天体力学N体力学研究会2012@千葉
October 26, 2012

深宇宙探査技術実験ミッションDESTINYにおける軌道計画の予備検討

Preliminary Study of the Mission Design for Small Engineering Demonstrator, DESTINY

中宮賢樹(京大)

Self Introduction

Masaki NAKAMIYA

WORK EXPERIENCE:

2012 - Present	Mission Researcher, Kyoto Univ.
2009 - 2012	Project Fellow, JAXA/ISAS

EDUCATION:

March 2009	Ph.D., The Graduate University for Advanced Studies (Sokendai) (Prof. H. Yamakawa and Prof. M. Yoshikawa), “Application to Interplanetary Transfer using Dynamical System Theory

INTEREST:

Orbital Mechanics (3-Body problem), Mission Design

CURRENT PROJECT ACTIVITIES

- Space Debris Removal (Orbital change of Debris)
- Engineering demonstrator for future deep space missions, DESTINY (Mission design)
- Small Solar power sail demonstrator, IKAROS project (Guidance)
- Next generation infrared astronomy mission, SPICA pre-project (Orbital design)
- Asteroid exploration, HAYABUSA2 mission (Mission design)

Point of This Presentation

This year's theme: "Spacecraft Trajectory Design"

For the mission design of DESTINY,

1. By using the Optimization problem
2. With the characteristic of Dynamical system theory

Background

What is the DESTINY?

Small Engineering Demonstrator

(Demonstration and Experiment of Space Technology for INterplanetary voYage)

To be proposed to JAXA's 3rd small satellite mission by using the next-generation solid propellant rocket (Epsilon rocket)

Target launch date: FY2018?

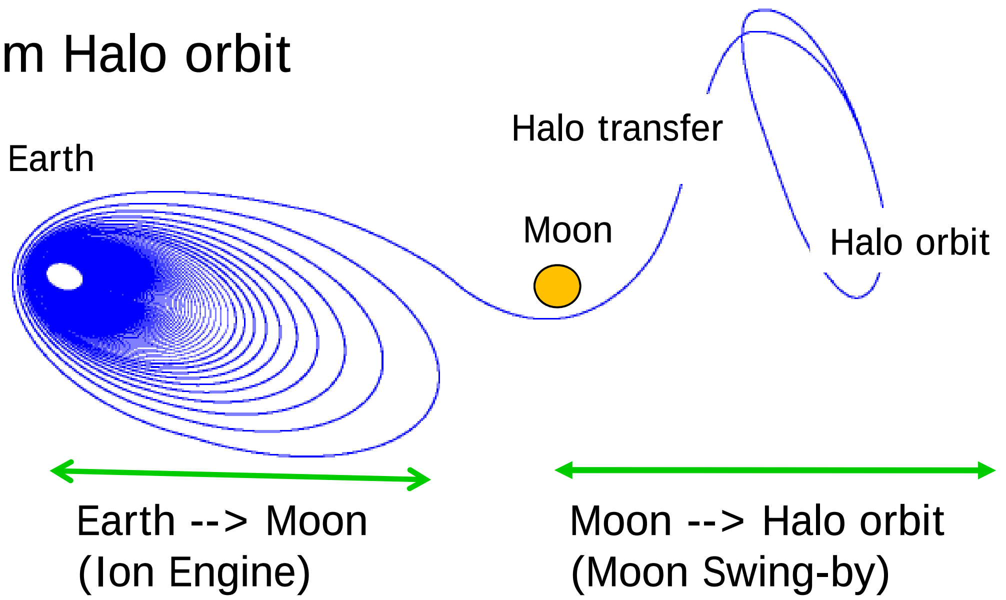
Mission Overview

8 Experiments of the Key Advanced Technologies
for the Future Deep Space Explorations

(1) High energy orbit injection by Epsilon rocket
(2) Thin-film lightweight solar panel
(3) Large-scale ion engine (μ20)
(4) Orbital determination under low thrust operation
(5) Advanced thermal control
(6) Automatic/autonomous onboard operation
(7) Halo orbit transfer and maintenance
(8) Advanced communication technology

Mission Profile

- Nominal
  - To increase the apogee by ion engine
  - To transfer/maintain the Sun-Earth L2 Halo orbit
- Option
  - To put into Earth-Moon Halo orbit
  - To return to the Earth from Halo orbit



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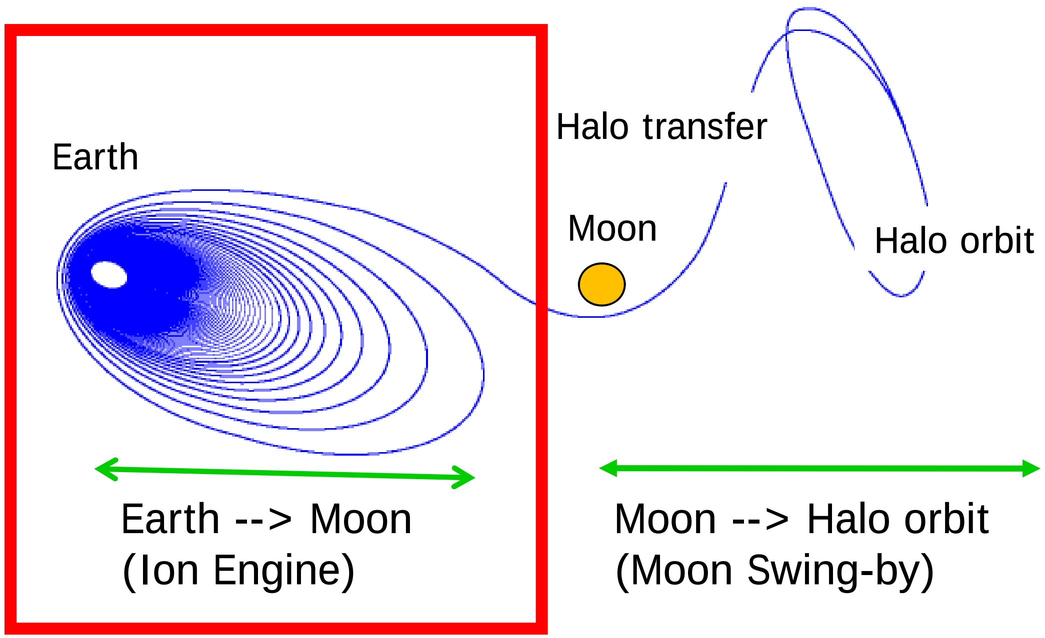
1

A study of the transfer from the Earth to the Moon by Multi-objective optimization problem



Mission Design

<Main request from a trajectory design>
- To minimize consumption of the propellant
- To minimize time of flight

<Specific requirement of DESTINY mission>
- To reduce degradation of the solar array panel especially because spacecraft go through the Van Allen Belt many times

==> Multi-objective optimization problem

To solve the complicated mission design problem under constraints, Multi-objective evolutionary computation (MOEC) is utilized.
- MOEC is robust and it optimizes globally.
- MOEC makes it possible to search for many solutions simultaneously and efficiently with parallel computation.

Objective

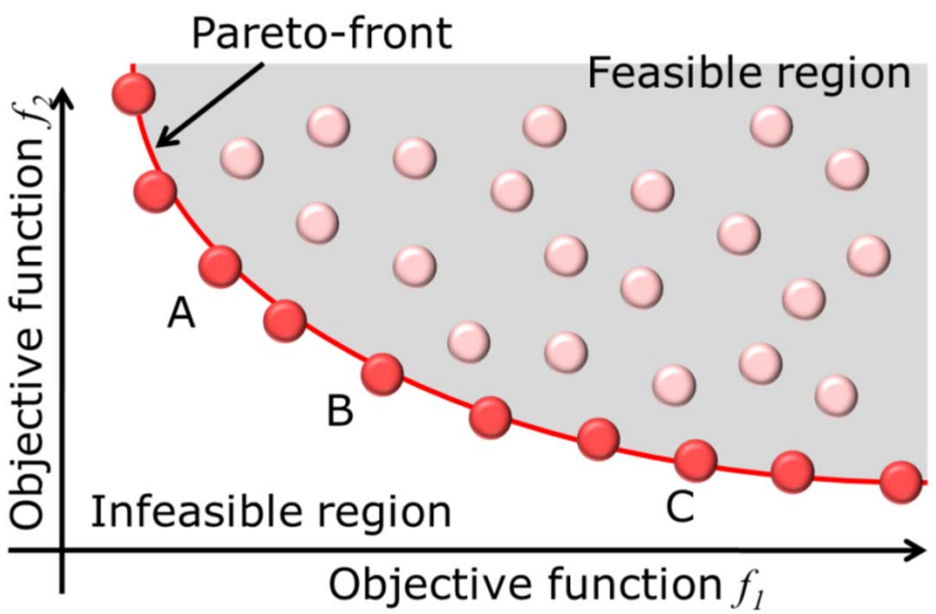
To investigate the mission design of lunar transfer phase in DESTINY by using MOEC

Theory & Assumption

Concept of Multi-objective Optimization

An example of minimizing two conflicting objectives f1 and f2.

- Gray-colored area = feasible region where solutions exist.
- Non-dominated solution: solutions on the edge of the feasible region (A, B, and C)
- These are optimal in the sense that there is no better solution in both objectives.
- One cannot say which is better among these non-dominated solutions because improvement in one objective degrades another.



