PRELIMINARY DESIGN OF THE PHASING STRATEGY OF THE LUNAR ORBIT RENDEZVOUS OPERATION FOR A SAMPLE RETURN MISSION

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Introduction

- For previous robotic lunar sample return missions, the lunar soil samples were delivered back to Earth by a vehicle taking off from the lunar surface and flying directly back to Earth.

- In this paper, a mission concept is considered in which the lunar sample is transferred to an orbiting spacecraft first through an unmanned lunar orbit rendezvous operation, and then the orbiter will transport the lunar sample back to Earth.

- The discussion is focused on the phasing strategy design of the lunar orbit rendezvous operation:

  - A 4-impulse phasing strategy is selected as the baseline design to help achieve the basic goal of the phasing stage of the lunar orbit rendezvous operation for the sample return mission.

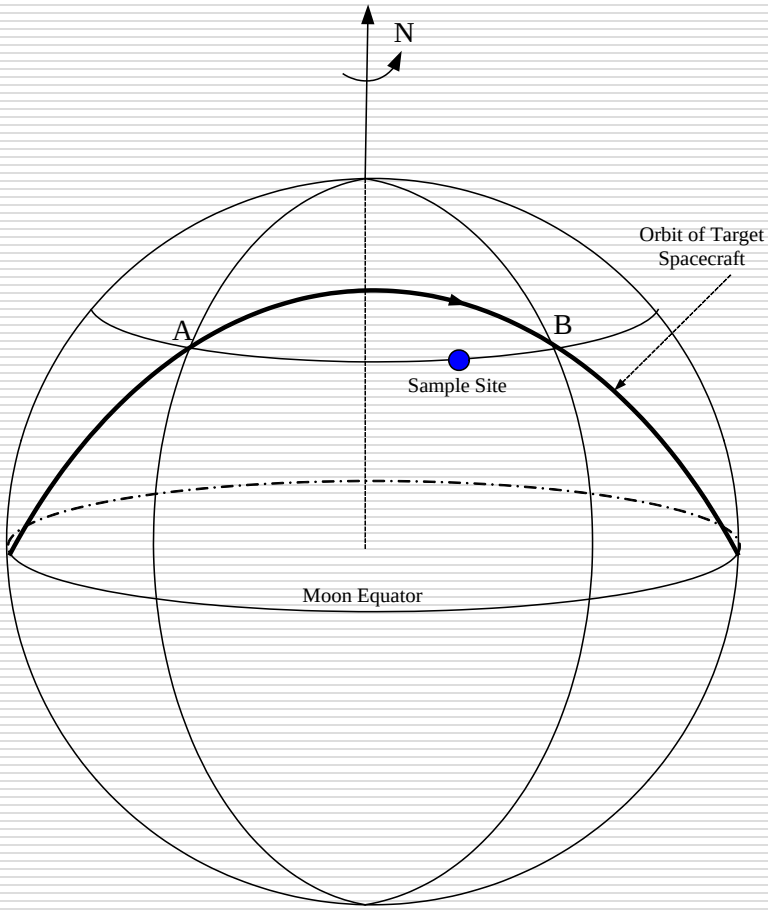
  - An optimal nominal phasing strategy is developed based on the analysis of tracking access and lighting conditions.

  - An orbit control strategy is devised to compute the maneuvers for actual rendezvous flying.

  - A discussion of aim point dispersion analysis using Monte Carlo simulations.

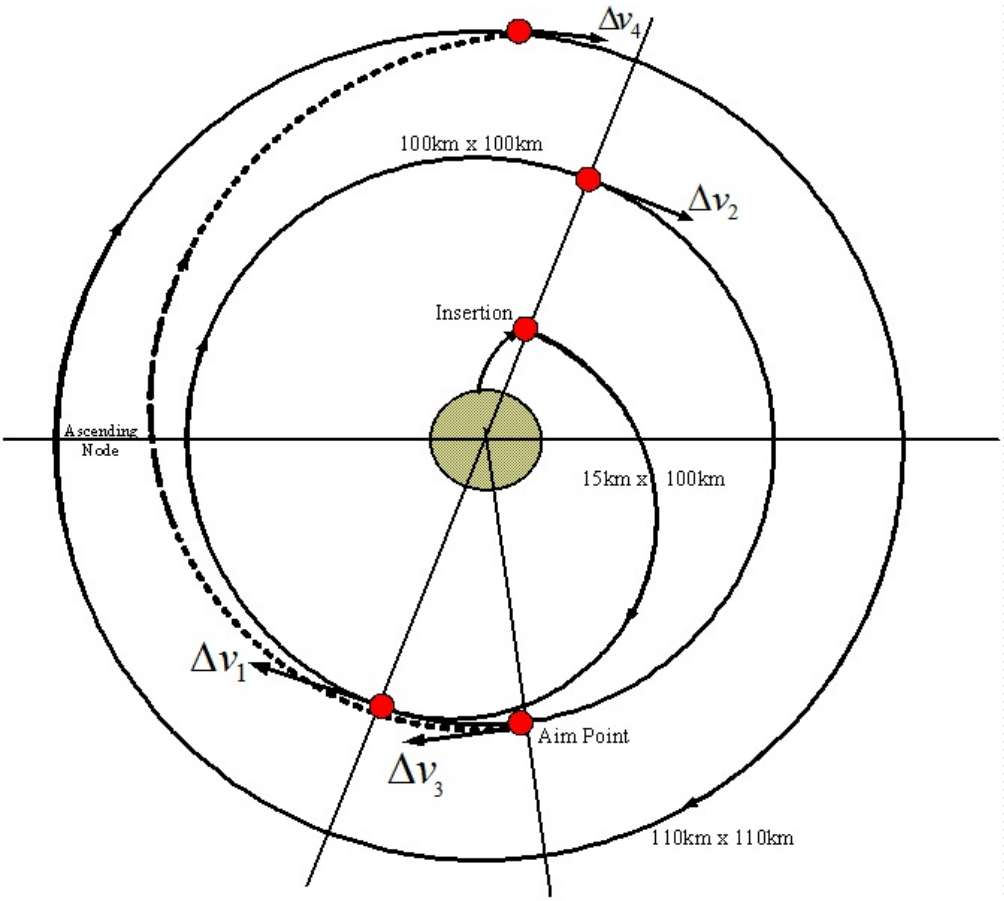
  - The test.

