ON ULTIMATELY THE MOST HIGHLY INCLINED, THE MOST CONSICE SOLAR POLAR TRAJECTORY WITH PRACTICALLY THE SHORTEST PERIOD

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ABSTRACT

This paper presents the extended orbital synthesis results from the author's work in 2009 to achieve ballistic and short period out-of ecliptic trajectories which possess ultimately the most highly and most concise solar polar properties. Those are realized through almost ballisticflight instead of using electric propulsion or solar sail acceleration. The strategy developed utilizes a Jovian gravity assist first, followed by very high speed synchronized multiple polar gravity assists by Earth or Venus.
While the author's work in 2009 presented the trajectories down to almost one year period, this paper will present the further sequences that make the semi-major axis lower than one AU and lower the perihelion distance closer to the Sun for close-up observation of the Sun.

Index Terms— Solar Polar, Swing-by, Jupiter

1. INTRODUCTION

This paper presents the ballistic and short period out-of ecliptic trajectories. They are ultimately the most highly and most concise solar polar orbits which are realized via ballistic flight, utilizing a Jovian gravity assist and synchronized multiple Earth gravity assists.
So far, the use of very high speed gravity assist has been conceived not practically useful to control the trajectory energy. However, this paper presents those still effectively contribute to amending the trajectories periods, in other words, to diminishing the size of them, and lead to acquiring small sized out-of-ecliptic ballistic trajectories. The process simply converts orbital energy associated with highly eccentric ellipses to inclination change. The biggest advantage of this strategy is to reduce propellant mass to be carried drastically, even close to zero, like ballistic flight.
This paper shows the refined trajectories with the semi-major axis lower than one AU and the lowered perihelion distance closer to the Sun even less than 0.1 AU.

2. BACKGROUND AND CONTEXT

In 2009, the author presented the idea about how the concise, short period solar polar trajectory is built. It utilizes the Eccentricity-to-Inclination (E-2-I) technique , which requests the repetition of multiple Earth (or Venus) gravity assists following the Jovian gravity assist. By that time, Ulysses mission had been referred to as to accomplishing highly inclined solar polar flights. It successfully performed the mission. However, the major drawbacks revealed were in the fact that the spacecraft could not make frequent observations during the mission. It failed to diminish the period. So far, the Jovian swing-by enables the inclination to be erect quite efficiently, but it results in very longer revolution periods that were hardly acceptable.
This paper presents how short-period, but erect trajectory is synthesized.

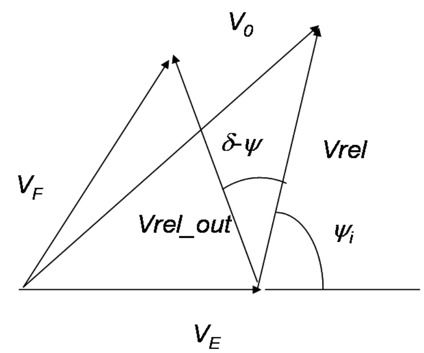

Fig. 1a Gravity Assist Geometry

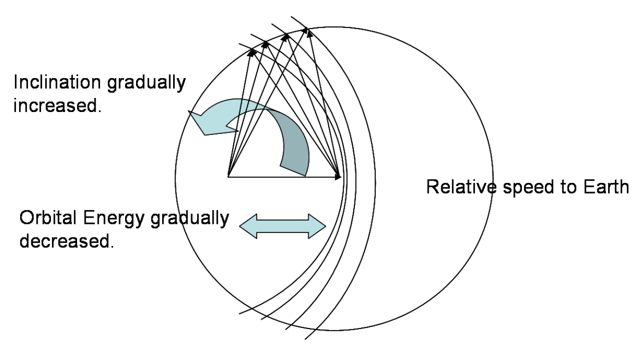

Fig. 1b Repetition of Gravity Assists

3. FUNDAMENTAL PROPERTIES

Figure-1a, 1b show the technique of E-2-I conversion taking the advantage of Earth (or Venus) gravity assist. In this application, the perihelion distance should be preserved and the eccentricity be amended at the same time, which correspond to the reduction of semi-major axis length. This in turn means the shorter revolution period. The strategies show a variety of trajectories.

