiple of 3. Reaction wheels are mounted in a pyramid configuration of 4 wheels, so their rotation is not independent, and their quantity must be a multiple of 4.

2.5.2 gyrostats

The number *count* of gyrostats is specified (must be a multiple of 3), along with a list of *parameters* for each gyrostat. For each gyrostat, the following is specified: a position vector (m) *location*, principal moments of inertia (kg*m^2) *inertia*, and angular velocity limits (rad/s) *limits* – three floating-point numbers, where only one component of the limit should be non-zero (the first if the axis is oriented along the X-axis, the second if along the Y-axis, the third if along the Z-axis).

2.5.3 reaction_wheels

The number *count* of reaction wheels is specified (must be a multiple of 4), along with a list of *parameters* for each set of wheels. The following are specified: a position vector (m) *location*, principal moments of inertia (kg*m^2) *inertia*, the initial speed of each of the 4 wheels *initial_speed*, angles *angles* in the order α, β, and the direction of the pyramid apex *pyramid_apex* — X, Y, or Z.

2.5.4 magnetorquers

These are magnetic actuators, for which the number *count* and a list of *parameters* are also specified. The parameters are the current value of the electric current (A) *current*, the maximum value of the magnetic dipole moment *max_dipol*) – a vector with a single non-zero component, and the mass (kg) *mass*.

2.5.5 pulse_engines

The number *count* of engines and a list of their *parameters* are specified. The parameters for each engine are: a position vector *position*, the maximum impulse – a vector with a single non-zero component corresponding to the direction of gas expulsion, and the initial mass *mass*.

2.5.6 control_order

The priority in which attitude control systems are used. *r* – reaction wheels, *g* – gyrostats, *m* – magnetorquers, *0* – engines. The first two priorities are specified. The third priority will always be the engines. This is effectively used to indicate the priority between magnetorquers and flywheel systems of one design or another.

2.6 Attitude modes

The *attitude_mode* block describes the scan and fixed attitude modes. The intervals of stop and scan attitudes should not overlap by more than one point. All intervals that are not scan or stop attitudes are free attitude modes.

2.6.1 stop_motion

The number of fixed attitude modes *count* and a list of their *parameters* are specified. The parameters passed are the initial epoch *start_time* in YYYY-MM-DDTHH:MM:SS.S format, the final epoch *stop_time* in the same format, and the quaternion of the maintained attitude *quaternion* in w x y z format.

The final epoch can exceed the final epoch of integration; in this case, attitude maintenance will occur until the end of the integration.

2.6.2 scan_motion

The number of scan attitude modes *count* and a list of their *parameters* are specified. The parameters passed are the initial epoch *start_time* in YYYY-MM-DDTHH:MM:SS.S format, the final epoch *stop_time* in the same format, and the angular velocity vector *velocity* in rad/s.

2.7 Forces

The *forces* block contains instructions on the force and torque model used in the simulation. Each of the parameters can take the value *true* if the model is used, and *false* if it is not.

- gravity_force — gravitational attraction of the Earth
- gravity_order — order of the expansion of the gravitational potential, a natural number. If 0, then a central field is used
- outer_gravity — attraction of the Sun, Moon, and planets of the solar system
- solar_pressure_force — solar radiation pressure force
- gravity_torque — torque generated by the gravitational attraction of the Earth
- solar_pressure_force — solar radiation pressure torque
- magnetic_torque — torque generated by interaction with the Earth's magnetic field

2.8 Filenames

The *filenames* block contains the names of used and created files. The created files are specified by the *output* parameter, *save_path* for the ephemeris file, and *telemetry_path* for the telemetry file.

Input files are specified by the *input* parameter under the following names:

- egm_path — file of coefficients for the Earth's gravitational potential model

- eop_path — file of Earth rotation parameters
- tls_path — file containing leap seconds
- eph_path — ephemeris file
- igrf_path — file of coefficients for the Earth's magnetic field model
- gm_path — file of gravitational parameters for the Sun, Moon, and planets of the solar system

Chapter 3

Example input JSON file

This chapter provides an example input file in which all possible parameters are used. This file cannot serve as an actual input parameter file because the attitude control systems *gyrostats* and *reaction_wheels* are used simultaneously.

It is also worth noting that when an orbit file *orbit_file* is used, it is pointless to consider any forces, as the orbit will still be taken from the file and not from calculations.

The polygons listed through the use of the *polygons* parameter displace (override) those specified in the *vtk_file*.