Problem Statement



- Initially the orbiter is in a 110km x 110km circular lunar orbit, and the chaser with the collected lunar soil sample is waiting at the sample site on the lunar surface.
- Ideally, when the sample site passes the orbit plane of the orbiter (point B) due to the spin of the Moon, the chaser takes off from the lunar surface, and enters a 15km x 90km initial orbit.
- The phasing stage starts at the lunar orbit insertion and ends when the prescribed aim point is achieved by the chaser. Upon reaching the aim point, on-board relative navigation capability should have been achieved and the far range rendezvous stage starts, followed by the close range operation and docking.
- The design of the maneuver strategy in the phasing stage is the focus of this paper.

SELECTION OF PHASING STRATEGY:
2 delta-v Scheme

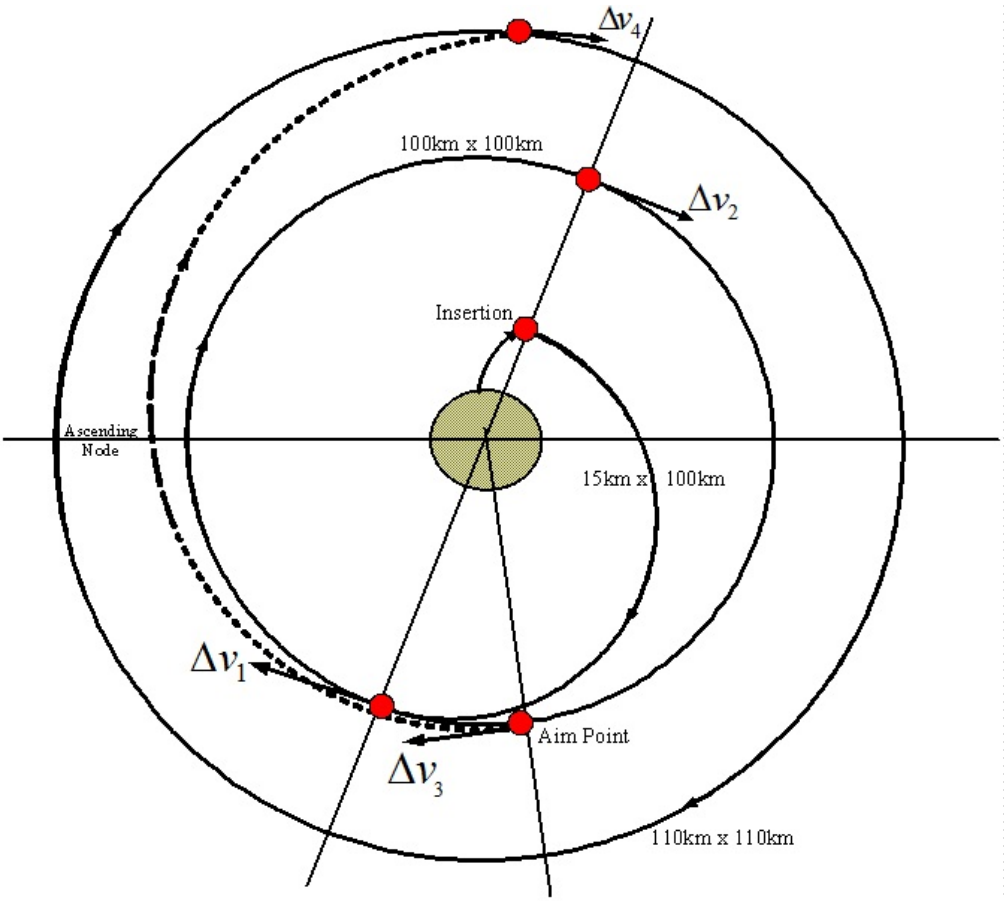


- The chaser makes an orbit maneuver (dv1) at the 1st apoapsis passage after entering the initial 15km x 100km lunar orbit; half revolution later, the chaser makes a comprehensive correction maneuver (dv2) with nominal value 0m/s, then coasts to the aim point. These two maneuvers can be computed using the Lambert algorithm.

- Also shown are the other two Lambert maneuvers (dv3, dv4) in the far range rendezvous stage, in which the chaser approaches the orbiter on 110km x 110km orbit until it arrives at the station-keeping point a few kilometers behind the orbiter.

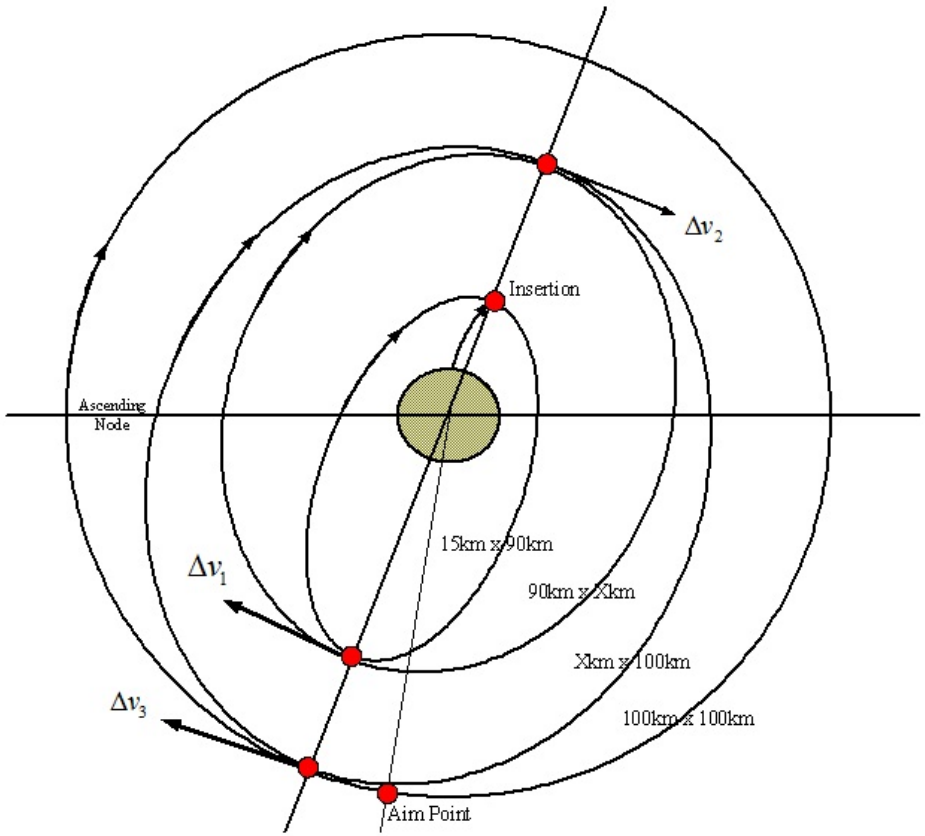
- Ideally the chaser would take off from the lunar surface when the sample site passes the orbit plane of the orbiter. However, the lunar ascent may occur earlier or be delayed for some reasons, and the powered ascent may lead to significant lunar orbit insertion errors. Therefore, orbit plane corrections is needed.