Since the Earth revolution speed is about 30 km/s, the inclination of 90 degrees along with the orbital period of one year request the v-infinity of 42 km/sec. It is hardly expected.

Erecting the orbital plane loses the orbital energy, which leads to the reduction of the semi-major axis. In case the perihelion distance is kept frozen, this implies the amendment of the eccentricity. That is why this conversion is called E-2-I conversion.

The next table shows what the previous study did. Fundamentally, as shown by Ulysses mission, obtaining high inclination itself is relatively easy. However, the size of the trajectory is really elliptic and very large. The synthesized trajectory is hardly practically available.

4. PREVIOUS RESULTS SUMMARY IN 2009

The trajectory sequences in previous paper presented in 2009 are summarized as follows:

[1] Strategy-1 (Seq.-1)
C_3: 106 km^2/s^2, 78deg,
1 (1.0) AU in 13 years, 73 deg,
1.1 AU in 10 years.
[2] Strategy-2 (Seq.-2)
C_3: 90 km^2/s^2, 39deg,
1 (1.0) AU in 7 years.
[3] Strategy-2+, -2+U(pper)
(Seq.-2+, Seq.-2+U)
C_3: 90 km^2/s^2, 39deg,
1AU in 7 years, 41 deg,
0.52 (0.7) AU in 8 years, 41 deg,
0.26 (0.4) AU in 10 years.
[4] Strategy-2+V(enus) (Seq.-2+V)
C_3: 90 km^2/s^2, 49deg,
1AU in 11 years, 45 deg,
1.6 (1.0) AU in 8 years, 50 deg,
0.9 (0.8) AU in 13 years.

The Table-1 below indicates some typical strategies to have highly erected trajectories using Jovian and Venus gravity assists. It is cited from previous paper. Among them, the strategy-1 is still attractive and infers the much more challenging trajectory may exist.

This simply indicates even 78 degrees is easy to have. Besides, the flight duration of 13 years may conclude the perfect trajectory that possesses both the smallest size and the highest inclination at the same time. It takes more than 13 years.

The subsequent sections of this paper describe how the sequence length can be reduced. The ballistic E-2-I conversion never asks the delta-V budget paid, while the flight period is never diminished. The subsequent illustration include the sequences with fuel consumption, which is paid by chemical or electric propulsion means.

The delta-V, if applied to shortening the period and to making the inclination high, is enormous and hardly applicable. Here is the motivation of the study.

Table-1 Use of a Single Powered Earth Swingby

	Strategy-1	Strategy -2+, -2+U	Strategy V2+	Strategy V2+U
Sequences Evolution	• 65deg, 5.5 (1.5) AU in 2 years, • 67 deg, 3.2 (1.4) AU in 5 years, E1 • 70deg, 1.6 (1.2) AU in 8 years, E2 • 73deg, 1.2 (1.1) AU in 10 years, E3 • 78deg, 1 (1.0) AU in 13 years. E4, E5, ...	• 30 deg, 5.5 (1.5) AU in 2 years, • 35 deg, 2.2 (1.4) AU in 5 years, • 39 deg, 1.0 (1.0) AU in 7 years, • 41 deg, 0.52 (0.7) AU in 8 years, • 41 deg, 0.26 (0.4) AU in 10 years.	• 42 deg, 5.5 (1.2) AU in 2 years, • 44 deg, 2.3 (1.1) AU in 5 years, • 45 deg, 1.6 (1.0) AU in 8 years, • 47 deg, 1.2 (0.9) AU in 9 years, • 49 deg, 1.0 (0.85) AU in 11 years. • 50 deg, 0.9 (0.8) AU in 13 years	• 39 deg, 5.5 (1.2) AU in 2 years, • 41 deg, 2.3 (1.1) AU in 5 years, • 42 deg, 1.6 (1.0) AU in 8 years, • 44 deg, 1.2 (0.9) AU in 9 years, • 46 deg, 1.0 (0.85) AU in 11 years. • 47 deg, 0.9 (0.8) AU in 13 years.
Observation Times	With NO scheduled Delta-V, Science Observation possible all the time.	With NO scheduled Delta-V but 27m/s. Science Observation possible all the time.	With NO scheduled Delta-V, Science Observation possible all the time.	With NO scheduled Delta-V, Science Observation possible all the time.

