Application of RIT-22 Thruster for InterhelioProbe Mission

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Annotation

It is considered application of electric propulsion (EP) module based on radiofrequency ion thruster RIT-22, as a main propulsion system of InterhelioProbe solar orbiter. It is presented comparison of RIT-22 option with stationary plasma thruster SPT-140D and bipropellant propulsion options. Carried out mission analysis shows the RIT-22 option is preferable for InterhelioProbe spacecraft.

Keywords

electric propulsion system; spacecraft radiofrequency ion thruster; InterhelioProbe mission; mission analysis

Introduction

InterhelioProbe spacecraft is designed to investigate inner heliosphere and the Sun from close distances and from out-of-ecliptic positions. Scientific goals of the space mission are following [1, 2]:

- to study the fine structure and dynamics of the solar atmosphere;
- to study the mechanisms of the coronal heating and solar wind acceleration;
- to study the origin and global dynamics of solar flares and coronal mass ejections and their influence on the heliosphere and space weather;
- to study the generation and propagation of solar energetic particles on the Sun and in the heliosphere;
- to investigate the magnetic fields in subpolar regions, and
- to study the mechanism of the solar dynamo and solar cycle.

Spacecraft is developing by Lavochkin Association. Main developer of scientific payload is Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation Russian Academy of Sciences (IZMIRAN) [1, 2].

1. Mission Profile

InterhelioProbe spacecraft inserts into the Earth escape trajectory using «Soyuz-2.1B» launch vehicle with Fregat upper stage from Baykonur launch site at 2017-2018. Now there are considered three options of spacecraft propulsion system:

- Electric propulsion module (EPM) having one radiofrequency ion thruster RIT-22 developed by EADS Astrium [3] (main option);
- EPM using two stationary plasma thrusters SPT-140D developed by Fakel design bureau (2 thrusters are required to provide necessary lifetime: only one thrusters is running at the same time);
- Bipropellant propulsion system (BPPS).

There were proposed nominal parameters for RIT-22 (thrust 150 mN, specific impulse 4500 s) and SPT-140D (thrust 180 mN, specific impulse 2700 s).

InterhelioProbe mission profile includes following phases:

- Insertion into the low Earth orbit (LEO) using «Soyuz-2.1B» launch vehicle and first burn of Fregat upper stage;
- Insertion into the Earth escape trajectory using Fregat upper stage;
- Heliocentric trajectory, including:
    - Ecliptic phase to reduce perihelion radius down to required minimal value using spacecraft propulsion and the Earth/Venus gravity assist maneuvers;
    - Out-of-ecliptic phase to increase inclination using sequence of Venus gravity assist maneuvers. To do it, after each Venus flyby (except last one) spacecraft inserts into a resonant orbit providing next Venus flyby after whole numbers of spacecraft and Venus revolutions around the Sun.

2. InterhelioProbe Trajectory Constraints

Set of constraints is imposed on InterhelioProbe trajectory. These constraints are connected with scientific goals, spacecraft design, and restrictions of onboard systems: power supply, thermal, communication. Main current constraints are following:

- It is required at least one flyby at heliocentric distance 60-70 radiuses of the Sun (RS). Closer approaching to the Sun is not permissible;
- It is required maximization of inclination of final orbit to the ecliptic plane;
- The orbital period should be minimized;

- Angle Sun-spacecraft-Earth should be greater than 90° at minimal heliocentric distance to provide shadowing of the high-gain antenna by the heat shield;
- Minimal heliocentric distance before EPM separation should be greater than 120 RS;
- Maximal heliocentric distance at running EPM should not exceed 1.25 AU;
- Spacecraft lifetime is 5 years;
- EPM thrust and specific impulse are fixed at all thrusting arcs (solar arrays provides required power supply up to 1.25 AU).

It should be noted the main trajectory constrains were revised more than once. For example, initially it was required approaching to the Sun down to 30…45 RS, and out-of-ecliptic phase was not considered. Minimal permissible heliocentric distance before EPM separation initially was bounded by 60…70 RS, but was increased up to 120 RS later. Besides, initially EPM provides simultaneously running of two thrusters (RIT-22 or SPT-140D), but later the option with one simultaneously running thruster was chosen. As a result, a number of heliocentric trajectories were considered to satisfy these trajectory constraints. These trajectories were differed each from other by different flybys and resonant orbits consequence, different duration of EPM burn time, etc. Some of considered trajectories are presented in [6].