SELECTION OF PHASING STRATEGY: 2 delta-v Scheme (continue)



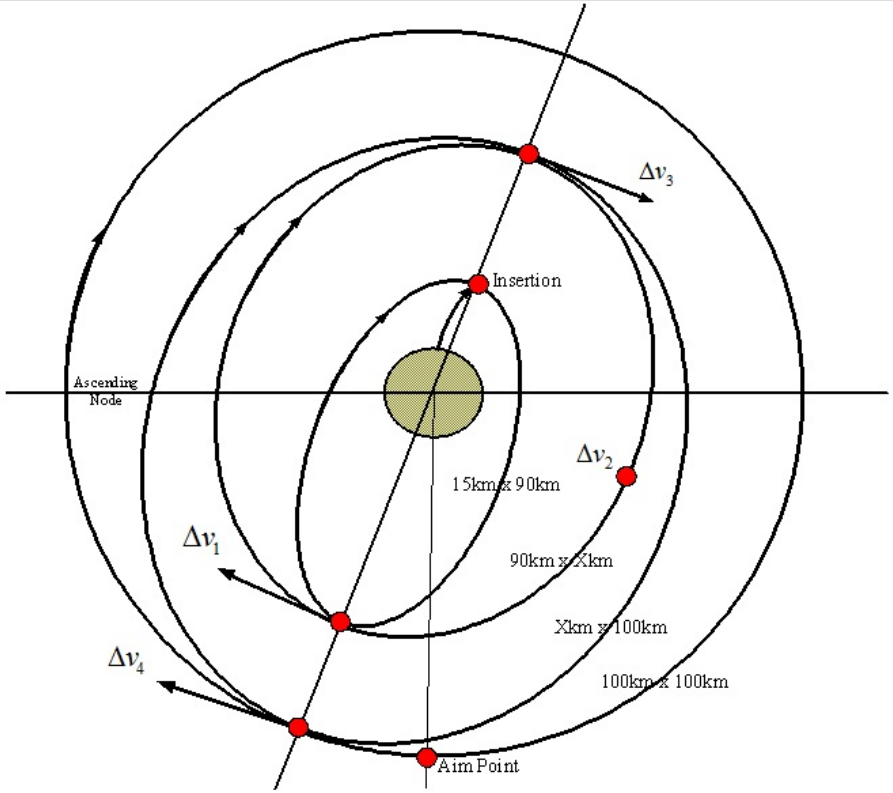
- For the 2-dv scheme, each dv may have two components: one transverse component for correcting semi-major axis, eccentricity, argument of periselene, and one normal component for orbit plane correction.
- If the maximum range of the relative navigation device cannot meet the needs in the phasing stage, then the determination of position and velocity of the vehicle can only rely on an inertial navigation system (IMU), which can leads to unacceptably large position and velocity errors at the aim point.
- The 2-dv scheme is not recommended for the mission of this study.

SELECTION OF PHASING STRATEGY:
3 delta-v Scheme



- After applying the phasing maneuver dv1 at apoapsis, the chaser enters the 90km x Xkm phasing orbit, where 'X' denotes an adjustable orbit altitude.
  - The 2nd maneuver dv2 is used to raise the apoapsis to 100km altitude (altitude maneuver).
  - The 3rd maneuver dv3 is used to circularize the orbit to achieve the 100km x 100km final orbit of the phasing stage (circularization maneuver).
- Both dv2 and dv3 have two components: one transverse component for in-plane orbital parameter correction, and one normal component for orbit plane correction.
  - The arguments of latitude of dv2 and dv3 are not efficient for inclination correction, and may lead to a significant dv for orbit plane correction.

SELECTION OF PHASING STRATEGY:
4 delta-v Scheme



- There is an additional maneuver dedicated to adjusting the orbital plane (dv2). The other three maneuvers (dv1, dv3, dv4) are all in transverse directions: phasing maneuver, altitude maneuver and circularization maneuver.