5. EXTENDED NEW RESULTS

5.1 Ballistic Sequence

The Table-2 summarizes the flight sequence that uses only natural, ballistic flights. The sequence is really prolonged, and it takes almost 25 years to have the goal. It must experience nine swing-bys. The resulted orbit has 0.42 AU for perihelion distance, with the inclination of 89 degrees. They may say it takes extraordinary flight period to the goal. But, beyond ten years from launch, every flight segment falls into the trajectory within 1.5 AU. This means the science mission may well start from ten years after the launch.

The 7th and 8th swing-bys are not well optimized, and the swing-by distance is not assured. It is true that some small delta-V may be required.

Table-2 Purely Ballistic Sequence

	Dates	Semi-Major Axis (AI)	Perihelion Distance (AU)	Period (Year)	Inclination (deg)	Delta-V at SW (m/s)	Swingby Alt. (km)	V-inf (km/s)
Launch	2015.11.19	5.27	0.99	N/A	2.3	0		10.30
1 (J)	2017.6.5	3.26	0.99	N/A	64.5	0	(933624)	(11.495)
2	2020.10.16	2.07	0.99	3	67.4	0	573	37.44
3	2023.10.16	1.58	0.99	2	70.0	0	1587	37.44
4	2025.10.16	1. 31	0.99	1.5	72.6	0	2533	37.44
5	2028.10.16	1.16	0.99	1.25	74.6	0	5431	37.44
6	2033.10.16	10.0	0.98	1.0	77.6	0	1628	37.44
7	2034.10.16	0.86	0.72	0.8	81.5	(0)	(61)	37.44
8	2038.10.16	0.76	0.53	0.67	85.9	(0*)	(-56)	37.44
9	2040.10.16	0.71	0.42	0.60	89.0	0	2093	37.44

* 40m/s for raising altitude.

Table-3 Sequence by Chemical Propulsion

	Dates	Semi-Major Axis (AI)	Perihelion Distance (AU)	Period (Year)	Inclination (deg)	Delta-V at SW (m/s)	Swingby Alt. (km)	V-inf (km/s)
Launch	2015.11.19	5.27	0.99	N/A	2.3	0		10.30
1 (J)	2017.6.5	3.26	0.99	N/A	64.5	0	(933624)	(11.495)
2	2020.10.16	2.07	0.99	3	67.4	0	573	37.44
3	2023.10.16	1.58	0.99	2	70.0	0	1587	37.44
4	2025.10.16	1.21	0.99	1.33	73.0	374	234	37.05
5	2029.10.16	1.0	0.98	1.0	76.4	96	231	36.95
6	2030.10.16	0.86	0.72	0.8	80.3	0	204	36.95
7	2034.10.16	0.76	0.53	0.67	84.2	77	243	36.87
8	2036.10.16	0.71	0.42	0.6	87.3	0	3223	36.87
9	2039.10.16	0.67	0.35	0.56	90.1	0	4266	36.87
10	2044.10.16	0.63	0.26	0.5	94.8	0	504	36.87
11	2045.10.16	0.59	0.18	0.45	100.4	108	231	36.76
12	2050.10.16	0.56	0.13	0.42	107.1	134	237	36.62

5.2 Sequence by Chemical Propulsion

Table-3 above shows an alternative trajectory that is not ballistic but with chemical delta-Vs. Needless to say, the trajectory with no delta-V has significance. But the trajectories with small Delta-Vs that can be executed by chemical propulsion extracts more interesting trajectories.
The sequence appears on Table-3 shows the closest observation under less than 0.5 AU becomes possible in 21 years. This sounds too long, but as pointed out in previous slides, the actual observation may be conceived to start five years after the launch, and is actually practical enough.