3. Methods of Trajectory Optimization

InterhelioProbe low-thrust multi-gravity assist trajectory was optimized during mission design. The indirect methods of optimization were used. Maximum principle was used to reduce the optimal control problem to boundary value problem for ordinary differential equations. The boundary value problem was formally reduced to the Cauchy problem using Newton homotopy (continuation on parameter). Intermediate power-limited problem was considered to enhance numerical convergence. In particularity, initial values of co-states for power-limited problem were used as guess values of corresponding values for thrust-limited problem. Important feature of applied numerical technique was using of complex-step differentiation for accurate computation of partial derivatives of sensitivity matrix [6-8].

4. Results of InterhelioProbe Mission Design: RIT-22 Option

Figure 1 shows typical heliocentric trajectory of InterhelioProbe spacecraft. Thrusting arcs are denoted by bold lines, and coasting arcs (as well as planets' orbits) are denoted by thin lines. The trajectory includes one Earth gravity assist maneuver and sequence of four Venus gravity assist maneuvers. EPM runs only in initial trajectory leg Earth-to-Earth. Typical trajectory includes three thrusting arcs; Earth-to-Earth leg begins and finishes by coasting arcs.

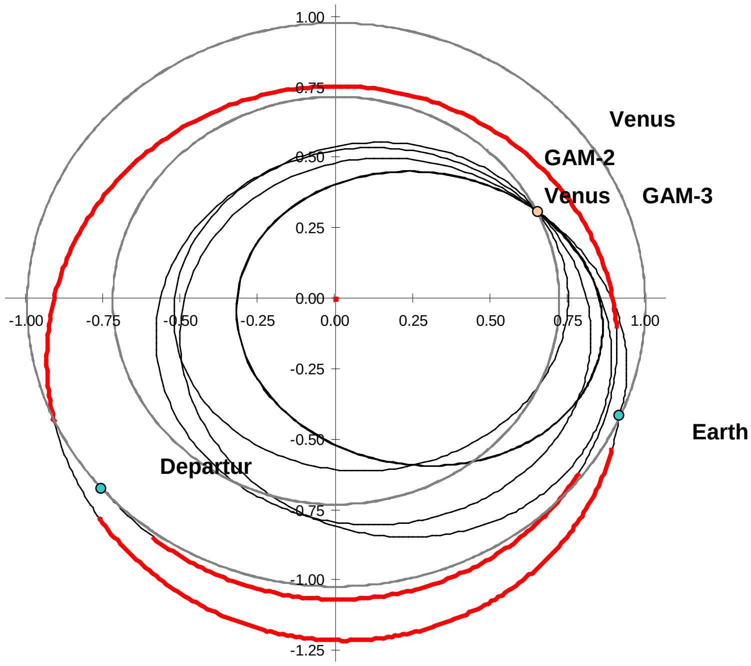

Figure 1 – Projection of InterhelioProbe Trajectory onto Ecliptic Plane (RIT-22 Option, and Launch Date - 01.05.2017)

Table 1 presents main parameters of the heliocentric trajectory for RIT-22 option and launch date 01.05.2017. Hyperbolic excess of velocity at Earth escape trajectory is 2900 m/s, initial spacecraft mass (after upper stage separation) is 1646.5 kg, and final spacecraft mass (before EPM separation) is 1527 kg. The launch vehicle and the upper stage capabilities provide duration of launch window more than one month with EPM propellant consumption less than 121.5 kg. Within launch window final spacecraft mass is varied within range 1525…1529 kg (see Figure 2) while required total burn time of RIT-22 is varied within range 9600…10000 hours.