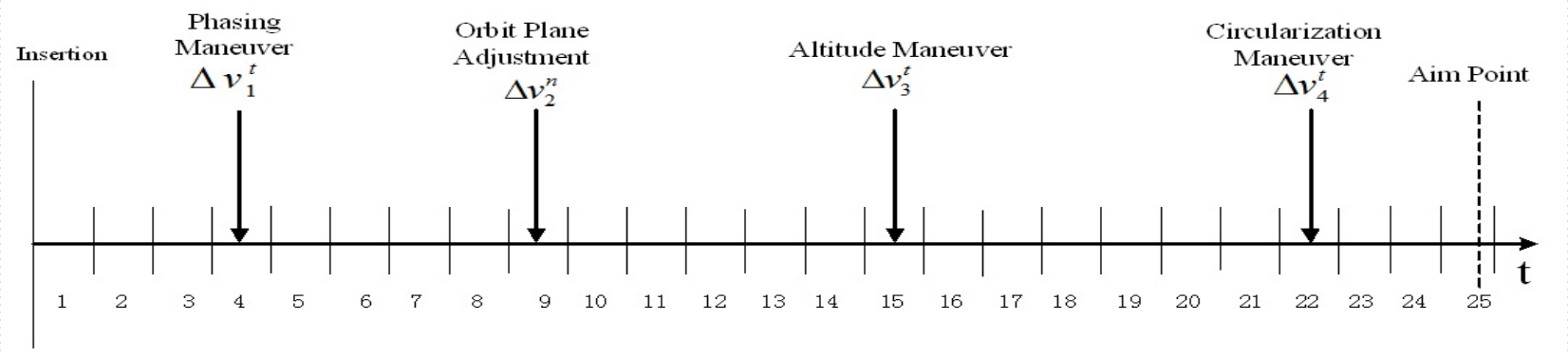
- The independent plane-correction dv (dv2) is energy optimal, and its argument of latitude can be computed from:

$$\tan u = \tan(u + \pi) = \frac{\Delta\Omega \sin i}{\Delta i}$$

  - There are two solutions for ‘u’, which are 180 deg apart.

  - The span of argument of latitude for which tracking access is available is usually greater than 180 deg, so at least one of the two solutions of ‘u’ can be selected for applying dv2 so that the maneuver can be monitored from the ground stations.

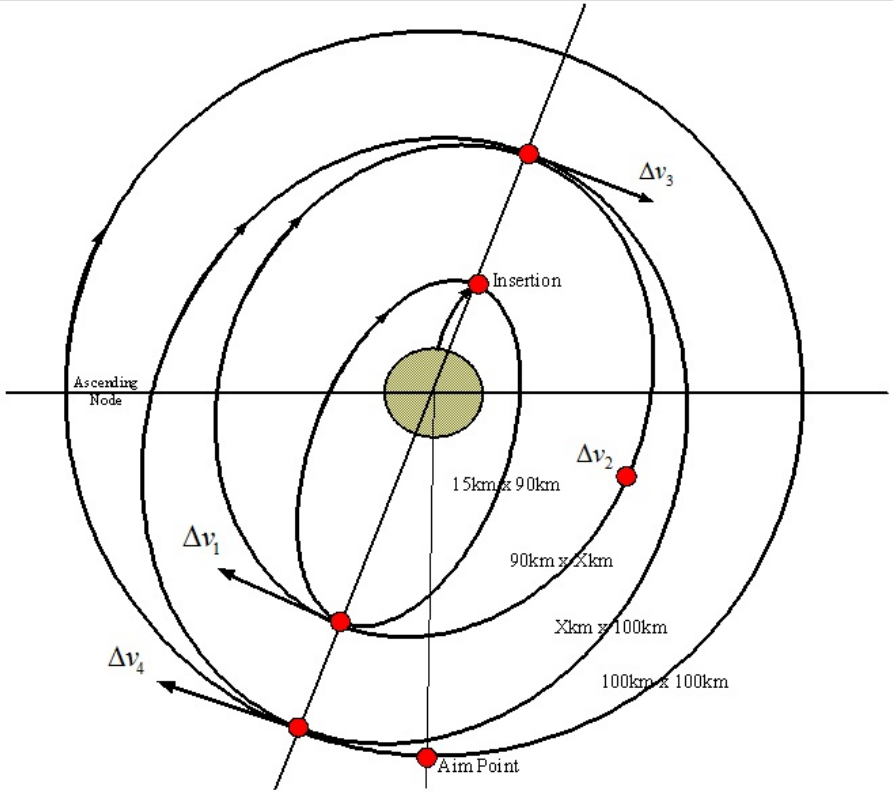
SELECTION OF PHASING STRATEGY:
4 delta-v Scheme (continue)



- This figure is an illustration of the arrangement of the number of revolution for each maneuver.
  - To ensure the accuracy of orbit determination before each maneuver, usually two revolutions are needed for orbit measurement using ground tracking stations, one additional revolution is needed for uploading the maneuver command, and the actual maneuver is executed in the fourth revolution. Therefore, there are at least four revolutions between two adjacent maneuvers.
  - This arrangement takes into account the tracking access requirements for the orbit insertion and aim point as well.
  - Two more revolutions of orbit are reserved for orbit determination after the last maneuver, which provides the inertial guidance input for the far range rendezvous stage.

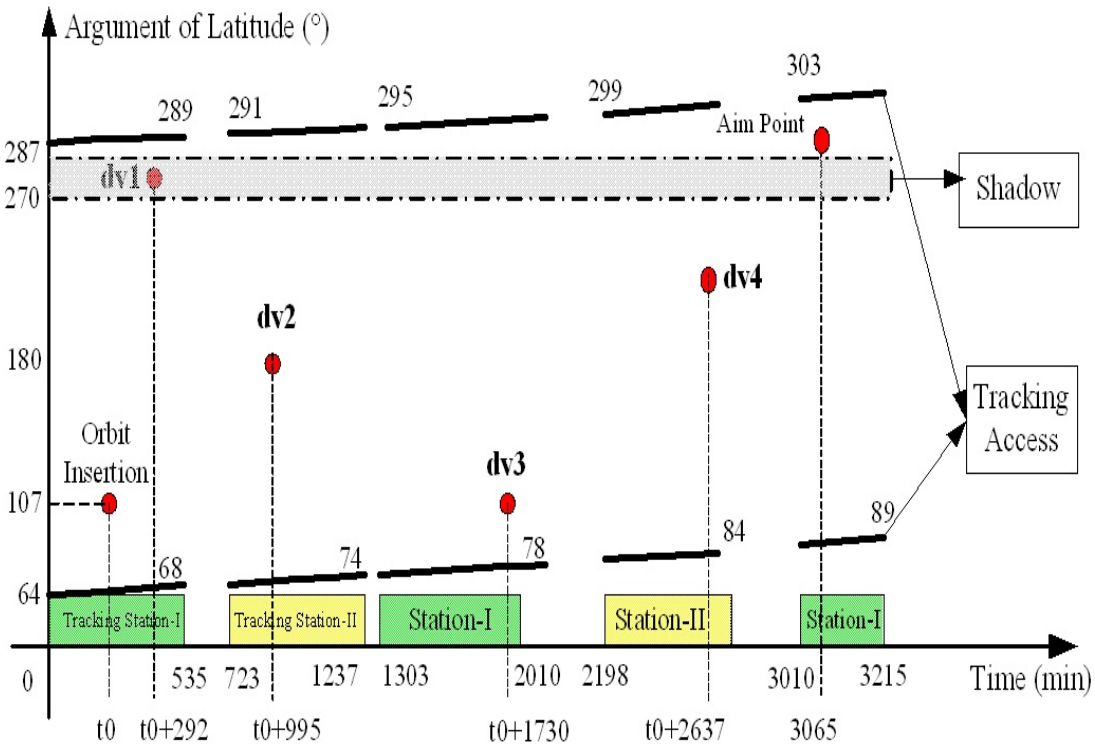
- **Based on the proceeding discussions, the 4-dv scheme has a better lunar surface ascent window, better fuel efficiency for orbit plane correction, or better orbit determination accuracy than the other three schemes. As such, the 4-dv scheme is selected as the phasing strategy for the mission of this study.**