The perihelion distance obtained is below 0.3 AU in 30 years, and below 0.13 AU in the end. It is extremely low down to the Sun with the period of 0.42 years, less than a half year.
Here, the delta-V budget magnitude is intentionally suppressed so that they can be accommodated by the typical chemical delta-Vs. Total delta-V costs about 800 m/s and not huge. All the delta-Vs here are assumed to take place at the perigee during the swing-by. Since the v-inf. is extraordinary high, the amplification factor associated with the powered swing-by is low, those delta-Vs can be performed even outside of the Earth gravity sphere.

Table-4 Sequence by Electric Propulsion

	Dates	Semi-Major Axis (AI)	Perihelion Distance (AU)	Period (Year)	Inclination (deg)	Delta-V at SW (m/s)	Swingby Alt. (km)	V-inf (km/s)
Launch	2015.11.19	5.27	0.99	N/A	2.3	0		10.30
1 (J)	2017.6.5	3.26	0.99	N/A	64.5	0	(933624)	(11.495)
2	2020.10.16	2.07	0.99	3	67.4	0	573	37.44
3	2023.10.16	1.58	0.99	2	70.0	0	1587	37.44
4	2025.10.16	1.21	0.99	1.33	73.0	0	2533	37.44
5	2028.10.16	1.0	0.98	1.0	73.8	1497	225	35.88
6	2029.10.16	0.82	0.65	0.75	75.4	1233	223	34.59
7	2032.10.16	0.76	0.53	0.67	77.8	0	4544	34.59
8	2034.10.16	0.71	0.42	0.60	80.5	0	3334	34.59
9	2037.10.16	0.63	0.26	0.50	79.8	1946	211	32.55
10	2038.10.16	0.58	0.17	0.44	83.9	1801	224	32.36
11	2042.10.16	0.54	0.088	0.40	79.2	2188	218	30.05
12	2044.10.16	0.53	0.058	0.33	81.5	0	5075	30.05

5.3 Sequence by Electric Propulsion

The Table-4 presents much more revolution sequences. The sequence allows much more high delta-Vs than those in the Table-2. How much of delta-Vs are spent depend on what kind of propulsion system is available. When the direct insertion is intended to have those concise solar polar trajectories , the delta-V required is tremendous and hardly reachable. This sequence costs almost 7.7 km/s by the end of the long mission.
The sequence shown here assumes the large delta-V is paid by electric propulsion performed near Earth. The trajectory well assures the perihelion distance below 0.3 AU in 20 years after the launch. While the ultimate orbit happens 30 years later after the launch, the perihelion distance can be lowered even to 0.058 AU that is similar to that in Solar Probe Plus, but with the highly inclined orbit almost perpendicular to the ecliptic plane. Besides, the final orbit has the revolution period of one third year, so that frequent observation be available.
Note the sequence assures practically operational trajectory ten years after the launch, so that the perihelion distance can be below one AU. In 17 years from the launch, perihelion distance becomes less than 0.5 AU with the synchronization of every two years with respect to Earth. And the sequence guarantees the perihelion distance of below 0.3 AU almost 20 years later after the launch. The ultimate orbit revealed here shows 120 days period orbit with complete polar inclination, also with the perihelion distance of less than 0.058 AU .

6. ASSOCIATED PROPERTIES

TheFigure-2 below shows the plan-form of the trajectory in Jupiter distance scale. It is clearly seen that the repetition of Earth gravity assists efficiently reduces the perihelion distance gradually. Note the plan-form does not show elliptic shapes, just because the trajectories are tremendously inclined to the ecliptic plane.