Table 1

Main Trajectory Parameters for RIT-22 Option and Launch Date 01.05.2017

t, days	t, years	Perihelion radius, RS	Inclination to the ecliptic plane, degrees	Orbital period, days	Orbital resonance with Venus
528.74	1.448	67.288	10.26	168.524	4:3
1202.84	3.293	97.419	14.97	224.699	1:1
1427.54	3.908	113.858	20.80	224.698	1:1
1652.23	4.524	112.126	24.65	189.371	--

Heliocentric distance and inclination to the ecliptic plane as functions of time are presented in Figure 3 and Figure 4. Minimal perihelion radius is reached after first Venus gravity assist maneuver when spacecraft inserts into orbital resonance 4:3. At this orbit, before next Venus flyby, spacecraft orbits around the Sun four times while Venus orbits three times. So, at this orbit spacecraft do four passes at minimal heliocentric distance 67.288 RS. After second Venus gravity assist maneuver spacecraft inserts into 1:1 resonant orbit and remains in this resonance after next

Venus flyby. Last three gravity assist maneuvers purpose to increase inclination to the ecliptic plane. The inclination reaches 24.65° after 4.5 years of flight.

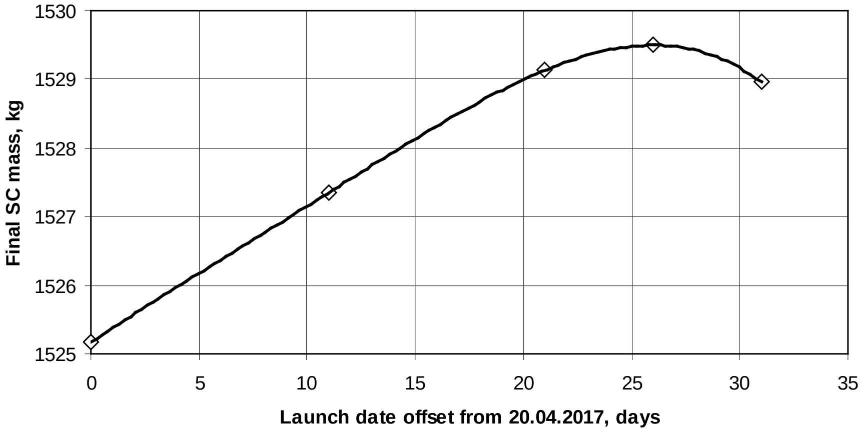

Figure 2 – Dependency of InterhelioProbe Final Mass (Before EPM Separation) vs. Launch Date

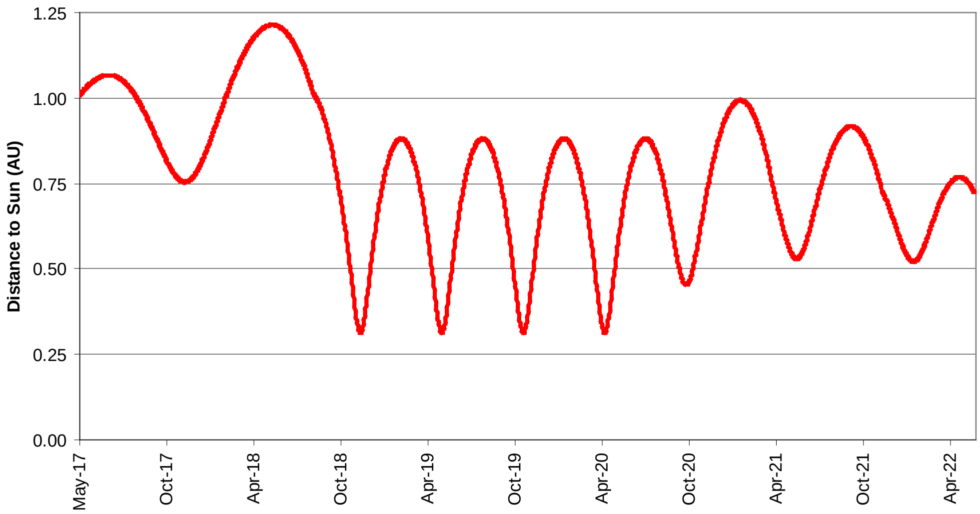

Figure 3 – Dependency of Heliocentric Distance vs. Time (InterhelioProbe, RIT-22 Option, and Launch Date 01.05.2017)