NOMINAL MANEUVER STRATEGY DESIGN



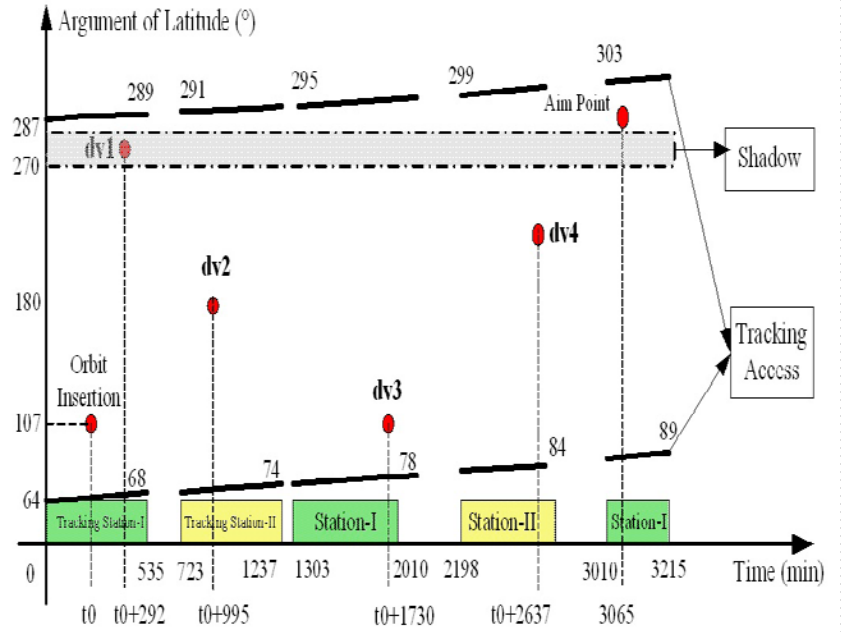
- A 4-dv scheme is selected as the baseline design to achieve the basic goal of the phasing stage for the chaser.
  - The 4-dv baseline design is essentially a special point maneuver scheme. The trajectory is optimal in terms of fuel consumption.
  - It is desired to monitor the maneuvers by the ground stations, so tracking access should be available for the maneuvers.
  - It is better for some maneuvers to be made in the shadow so that the spacecraft will have more time to charge its battery when it is illuminated after getting out of the shadow.
  - The magnitude of the transverse burn dv should be considered in optimizing the design (e.g. make sure dv4<10m/s) so that significant orbit parameter dispersions at the aim point can be avoided.
- An optimal nominal maneuver strategy design is obtained after the above practical engineering constraints have been taken into consideration.

NOMINAL MANEUVER STRATEGY DESIGN: Optimization of Argument of Latitude



- The figure shows the profile of tracking and lighting conditions for the chaser for all candidate Earth launch windows.
- Stations-I is the primary tracking station group as it can achieve much better orbit determination accuracy.
- Time ‘0’ refers to the instant when the lunar orbit becomes visible from Stations-I.
- The timing of the maneuvers should be set in the time spans when the orbit is visible from the ground stations.
- The two groups of solid lines indicate the boundary values (upper and lower limits) of argument of latitude at which tracking access is available.
- The maneuvers should occur somewhere between the upper and lower boundary values.
- Also shown is the scope of the values of argument of latitude at which the spacecraft is in the shadow (the shaded region).

NOMINAL MANEUVER STRATEGY DESIGN: Optimization of Argument of Latitude (continue)



- The optimal arguments of latitude of the maneuvers in the 4-dv scheme can then be found by a search within the eligible scope of the argument of latitude as shown in the figure. This will guarantee the tracking conditions desired for the four orbit maneuvers, and will make sure that some of them occur in the shadow as well.

- The time of each maneuver should be chosen in the time span when the orbit is visible from the ground stations (Stations-I or Stations-II).

- Additional practical engineering constraints are considered. A typical optimization result of the arguments of latitude of the four maneuvers is given in the table:

Maneuvers	Arguments of Latitude (°)
1st Maneuver	280 ± 1
2nd Maneuver	80 - 280
3rd Maneuver	85 ± 5
4th Maneuver	270 ± 10

NOMINAL MANEUVER STRATEGY DESIGN: Design Results

- The preceding optimization method is applied in the design of the nominal maneuver strategy for the chaser. The design results are given in the table.