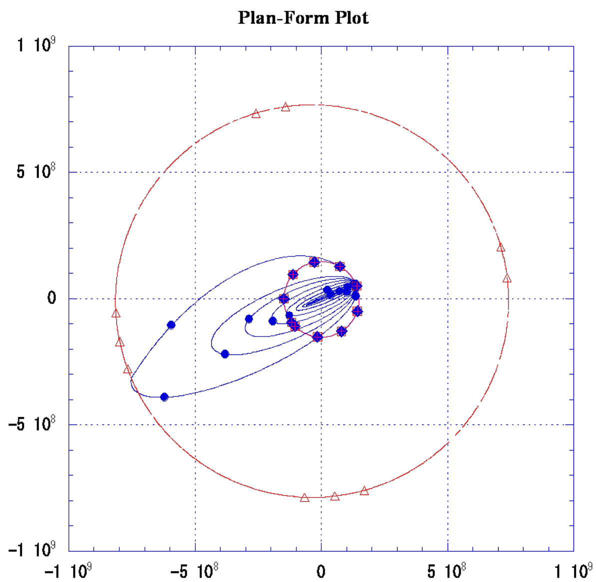

Fig. 2 Trajectory Alteration

TheFigure-3 below shows also the plan-form of the trajectory in Earth distance scale. It also clearly shows how the gravity assists contribute to E-2-I conversion.As seen in the figure, the trajectories flies over the polar region, showing it drawn like a straight line.

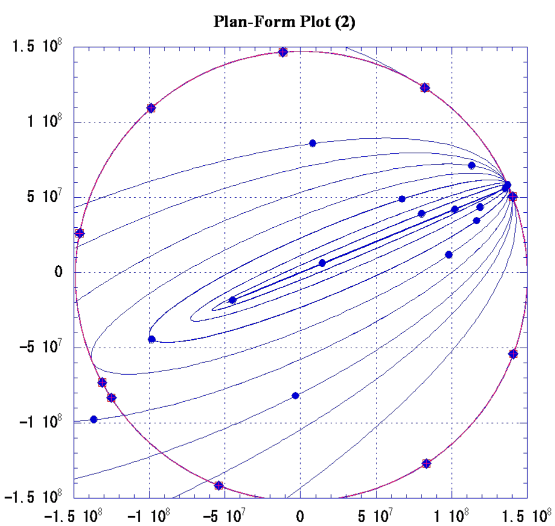

Fig. 3 Trajectory Alteration within 1 AU

When the trajectory is glimpsed from Sun-Earth fixed coordinate, the trajectory draws the loci in the Figure-4. As the inclination is so high that the loci seem to fly quite near to the Sun apparently. The same feature is seen in the Figure-5 in which the synchronized lines are drawn to show the spatial coverage of the Sun.