Assumption

Parameters of Orbit propagator

<Initial orbit>
150 x 29000 km, LAN = 25 deg, inc = 32 deg, argp = 124 deg, MA = 5 deg
(by Epsilon rocket from the Japanese Launch site)

<Ion Engine System (IES)>
Thrust = 40 mN, Isp=3800 s, Accelerated direction = Tangential to velocity

<Spacecraft Wet Mass>
400 kg

<Dynamical model>
Ephemeris of the Earth, Moon, Sun

Assumption

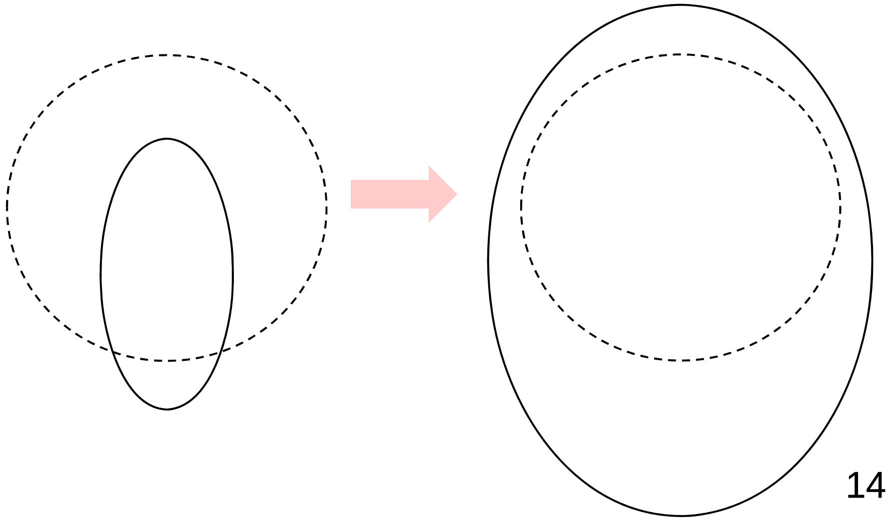
Condition and Strategy of Orbit propagator

<Stop Condition of propagator>

- Approach the moon within 20000 km
- Ascending/Descending distance > 380000 km
  (Not consider the lunar encounter)

<Strategy of IES control>

0: Initial orbit (150km x 29000km)
1: Perigee UP control to pass through the Van Allen Belt (below 20000km) ASAP!
2: Apogee UP control (until the Moon)



Overview of MOEC optimization

Objectives

(1) Minimization of the transit time below 20000 km (h2e4km)

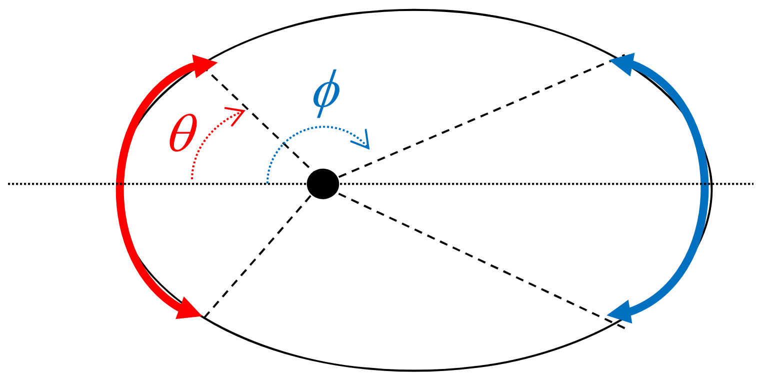
(2) Minimization of the transfer time to the Moon (TOF)

(3) Minimization of the operation time of ion engine (IES)

Overview of MOEC Optimization

Design Parameters

- StartDate/Time (2017.1.1 ~ 2018.1.1)
- Range of use of IES for Perigee UP, 180 $\pm(180 - \phi)$ deg (ϕ : 0 ~ 180 deg)
- Range of use of IES for Apogee UP, 0 $\pm\theta$ deg (θ : 0 ~ 180 deg)
- Change time of switching control from peri UP to apo UP (90 ~ 365 day)

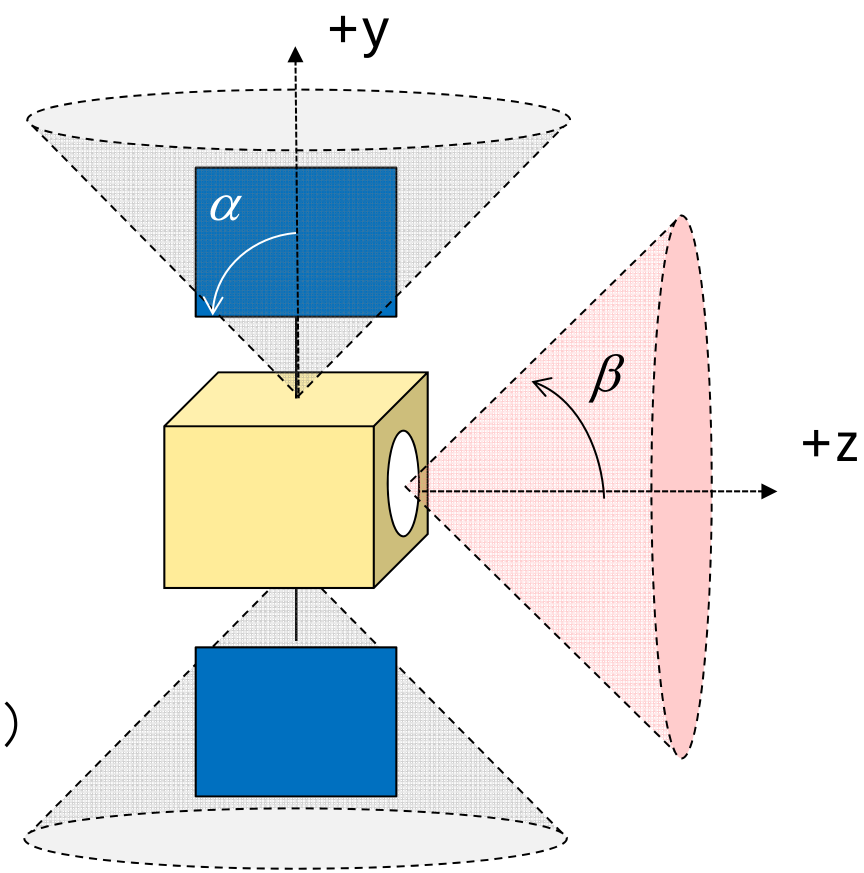


Overview of MOEC Optimization

Constraints

<Unusable IES>

- For the first month from launch
- Eclipse
- Duration of small solar incident to y-plane of spacecraft (alpha)
- Duration of small solar incident to z-plane of spacecraft (beta)
- （Duration of small power generation）



Assumption

MOEC Parameters

Item	
Algorism	NSGA－II
Seed of pseudo random number	0.1
Population size	300
Number of generation	200
Crossover probability	1.0
Mutation probability	0.05
Index of crossover distribution	5
Mutation distribution	10

Optimization Results

Test Case

Island	Thread	Population x generation	Sun incident angle α	Sun incident angle β
1	8	300 x 200	60 [deg]	0 [deg]

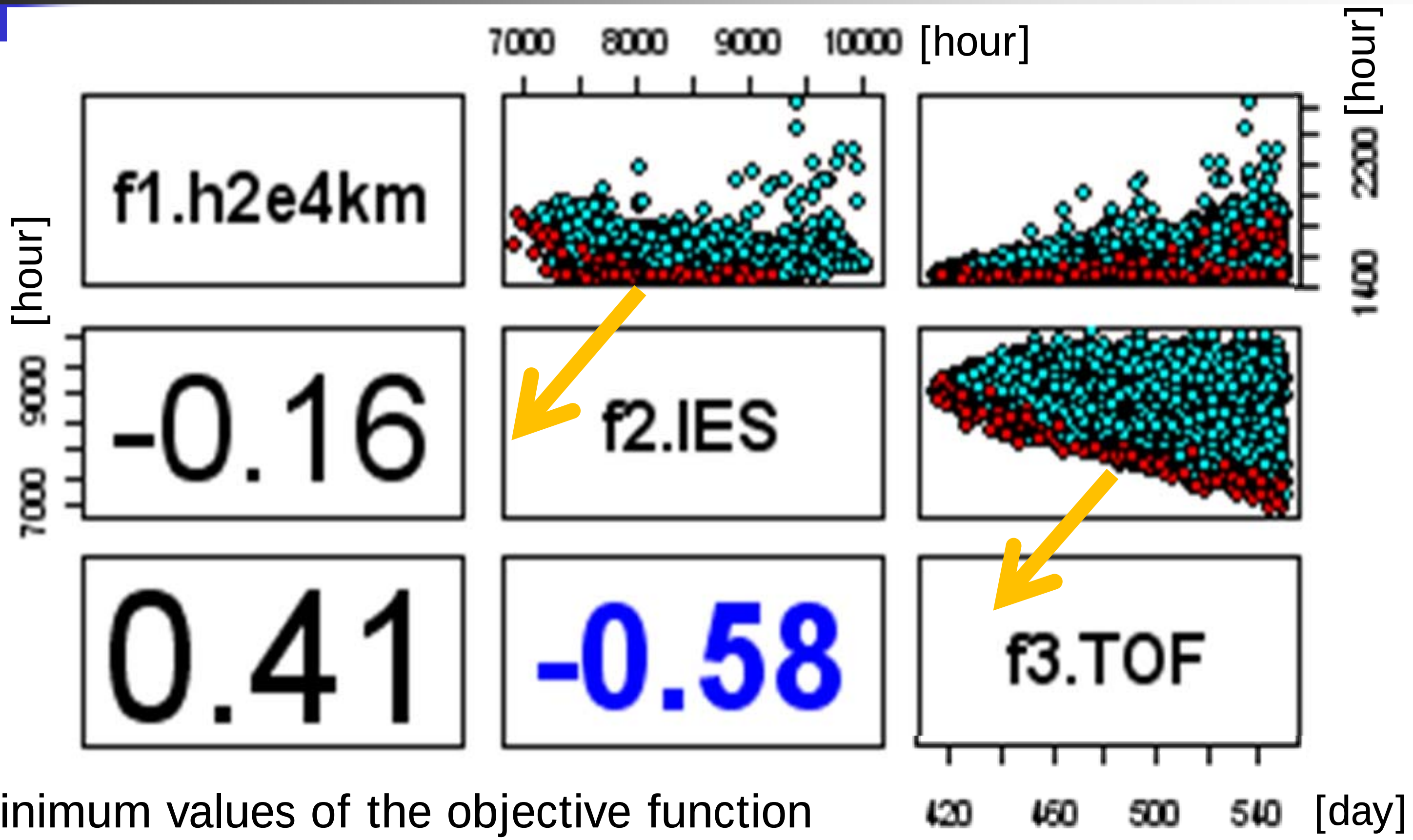
Computation time: 39 hours (Core i7 @ 2.93GHz)