Events	Number of Revolution	Typical delta-V (m/s)	Periselene Altitude (km)	Apoapsis Altitude (km)	Arguments of Latitude (°)	Tracking Stations
Insertion	1		15	90	105	Stations-I
1st Maneuver	4	16.2	X	90	280 ± 1	Stations-I
2nd Maneuver	9	0	X	90	80 - 280	Stations-II
3rd Maneuver	15	2.2	X	100	85 ± 5	Stations-I
4th Maneuver	22	3.3	100	100	270 ± 10	Stations-II
Aim Point	25		100	100	275	Stations-I

ORBIT CONTROL STRATEGY

Maneuvers	Design Parameters	Desired Aim Point Condition
1st Maneuver	$\Delta v_1^t, \Delta v_2^n, u_2, \Delta v_3^t, \Delta v_4^t, u_4$	$\Delta a = 0, \Delta e_x = 0, \Delta e_y = 0, \Delta u = 0$ $\Delta i = 0, \Delta\Omega = 0$
2nd Maneuver	$\Delta v_2^n, u_2, \Delta v_3^t, u_3, \Delta v_4^t, u_4$	$\Delta a = 0, \Delta e_x = 0, \Delta e_y = 0, \Delta u = 0$ $\Delta i = 0, \Delta\Omega = 0$
3rd Maneuver	$\Delta v_3^t, u_3, \Delta v_4^t, u_4$	$\Delta a = 0, \Delta e_x = 0, \Delta e_y = 0, \Delta u = 0$
4th Maneuver	$\Delta v_4^t, u_4$	$\min\ J = k_1\lvert\Delta x\rvert + k_2\lvert\Delta y\rvert + k_3\lvert\Delta z\rvert$ $+ k_4\lvert\Delta v_x\rvert + k_5\lvert\Delta v_y\rvert + k_6\lvert\Delta v_z\rvert$

- The actual orbit will deviate from the nominal design orbit because of the influences from the chaser's lunar orbit insertion error, navigation error, maneuver execution error and other error sources, which may lead to unacceptable large dispersions at the aim point.

- To reduce the influences of these errors on the aim point conditions and keep the actual orbit close to the nominal design orbit, an orbit control strategy needs to be devised, namely, before each maneuver, all the remaining maneuvers have to be re-computed, based on the latest orbit determination results.

- The control strategy devised for the chaser is given in the table.
  - The superscript 't' and 'n' denote the components in transverse and normal directions.
  - Letter 'u' is used to denote argument of latitude.
  - 'ex' and 'ey' denote the two components of eccentricity vector.
  - 'J' is the weighted function of the relative position and velocity errors at the aim point.

Dispersion Analysis of the Aim Point

- Applying the orbit control strategy, a Monte Carlo simulation study can be performed for the given lunar orbit insertion error, navigation error and maneuver execution error, and the statistics of the relative position and velocity errors at the aim point are obtained :

Statistics	Position Error (m)			Velocity Error (m/s)		
	R	T	N	R	T	N
Mean	-44	3714	5	-5.9	0.4	0.05
3-sigma	3157	99076	3537	90.6	6.1	3.3
Max	2933	77538	2777	73.8	4.8	3.0
Min	-3219	-84836	-2522	-74.8	-5.2	-3.2

- As an example, the ground navigation accuracy and maneuver execution error data from the preliminary design of the GNC systems of Orion and Altair are used in the Monte Carlo simulation study.

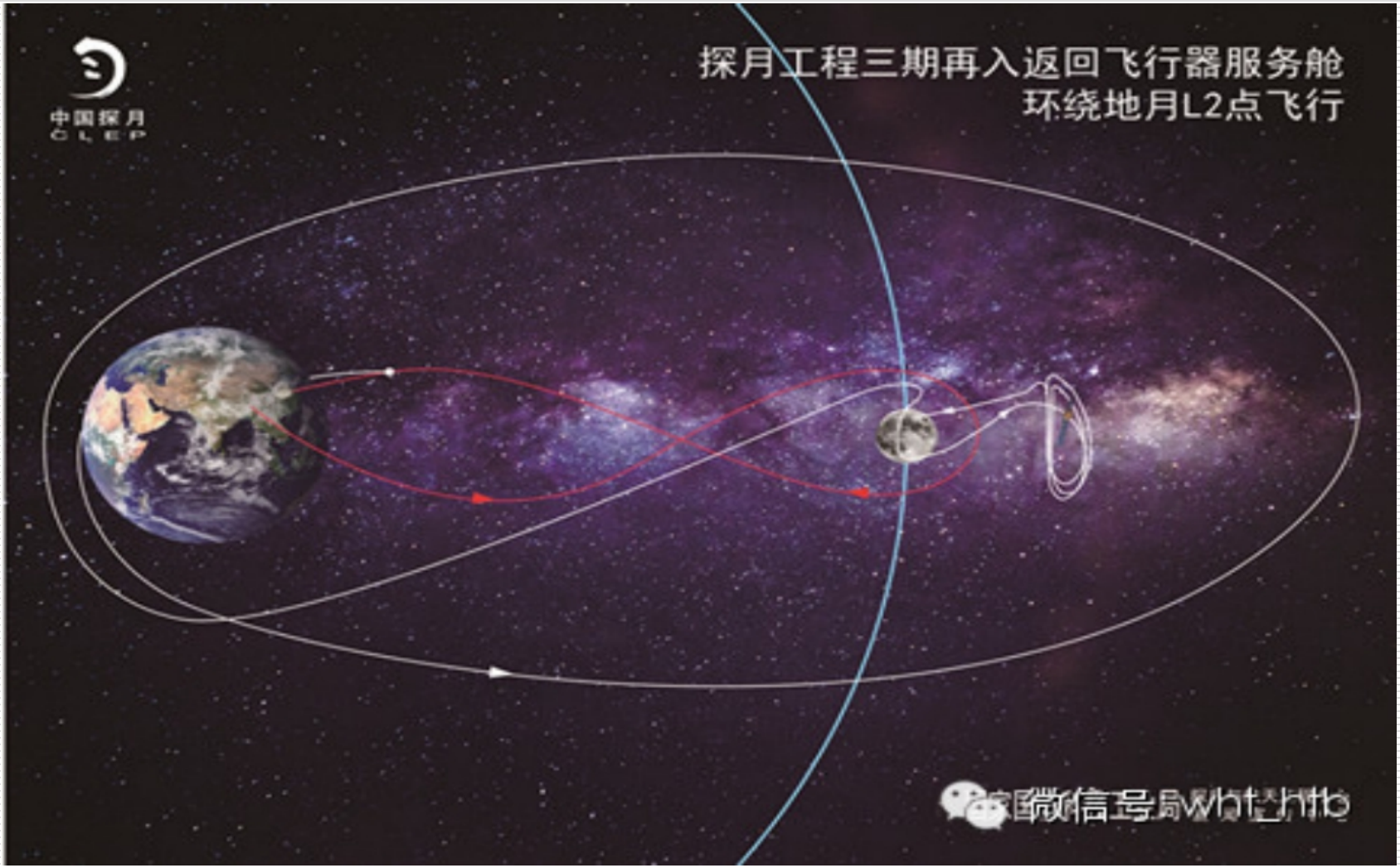
- Apparently the aim point relative position error looks huge and unacceptable. However, it can be shown that the computed dispersions can be reduced about one order of magnitude if the covariance matrix information for the navigation errors is available, or the navigation error data is given in terms of orbital elements.