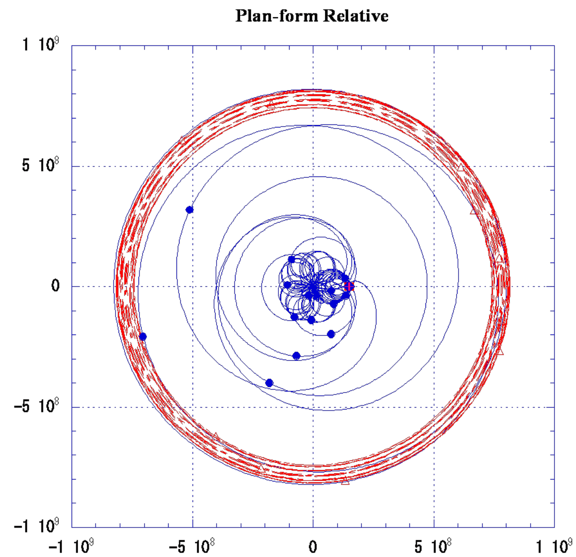

Fig. 4 Sun-Earth-Line Fixed Coordinate

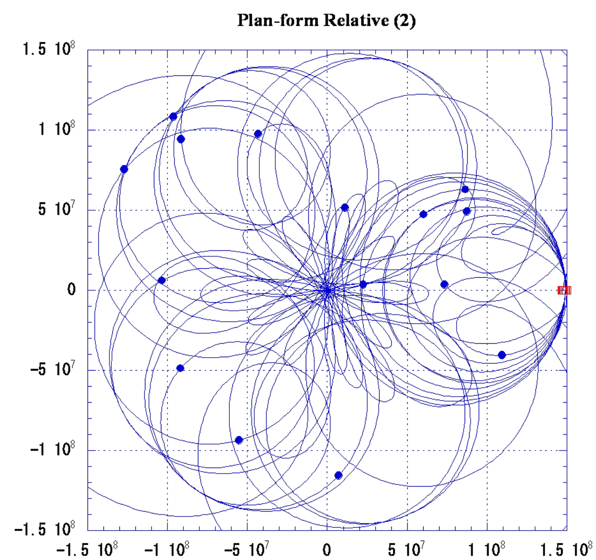

Fig. 5 Sun-Earth-Line Fixed Coordinate within 1 AU

The Figure-6 schematically shows the trajectory alteration is performed. E-2-I conversion is now depicted comprehensively. The Figure-7 well indicates how the inclination is controlled to be raised gradually. The first inclination of about 75 degrees is made almost normal to the ecliptic plane.

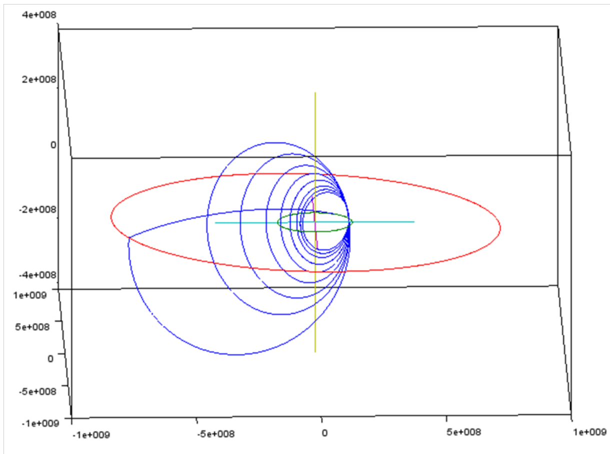

Fig. 6a Sun-Earth-Line Fixed Coordinate

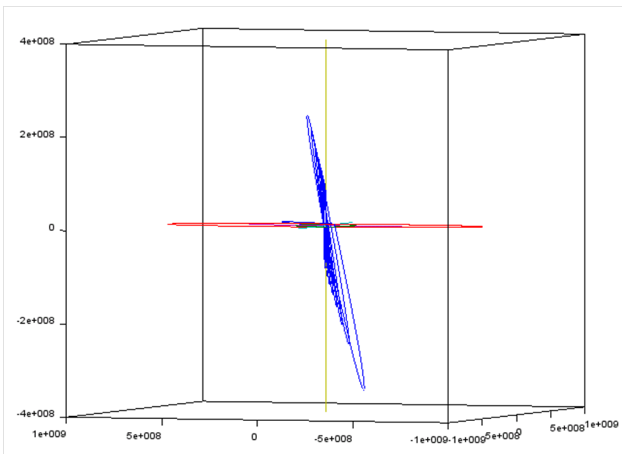

Fig. 6b Sun-Earth-Line Fixed Coordinate

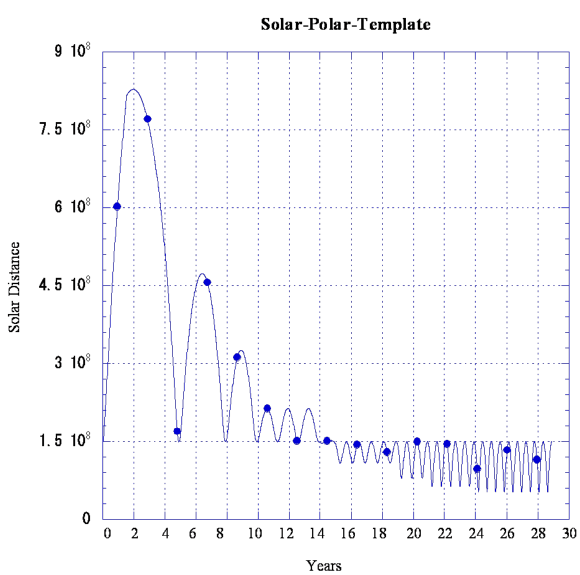

Fig. 7 Distance History for Chimecally Propelled Seq.