Number of Non-dominated solutions = 137 (TOF < 1.5 years)

Scatter Plot Matrix

Relation between objective functions

Non-dominated solutions
Dominated solutions

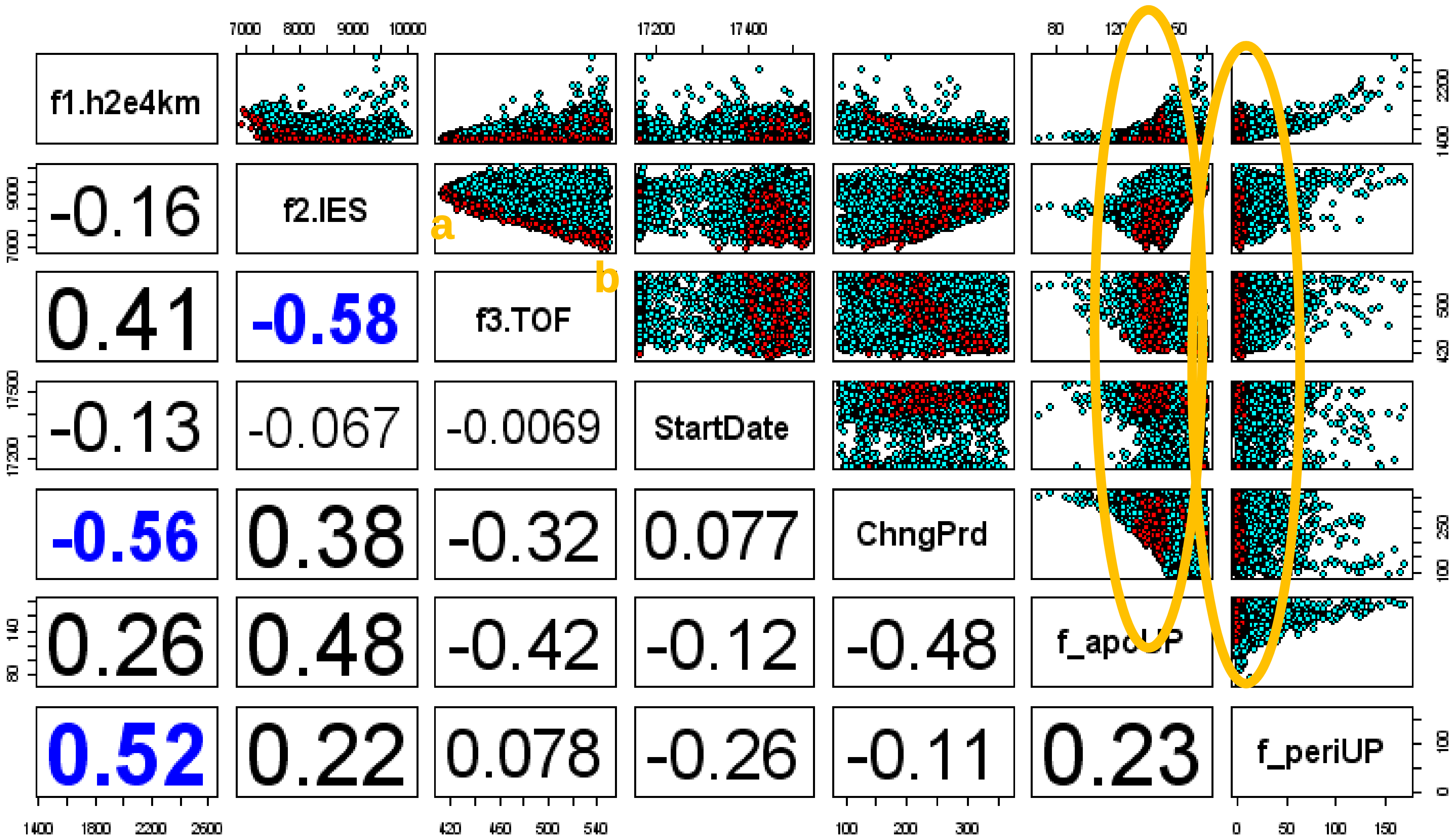


Minimum values of the objective function

- Transit time below 20000 km: about 1400 hour
- IES operation time: about 6900 hour
- Time of flight: about 410 day

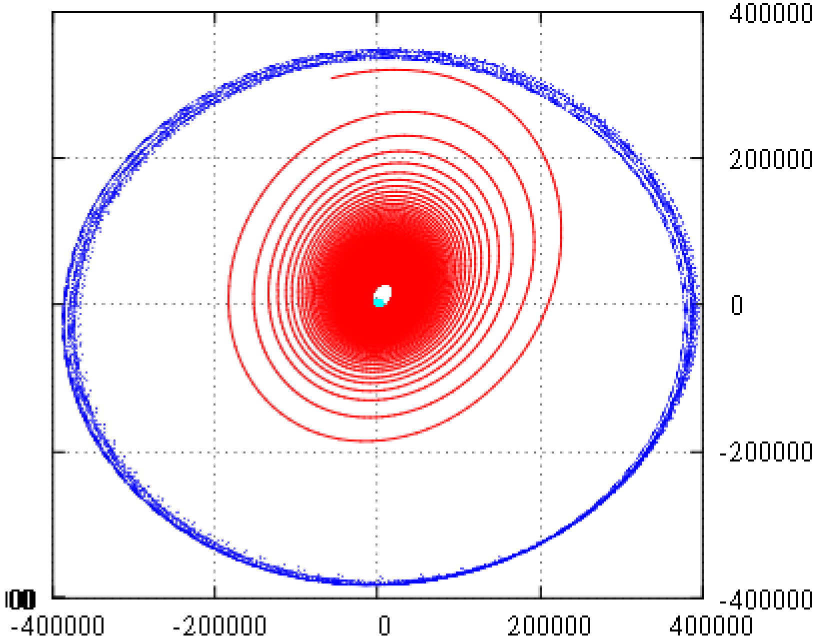
Scatter Plot Matrix

Relation between objective function and design parameter



Example Trajectory

Minimum TOF (case a)



Geocentric equatorial coordinate

<Parameters>

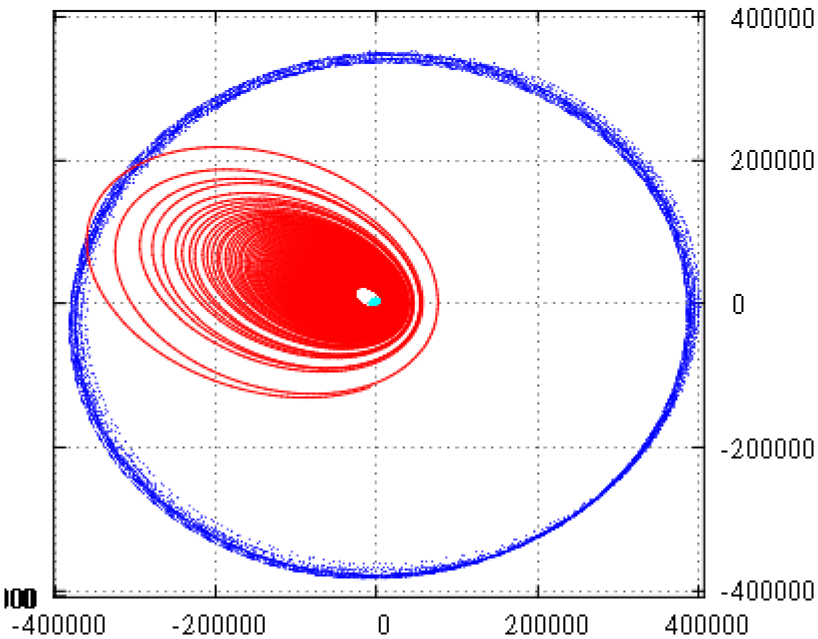
StartDate: 2017/10/10 04:39:10
ChangeDate: 231.162 day
PeriUP: 180±175.1 deg (ϕ = 4.9)
ApoUP: 0±178.2 deg (θ = 178.2)

<Result>

Time below 20000km：1463 hour
IES operation: 8971 hour
TOF: 412.6 day
Revolution: 486 times

Example Trajectory

Maximum TOF (case b)



Geocentric equatorial coordinate

<Parameters>

StartDate: 2017/12/27 04:39:42

ChangeDate: 226.026 day

PeriUP: 180±179.6 deg (ϕ = 0.4)

ApoUP: 0±133.4 deg (θ = 133.4)