- The main challenge of orbital control strategy design for the phasing stage is to reduce the relative position error in transverse direction at the aim point. This can be achieved by:

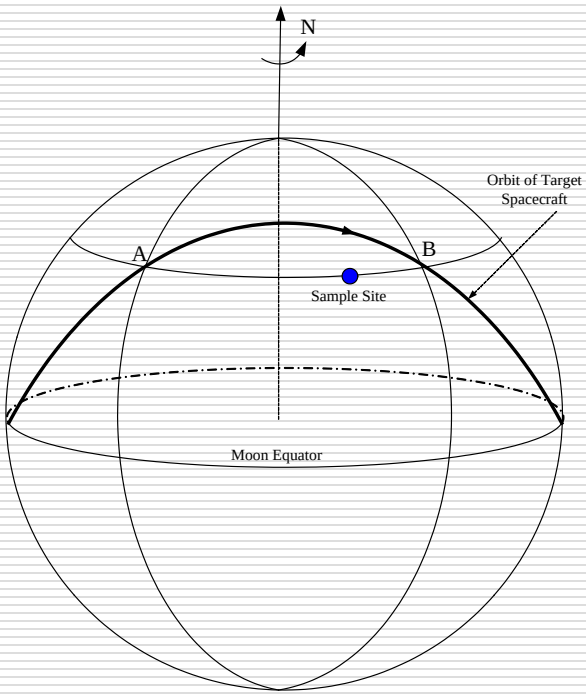
(1) Improve the tracking and maneuver execution accuracy;

(2) In the simulation, the stop condition for the aim point is the actual time when the orbiter achieves the specified argument of latitude, however, **in actual rendezvous operations, the relative position error in transverse direction can be effectively reduced by selecting the aim point stop condition as when the desired phase angle difference between the two vehicles (60km apart along-track) is achieved.**