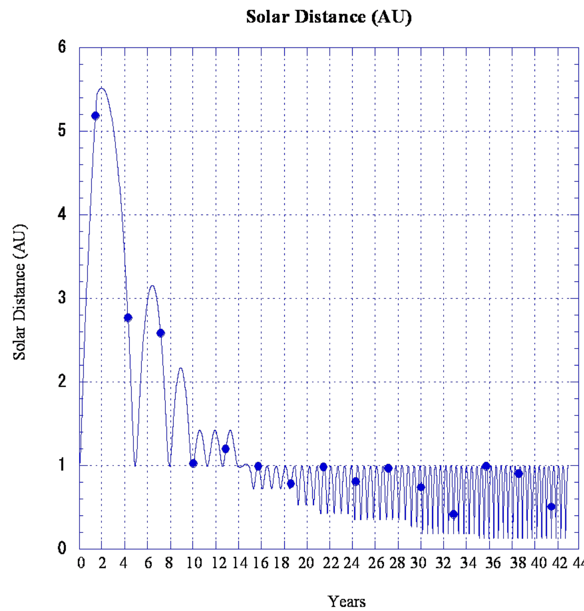

Fig. 8 Distance History for Electrically Propelled Seq.

The Figure-7 and -8 show the solar distance history of the probe. Figure-7 indicates the properties associated with the trajectory amended purely ballistic, while the Figure-8 presents those about the trajectory controlled via a chemical propulsion way. Both show very long flight periods, but it should be noted that the practical observation can start even ten years after the launch.

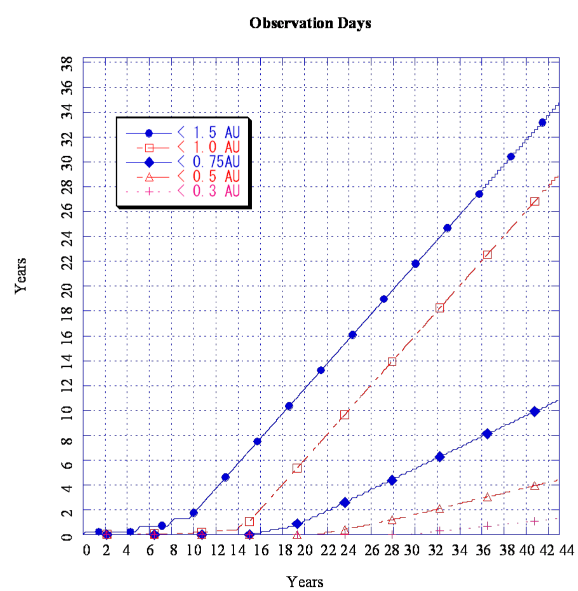

Fig. 9 Availbale Observation Duration

The Figure-9 presents how many days the solar observation is possible. The flight period seems very much prolonged, but the sequence is found very much feasible in terms of how frequently the observation period is provided. From 15 years from the launch the whole flight stays within one AU, and half of the flight is within 0.75 AU beyond 20 years from the launch.

7. CONCLUDING REMARKS

The flight sequence presented here shows the new strategies to have the most concise, the shortest period, the highest inclined orbit is synthesized . The author previously presented the sequence using Venus. However, targeting precise swing-by with respect to the Venus is hardly practical from the navigation accuracy point of view. So, the paper here does not provide those sequence.
And the author also presented before about the use of the combination of both Venus and Earth instead of the use of Jupiter. This paper did not refer to them, as the highest inclination is the primary focus of the paper.

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