<Result>

Time below 20000km：1445 hour

IES operation: 7315 hour

TOF: 549.6 day

Revolution: 528 times

Summary

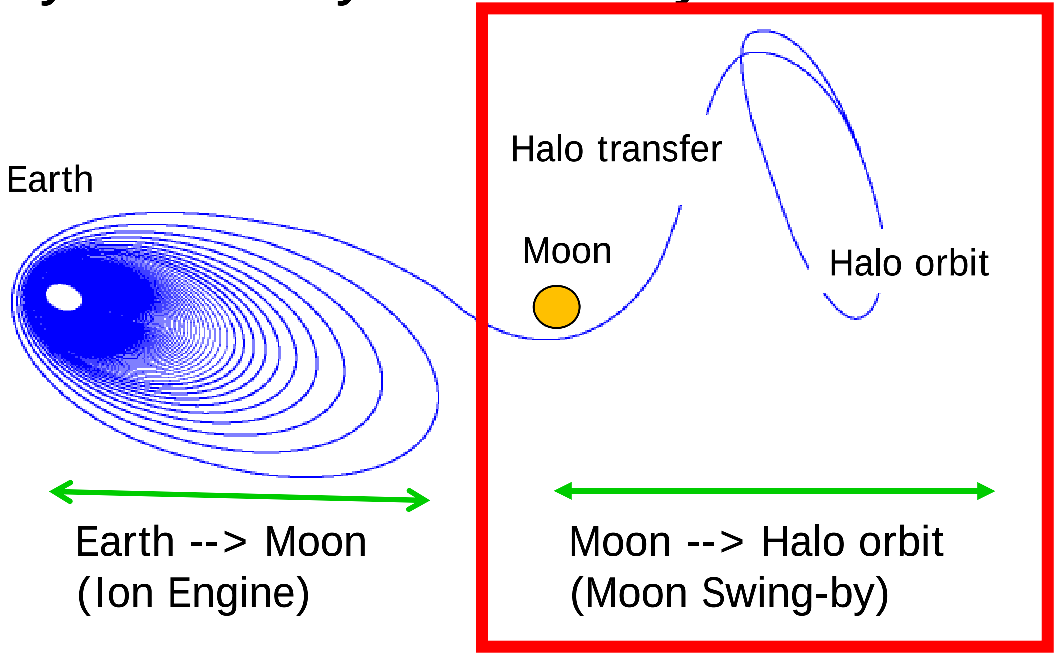
1. Investigated the mission design of lunar transfer phase in DESTINY by using GA Multi-objective optimization.

2. Found relations between objective function and design parameter
   - Tradeoff among IES operation time, duration 20000km and TOF

3. Obtained minimum values of the objective function
   - Transit time below 20000 km: about 1400 hour
   - IES operation time: about 6900 hour
   - Time of flight: about 410 day

2

A study of the transfer from the Moon to the Sun-Earth Lagragian point with Dynamical system theory



Objective

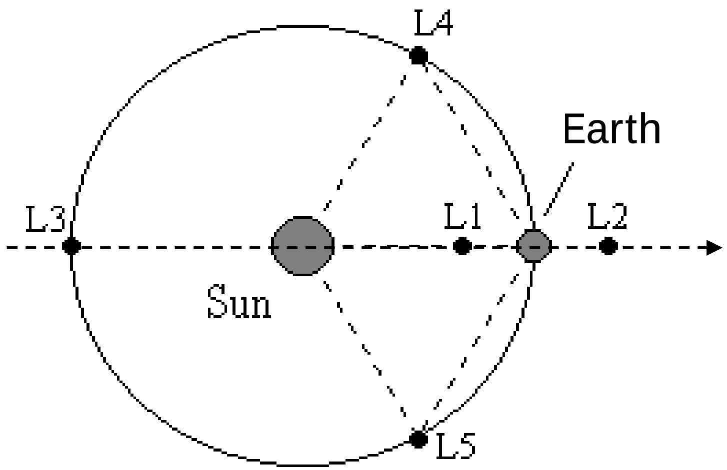
To investigate the ΔV and TOF for the transfer
from the Moon to Sun-Earth Halo orbit with the invariant manifold

1. Characteristics of the Dynamical System
(Halo orbit, Stable manifold)

Lagrange Point

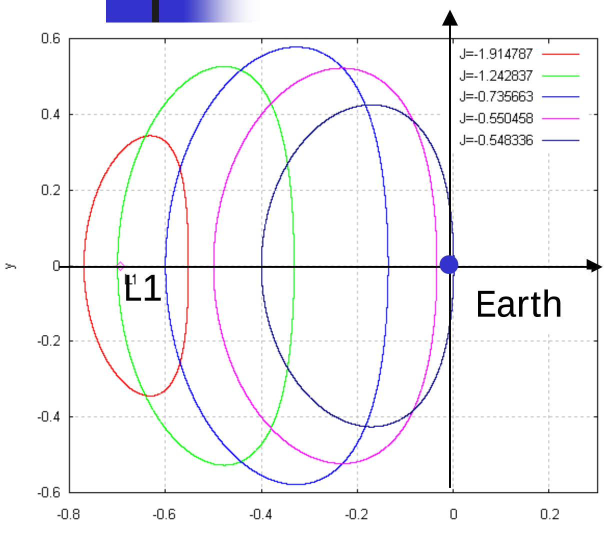
- Equilibrium point where the gravities of the primaries are balanced
- Exit five Lagrange points in a system

Sun- Earth L1&L2: about 1.5 million km from Earth
Earth-Moon L1&L2: about 60000 km from Moon

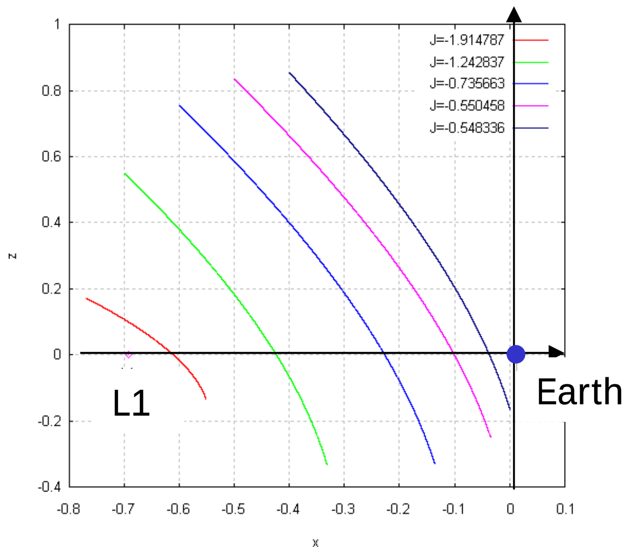


Halo Orbit

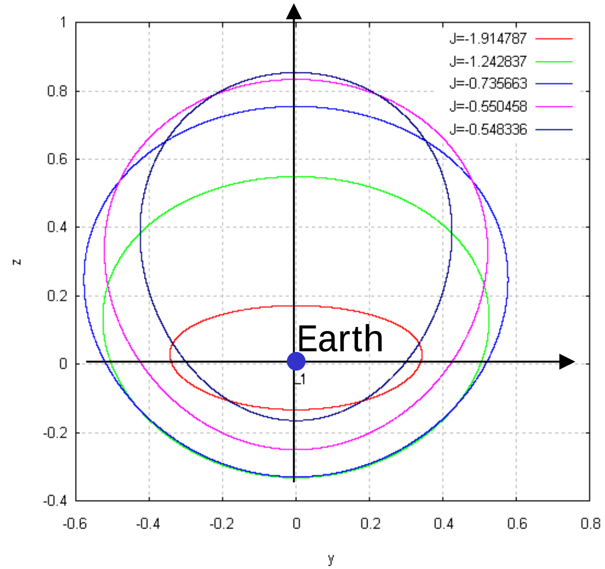
(Sun-Earth L1)



X-Y plane



X-Z plane

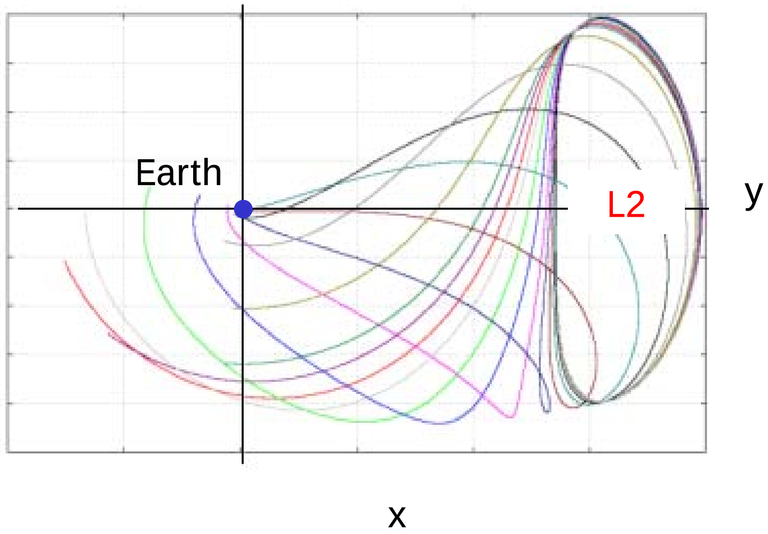


Y-Z plane

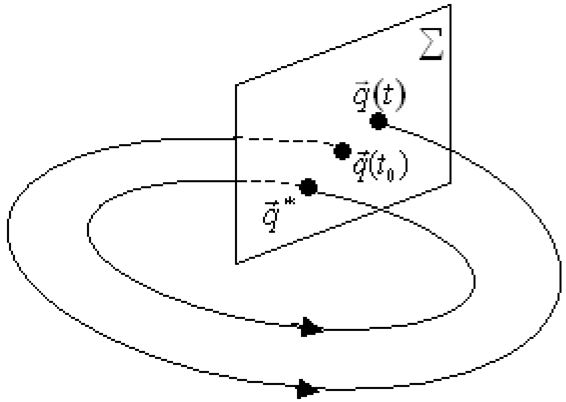
- 3D periodic orbit around Lagrange point
- Size depends on the orbital energy