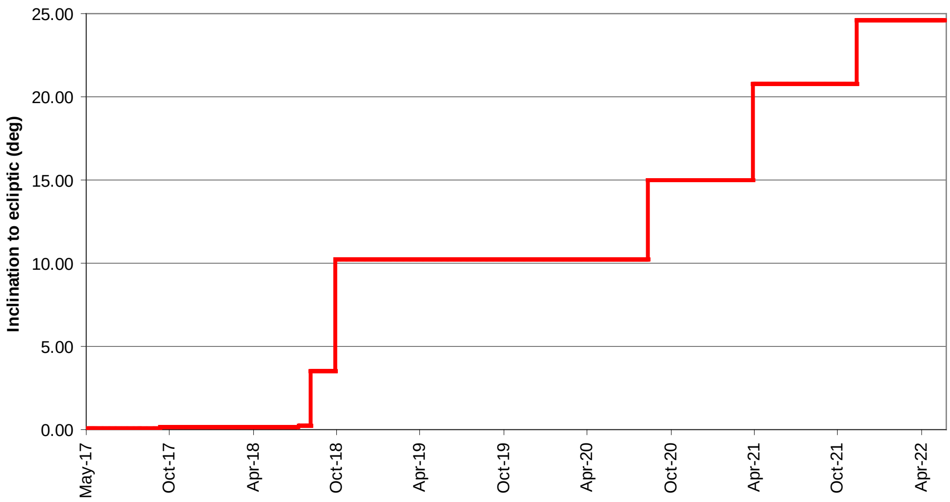

Figure 4 – Dependency of Inclination to Ecliptic Plane vs. Time (InterhelioProbe, RIT-22 Option, and Launch Date 01.05.2017)

Next launch window (26.11.2018-05.01.2019) allows increasing of final inclination up to 27.15°, while minimal heliocentric distance is decreased down to 63.57 RS (see Table 2). Required xenon consumption (providing 40-days launch window) is 129.5 kg. Final spacecraft mass before EPM separation is 1517…1522 kg, depending on launch date. Both launch windows (2017 and 2018-2019) provide margin of spacecraft dry mass 20…23 %.

Table 2

Main Trajectory Parameters for RIT-22 Option and Launch Date 06.12.2018

t, days	t, years	Perihelion radius, RS	Inclination to the ecliptic plane, degrees	Orbital period, days	Orbital resonance with Venus
515.83	1.412	63.570	7.68	168.523	4:3
1189.92	3.258	88.530	13.46	224.699	1:1
1414.62	3.873	99.577	21.22	224.697	1:1
1639.32	4.488	104.452	27.15	199.589	--

5. Comparison of RIT-22, SPT-140D, and BPPS Options

SPT-140D using instead RIT-22 leads to decreasing of optimal Earth escape asymptotic velocity from 2900 m/s to 2100 m/s and to increasing of initial spacecraft mass up to 1801.6 kg, while final spacecraft mass increases to 1550…1560 kg. But lower specific impulse leads to increasing of Xenon consumption in two times (up to 242 kg). As a result, required burn time of SPT-140D becomes close to 10000 hours also while its qualified lifetime is about 5000 hours. So, there are required two SPT-140D to provide required burn time. Additional thruster along with increased mass of Xenon lead to decreasing of margin on 50…60 kg.

BPPS option provides perihelion radius 65 RS and inclination 17° only at the end of 5-years spacecraft lifetime (more exactly, after 4.8 years of flight). Therefore, BPPS option loses to RIT-22/SPT-140D options providing required perihelion radius after 1.4…1.5 years of flight and inclination 24.6…27.2° after 4.5 years of flight.

6. Comparison of InterhelioProbe's and ESA Solar Orbiter's Trajectory Parameters

European Space Agency (ESA) is developing Solar Orbiter mission which has goals and parameters similar to ones of InterhelioProbe mission. ESA Solar Orbiter uses BPPS as main propulsion system. Its design lifetime is ten years, twice more than InterhelioProbe lifetime. Figures 5 and 6 present comparison of heliocentric distance and inclination time histories for ESA Solar Orbiter (red lines) and InterhelioProbe (blue line) missions in case of launch in 2018.