The last two remarks won't cause the program to crash but can clearly lead to unexpected results.

```
  {
"simulation": {
  "start_time": "2016-05-31T00:00:00.0",
  "interval": 10000,
  "step": 1.0,
  "output_step": 1.0,
  "orbit_file": "/media/alexey/Disk/asc/orbit.txt"
},
"spacecraft": {
  "state_vector": [5957.4, 0.0, 3439.5, 0.0, 7.6, 0.0],
  "quaternion": [0.19378, 0.033945, 0.010695, 0.9804],
```

```
  "angular_velocity": [0.0, 0.0, 0.0],
  "inertia_tensor": [
    [27.0, 0.0, 0.0],
    [0.0, 200.0, 0.0],
    [0.0, 0.0, 200.0]
  ],
  "mass": 100.0
},
"geometry": {
  "polygons": {
    "count": 2,
    "parameters": [
      {
        "position": [0.75, 0.0, 0.0],
        "normal": [1.0, 0.0, 0.0],
        "area": 1.6,
        "albedo": 0.5,
        "specularity": 0.5
      },
      {
        "position": [-0.75, 0.0, 0.0],
        "normal": [-1.0, 0.0, 0.0],
        "area": 1.6,
        "albedo": 0.5,
        "specularity": 0.5
      }
    ]
  },
  "solar_panels": {
    "count": 2,
    "parameters": [
    {
      "position": [-1.25, 0.0, 0.0],
      "normal": [0.0, 1.0, 0.0],
      "area": 0.8,
      "albedo": 0.5,
      "specularity": 0.5,
```

```
        "rai": 0
      },
      {
        "position": [0.0, 1.25, 0.0],
        "normal": [0.0, 0.0, 1.0],
        "area": 0.8,
        "albedo": 0.5,
        "specularity": 0.5,
        "rai": 1
      }
    ]
    },
    "vtk_file": "/media/alexey/Disk/asc/polygons.vtk"
  },
  "control_systems": {
    "gyrostats": {
      "count": 3,
      "parameters": [
          {
            "location": [0.0, 0.0, 0.0],
            "angular_velocity": 0.0,
            "mass": 5.0,
            "inertia": [0.02388, 0.001, 0.001],
            "limits": [628.0, 0.0, 0.0]
          },
          {
            "location": [0.0, 0.0, 0.0],
            "angular_velocity": 0.0,
            "mass": 5.0,
            "inertia": [0.001, 0.02388, 0.001],
            "limits": [0.0, 628.0, 0.0]
          },
          {
            "location": [0.0, 0.0, 0.0],
            "angular_velocity": 0.0,
            "mass": 5.0,
            "inertia": [0.001, 0.001, 0.02388],
```

```
        "limits": [0.0, 0.0, 628.0]
      }
    ]
  },
  "reaction_wheels": {
    "count": 8,
    "parameters": [
      {
        "location": [1.0, 0.0, 0.0],
        "angles": [30, -90],
        "inertia": [0.001, 0.001, 0.01],
        "mass": 5.0,
        "initial_speed": [0.0, 0.0, 0.0, 0.0],
        "speed_limit": 628.0,
        "pyramid_apex": Y
      },
      {
        "location": [1.0, 0.0, 0.0],
        "angles": [-30, -90],
        "inertia": [0.001, 0.001, 0.01],
        "mass": 5.0,
        "initial_speed": [0.0, 0.0, 0.0, 0.0],
        "speed_limit": 628.0,
        "pyramid_apex": "Y"
      }
      ]
  },
  "magnetorquers":{
    "count": 2,
    "parameters": [
      {
        "max_dipole": [10.0, 0.0, 0.0],
        "mass": 0.3,
        "current": 0.1
      },
      {
        "max_dipole": [0.0, 0.0, 10.0],
```

```
        "mass": 0.3,
        "current": 0.1
      }
    ]
  },
  "pulse_engines": {
    "count": 6,
    "parameters": [
      {
        "position": [0.75, 0.75, 0.0],
        "limits": [0.0, 200000.0, 0.0],
        "mass": 10.0
      },
      {
        "position": [0.75, 0.0, 0.75],
        "limits": [0.0, 0.0, 200000.0],
        "mass": 10.0
      },
      {
        "position": [0.0, 0.75, 0.75],
        "limits": [0.0, 0.0, 200000.0],
        "mass": 10.0
      },
      {
        "position": [-0.75, -0.75, 0.0],
        "limits": [0.0, 200000.0, 0.0],
        "mass": 10.0
      },
      {
        "position": [-0.75, 0.0, -0.75],
        "limits": [0.0, 0.0, 200000.0],
        "mass": 10.0
      },
      {
        "position": [0.0, -0.75, -0.75],
        "limits": [0.0, 0.0, 200000.0],
        "mass": 10.0
```

```
        }
      ]
    },
    "control_order": {
      "first": "r",
      "second": "m"
    }
  },
  "attitude_modes": {
    "stop_motion": {
      "count": 2,
      "parameters": [
          {
            "quaternion": [0.19378, 0.033945, 0.010695, 0.9804],
            "start_time": "2016-05-31T00:00:00.0",
            "stop_time": "2017-05-31T13:48:00.0"
          },
          {
            "quaternion": [1.0, 0.0, 0.0, 0.0],
            "start_time": "2017-05-31T13:48:30.0",
            "stop_time": "2018-05-31T13:48:00.0"
          }
        ]
    },
    "scan_motion": {
      "count": 2,
      "parameters": [
        {
          "velocity": [1.0, 0.0, 0.0],
          "start_time": "2019-05-31T00:00:00.0",
          "stop_time": "2020-05-31T00:00:00.0"
        },
        {
          "velocity": [0.0, 2.0, 0.0],
          "start_time": "2020-05-31T00:00:00.0",
          "stop_time": "2021-05-31T00:00:00.0"
        }
```

```
      ]
    }
  },
  "forces": {
    "gravity_force": true,
    "gravity_order": 36,
    "outer_gravity": true,
    "solar_pressure_force": true,
    "gravity_torque": true,
    "solar_pressure_torque": true,
    "mangetic_torque": true
  },
  "filenames": {
  "output": {
    "save_path": "./output/ephemeris.txt",
    "telemetry_path": "./telemetry/telemetry.txt"
    },
  "input": {
      "egm_path": "/media/alexey/Disk/asc/Files/EGM2008.dat",
      "eop_path": "/media/alexey/Disk/asc/Files/eop_new.txt",
      "tls_path": "/media/alexey/Disk/asc/Files/naif0012.tls",
      "eph_path": "/media/alexey/Disk/asc/Files/de440.bsp",
      "gm_path": "/media/alexey/Disk/asc/Files/gm_de440.tpc",
      "igrf_path": "/media/alexey/Disk/asc/Files/igrf.dat"
    }
  }
}
```