Stable Manifold

Eigenstructure associated with the Halo Orbit



- Trajectories to converge Halo naturally
- Allow us to avoid critical operation
- Propagating the displacement of stable direction from Halo, backward in time



State Transition Matrix
for a period of the Halo orbit

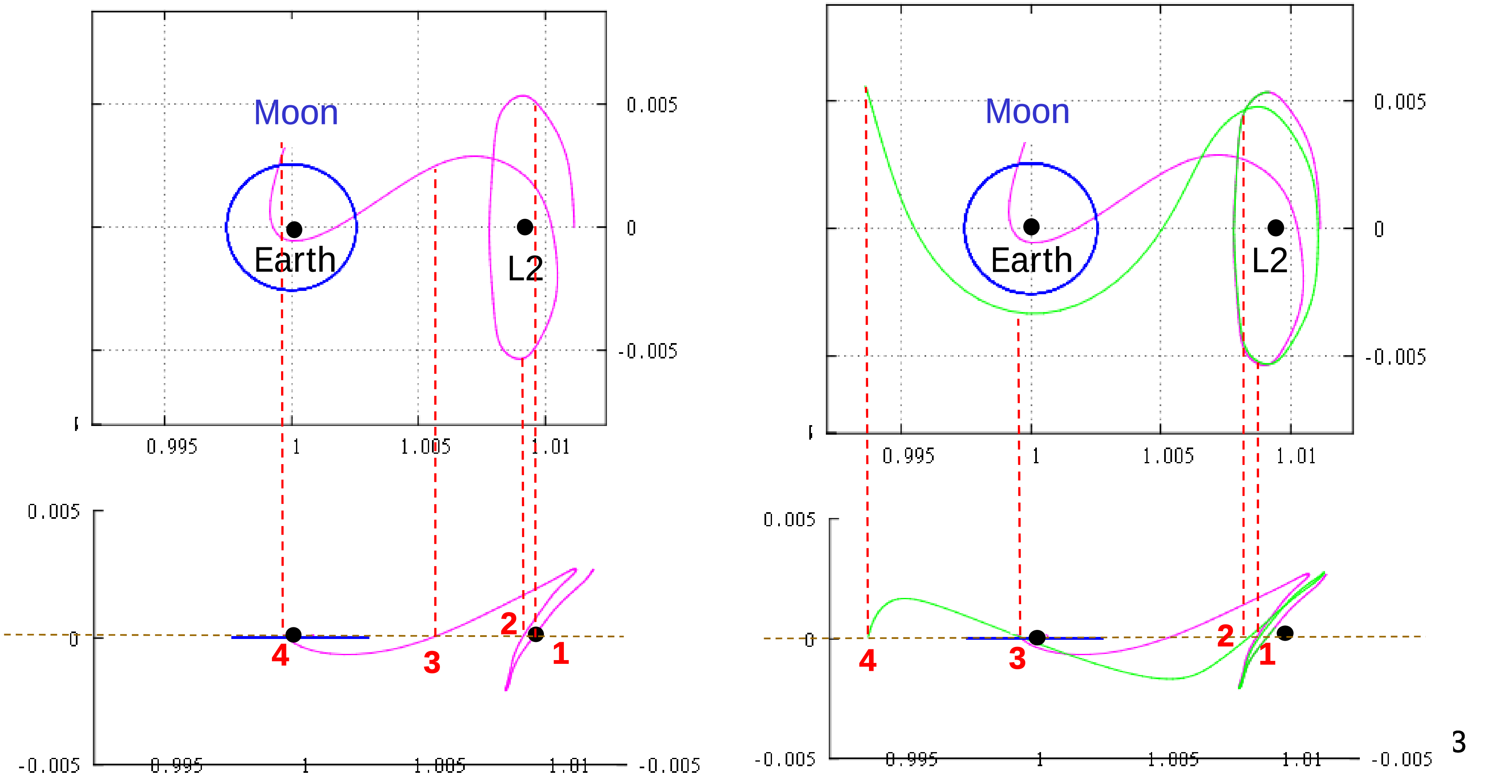
e.g.) $\lambda^{-1} \cong 1/1500$

$$M_J = \begin{pmatrix} \begin{matrix} \lambda & 0 \\ 0 & \lambda^{-1} \end{matrix} & & 0 \\ & \begin{matrix} 1 & \varepsilon \\ 0 & 1 \end{matrix} & \\ 0 & & \begin{matrix} \cos\Gamma & -\sin\Gamma \\ \sin\Gamma & \cos\Gamma \end{matrix} \end{pmatrix}$$

2. Transfer from the moon to the Halo orbit using the stable manifold

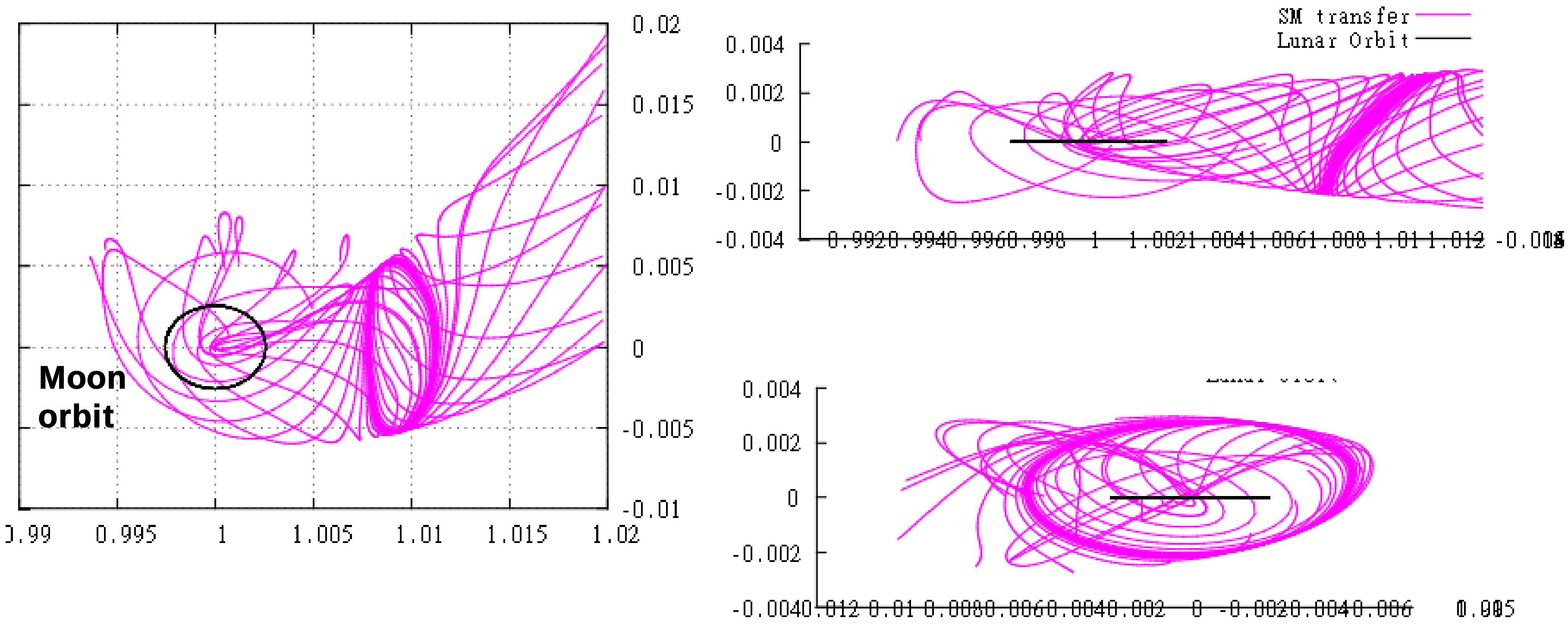
Characteristics of the Stable Manifold

Propagating backward in time until 4th intersection
at Ecliptic plane from the Halo orbit



Characteristic of the Stable Manifold

Propagating until 4th intersection at Ecliptic plane from Halo orbit



Connectivity of Stable Manifold with Moon

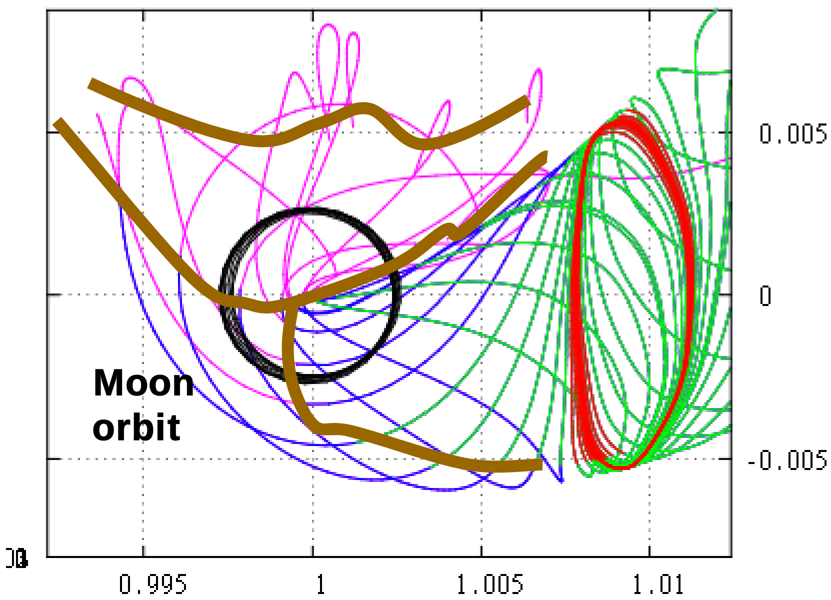
Extraction conditions of connection point