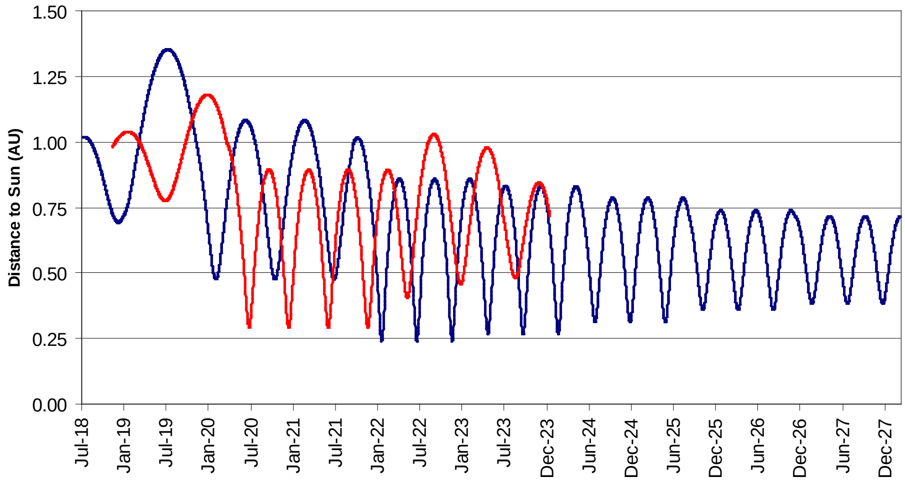

Figure 5 – Comparison of ESA Solar Orbiter (Red Line) and InterhelioProbe (Blue Line) Heliocentric Distance with Respect to Time for 2018 Launch Window

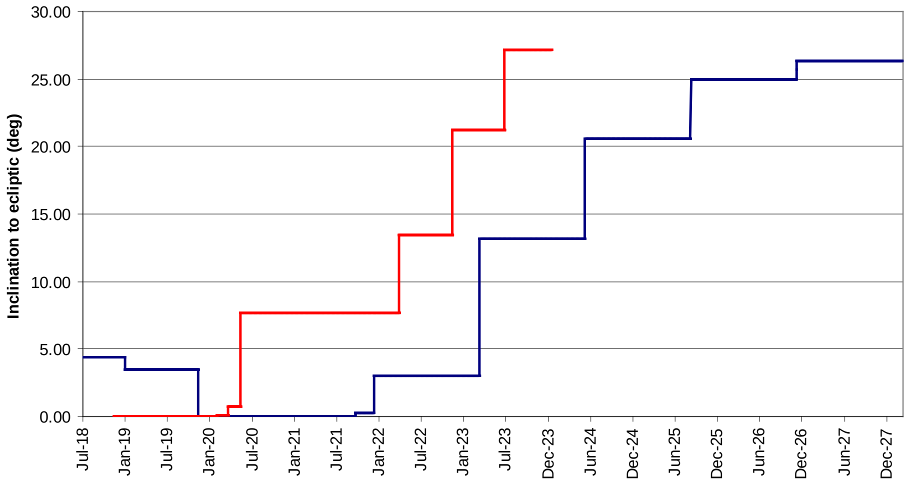

Figure 6 – Comparison of ESA Solar Orbiter (Red Line) and InterhelioProbe (Blue Line) Inclination to Ecliptic with Respect to Time for 2018 Launch Window

Figure 5 and Figure 6 shows that InterhelioProbe provides approximately same minimal distance to the Sun and inclination despite of twice lower lifetime because of RIT-22 using.

Conclusions

- EPM option allows to decrease flight time down to required heliocentric distance (60…70 RS) to 1.5 year (from 4.8 years for BPPS option);
- EPM option allows to increase maximal inclination up to 24.7…27.2° (from 17° for BPPS option);
- EPM option satisfies to all main mission constraints;
- RIT-22 demonstrated lifetime (10000 hours) satisfies to mission constraints;
- RIT-22 is preferred option for InterhelioProbe main propulsion.

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