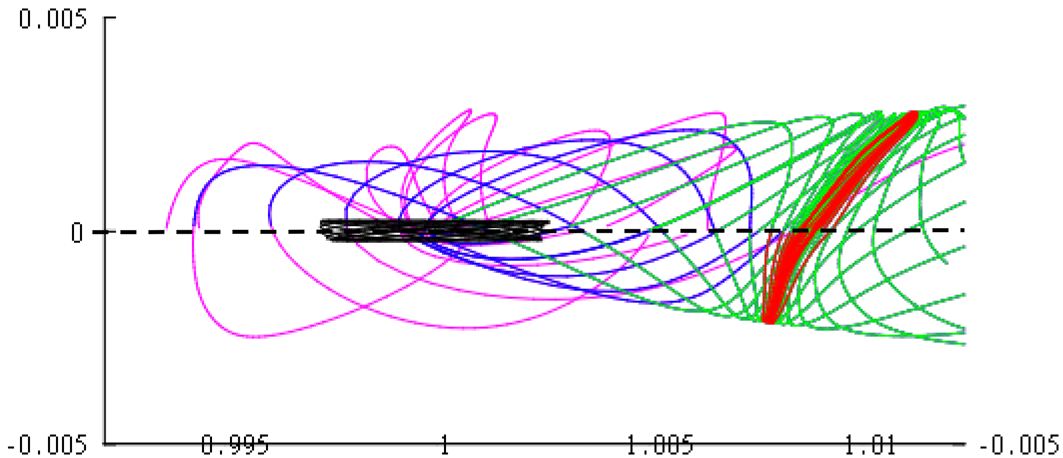
1: Intersections of stable manifold with Ecliptic plane
(≈ Moon's orbit plane)

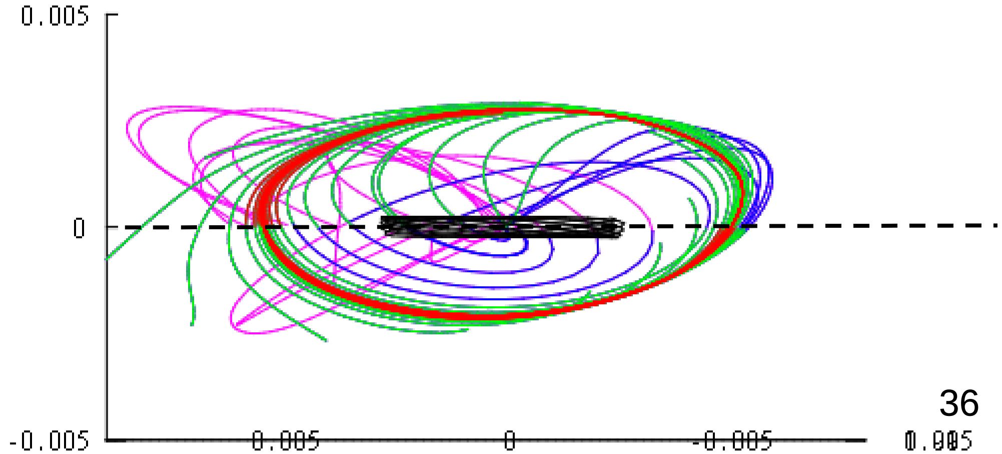
2: The distance from geocentric is about 380000 km

Connectivity of Stable Manifold with Moon

Stable manifold in different colors with every intersect
with Ecliptic plane from Halo orbit



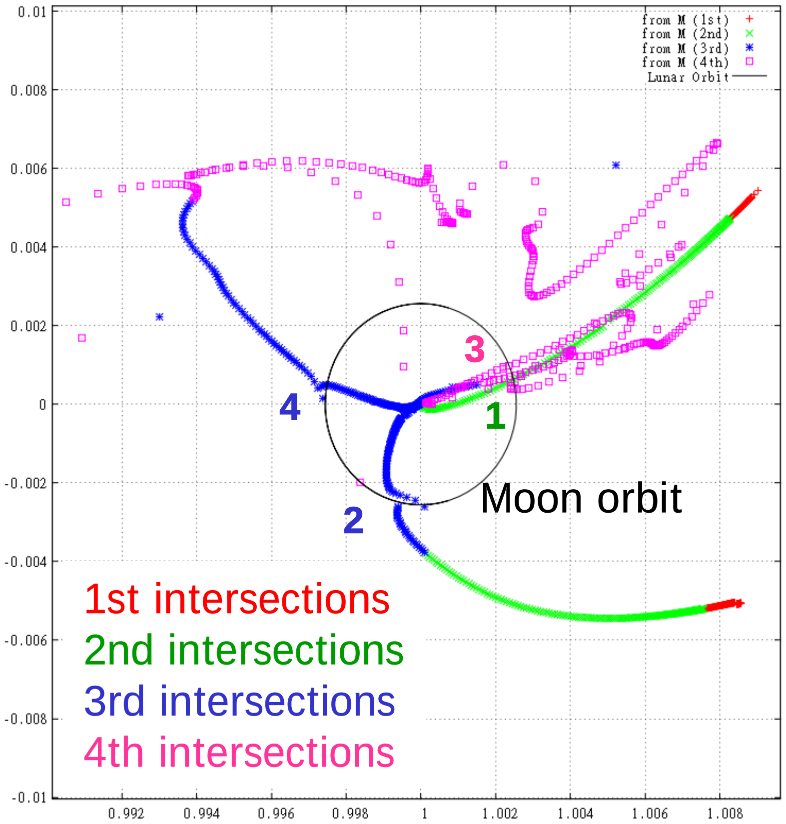


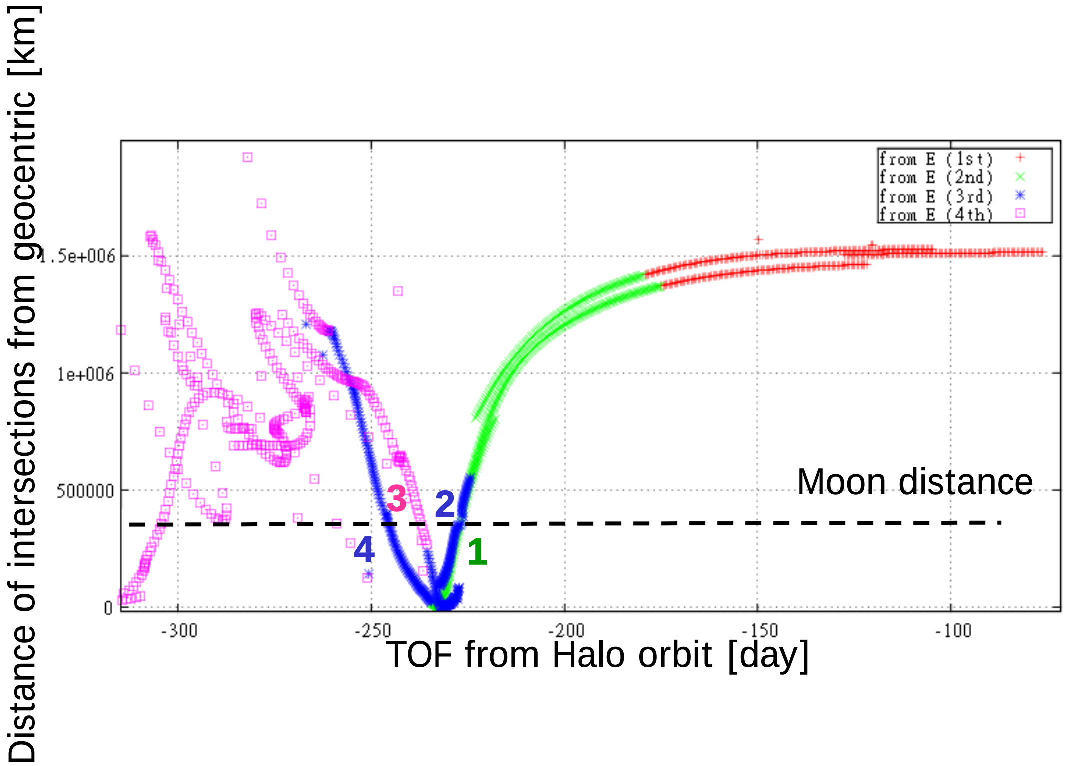


From Halo to 1st intersection
From 1st intersection to 2nd
From 2nd intersection to 3rd
From 3rd intersection to 4th

Connectivity of Stable Manifold with Moon

Characteristic of the intersections

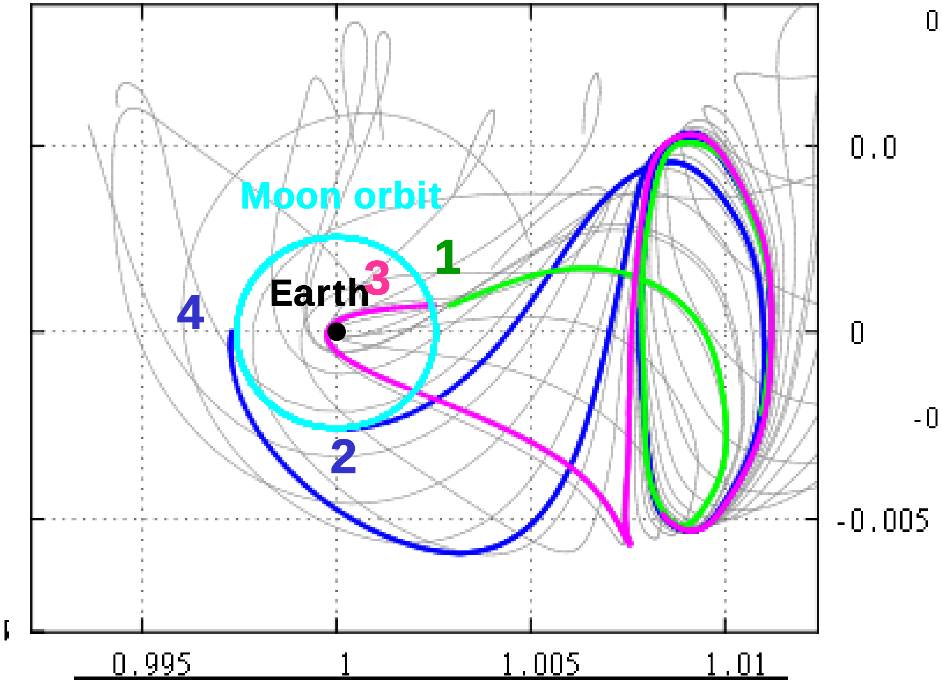




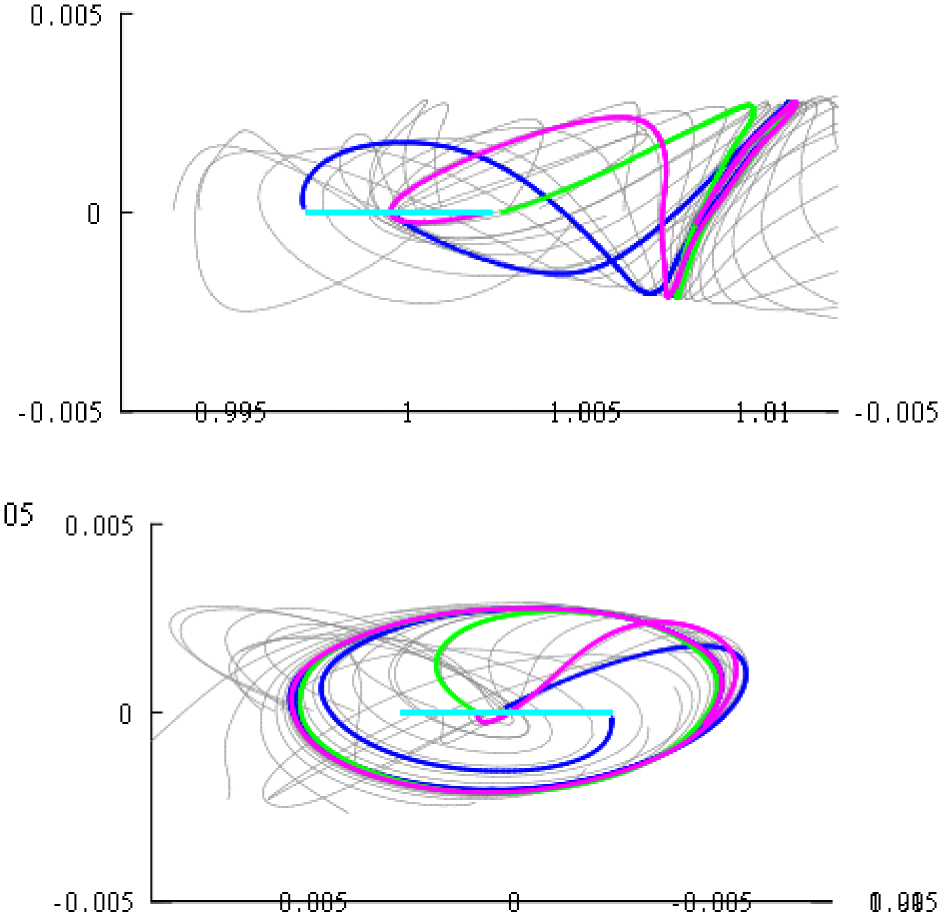
Four solutions !

TOF is about 230 days !

Example of Transfer Trajectories from Moon to Halo orbit



	Relative V to Moon	TOF
1	1390 m/s	227日
2	400 m/s	226日
3	1520 m/s	237日
4	420 m/s	245日



Conclusions

Transfer trajectories from the Moon to the Halo orbit by using stable manifold for DESTINY was investigated.

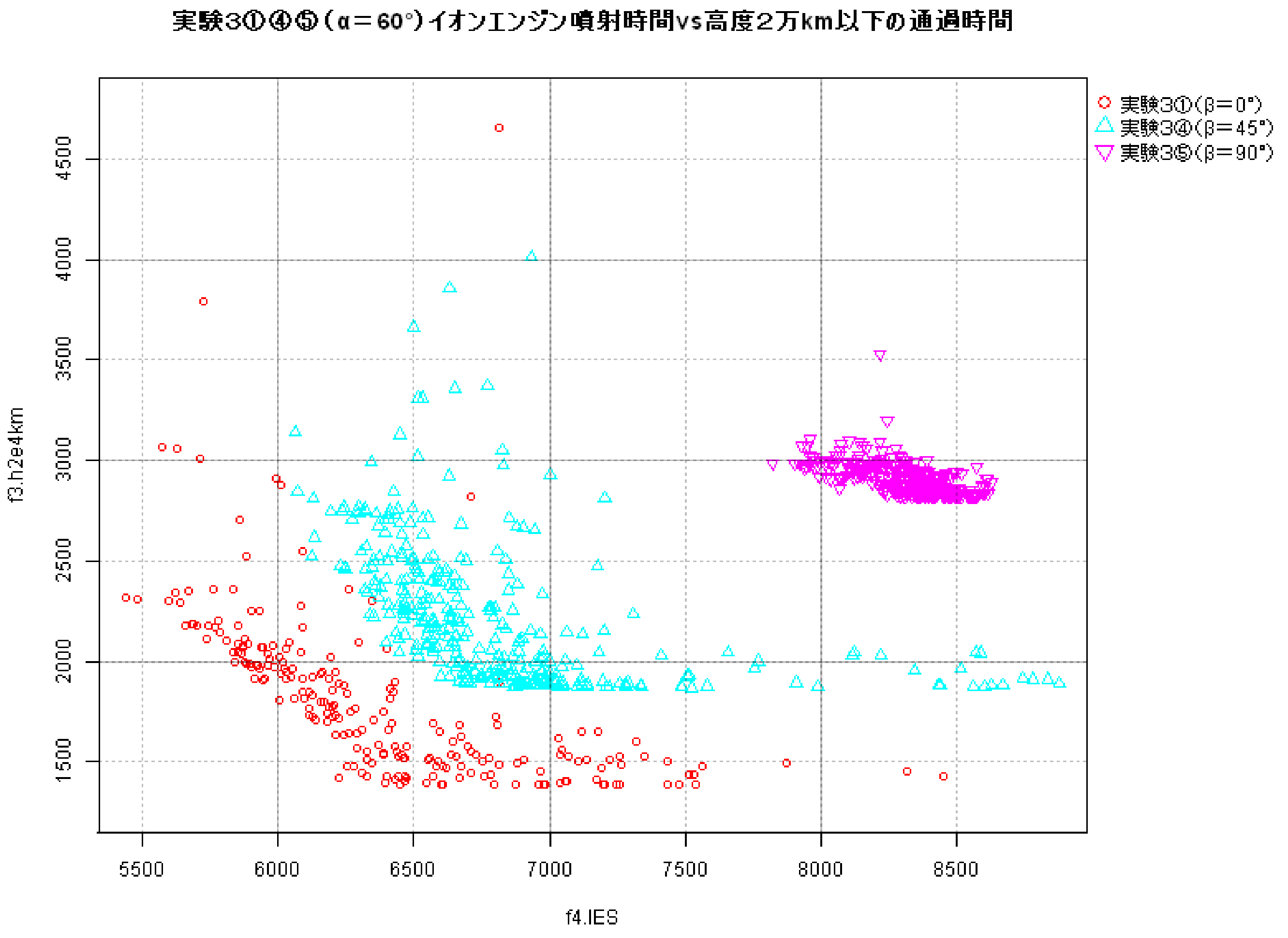
- Required velocity at the Moon : 400 m/s ~
- TOF from Moon to Halo orbit: 226 days ~

Thank you for your attention!

DESTINY

Apogee altitude vs. IES operation time

DESTINY

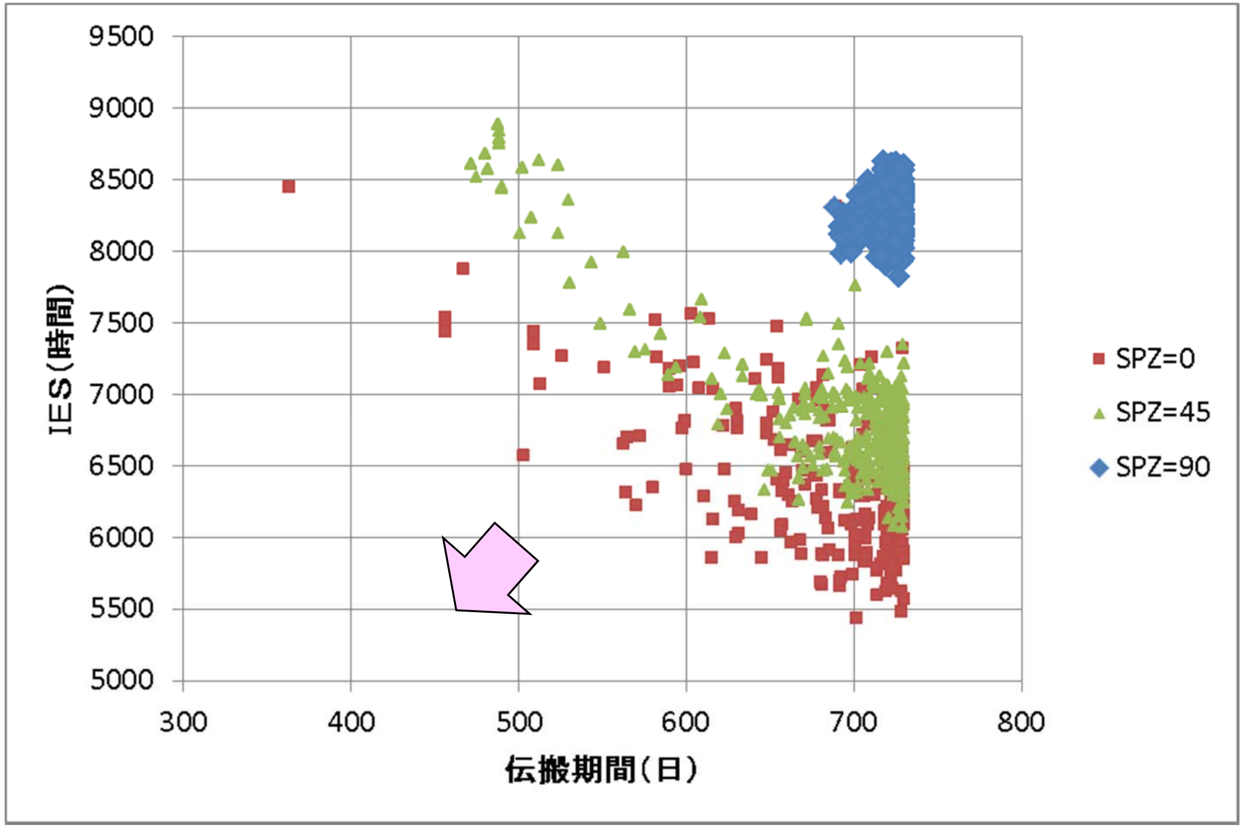


地球中心赤道面座標系

多目的GA結果（システム制約）

SPZ角の感度解析「伝搬期間 vs IES時間」
（ランク=1, 近点>2万km, 30万km<遠点<40万km, 伝搬期間<730日）

IES時間を小さくしようとすると、伝搬期間が長くなる

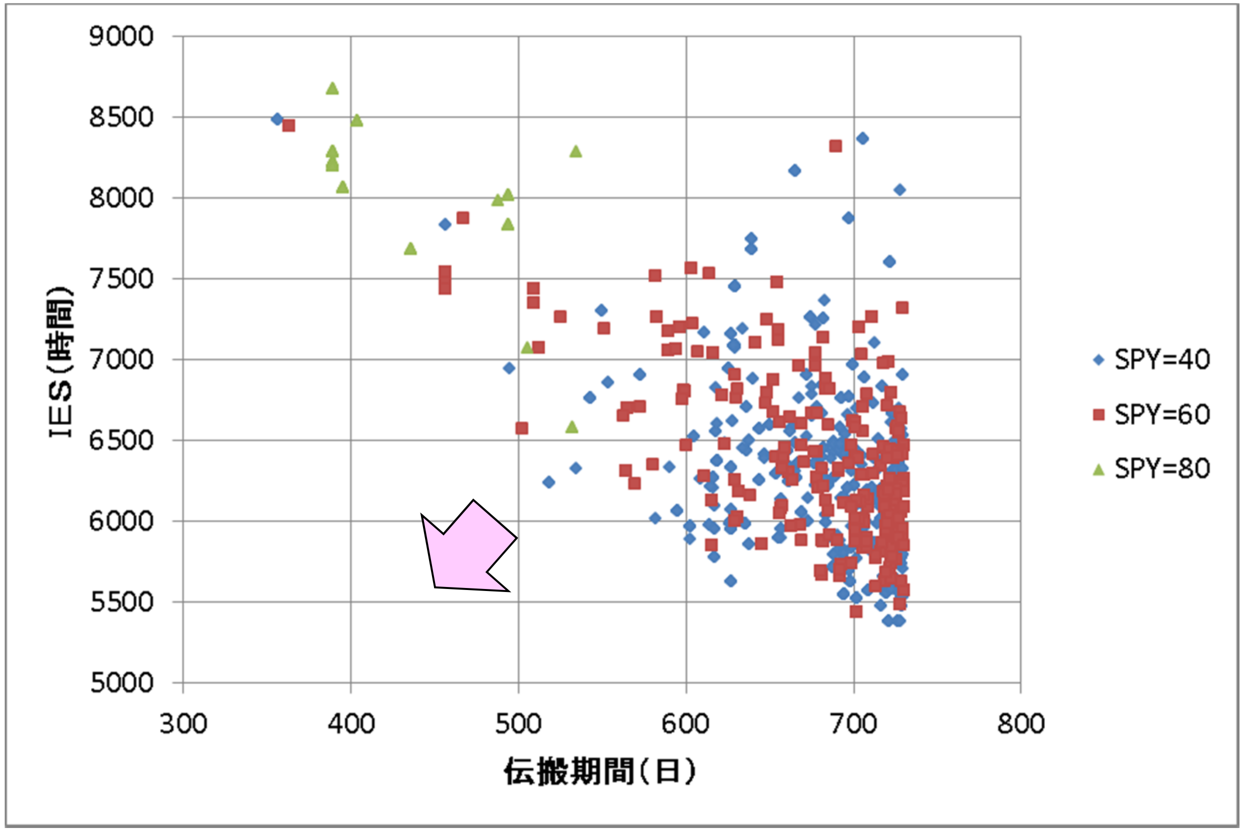


多目的GA結果（システム制約）

SPY角の感度解析「伝搬期間 vs IES時間」

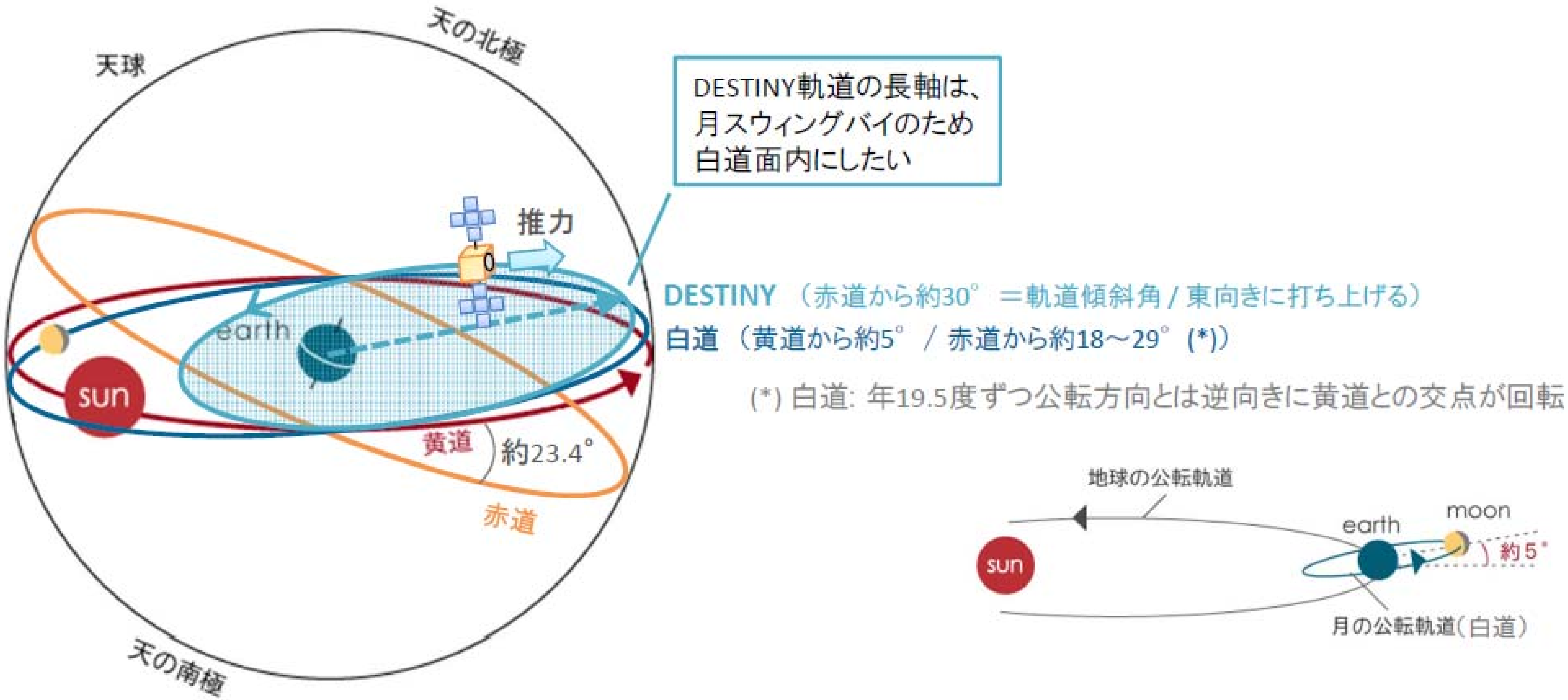
（ランク=1, 近点>2万km, 30万km<遠点<40万km, 伝搬期間<730日）

SPY角をふっても同じ傾向（分布は異なる）



1．1．高度上昇フェーズ（基本）

ジオメトリ（システム設計の観点から）



（図：廣瀬）