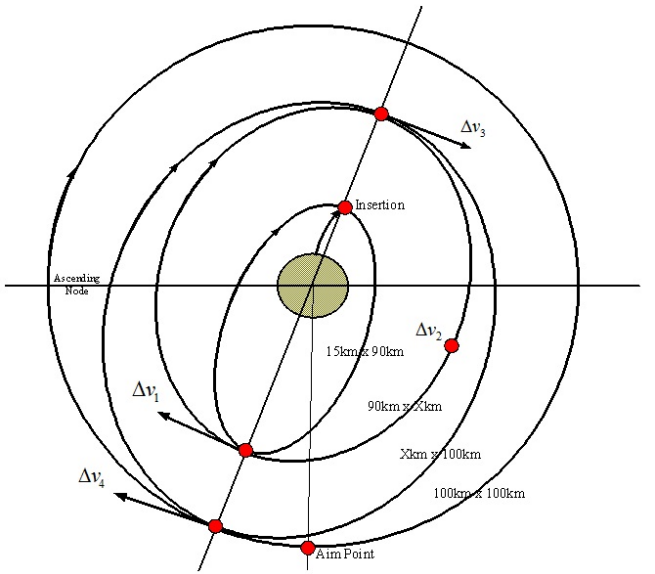
The Extended Mission



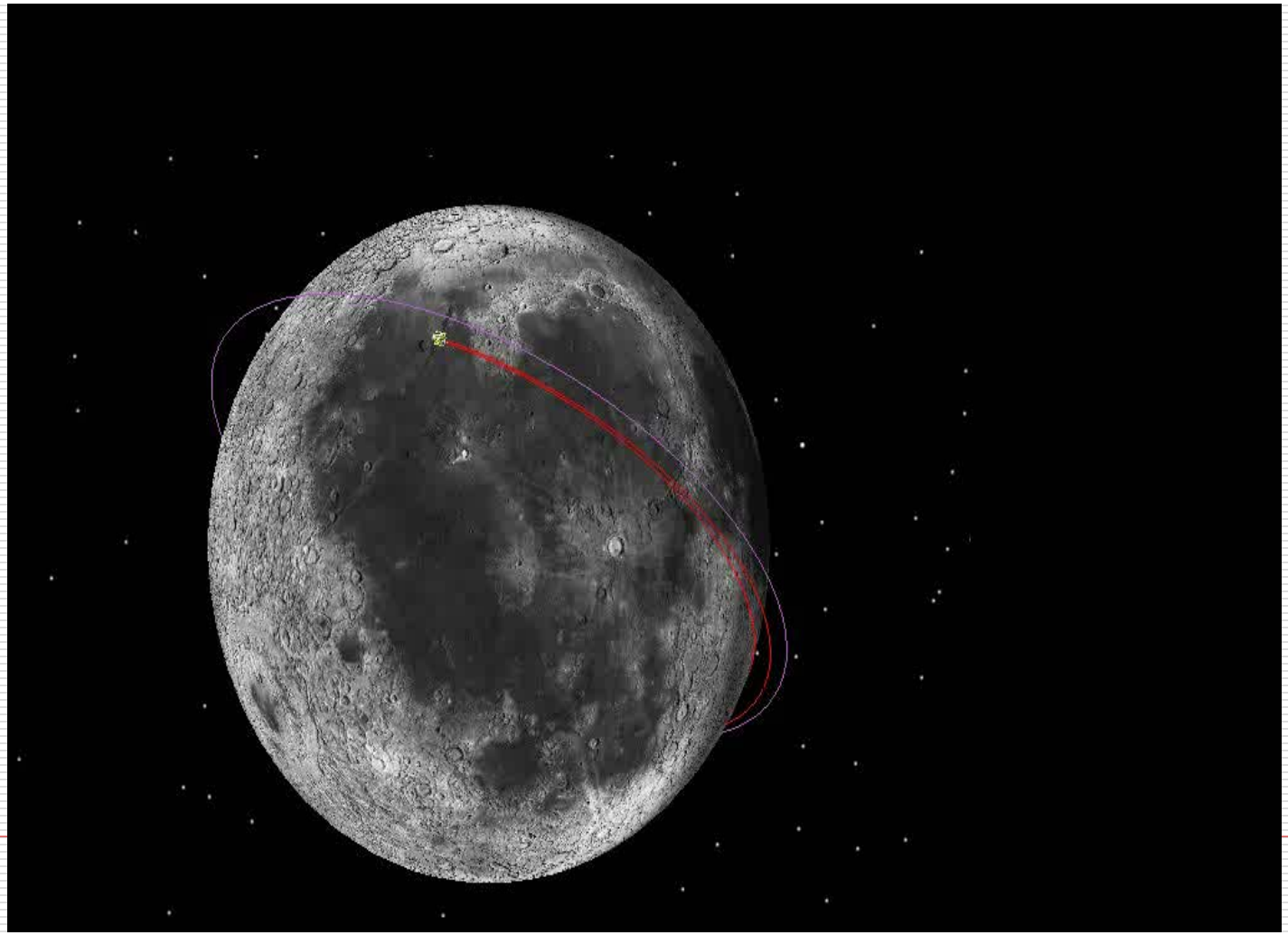
The Rendezvous Test



- Orbiter Maneuver Test: 3 maneuvers, February 2015
- Chaser (ascent module) Maneuver Test: 4-dv scheme, March 2015
  - Orbiter? No target?



The Rendezvous Test



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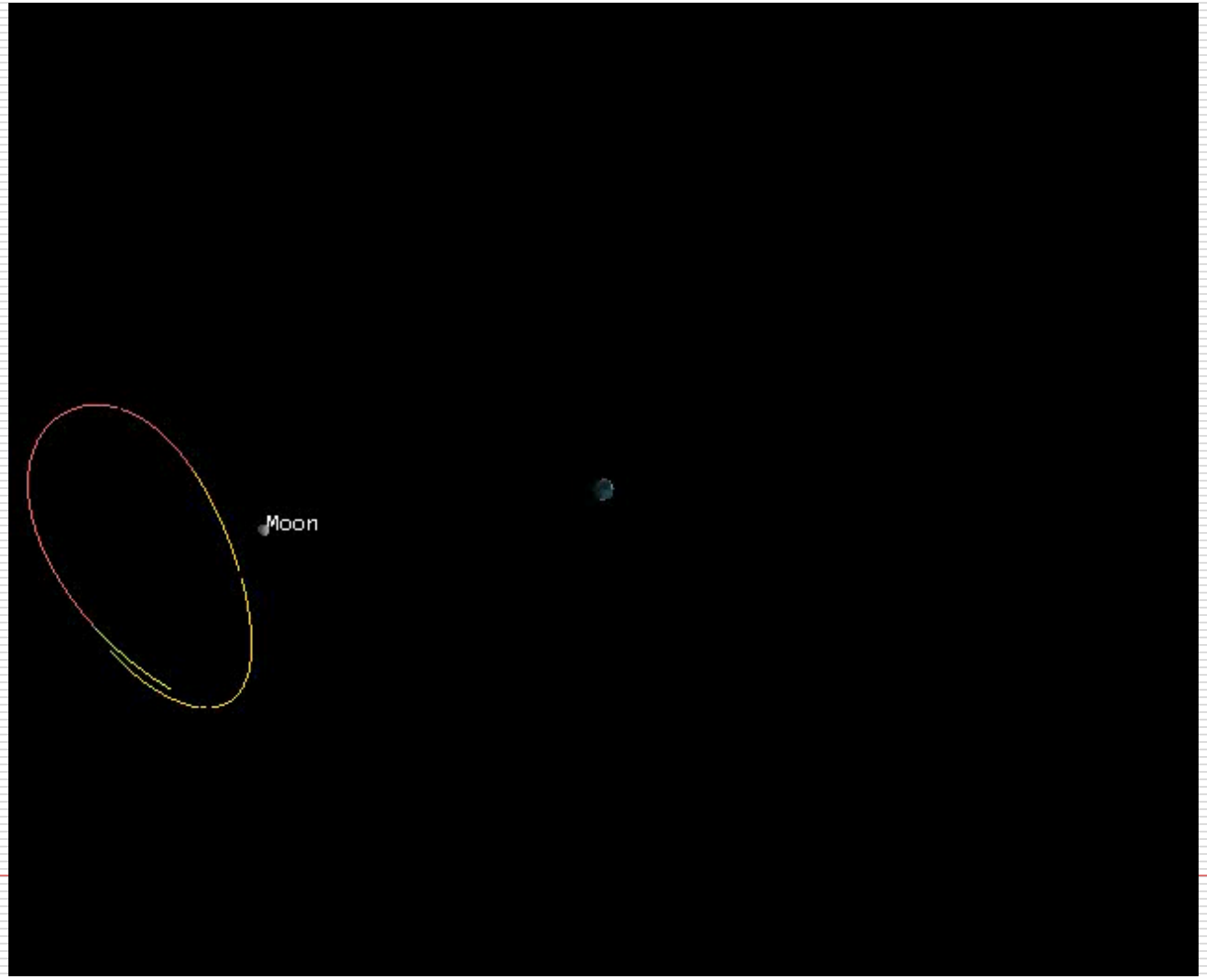

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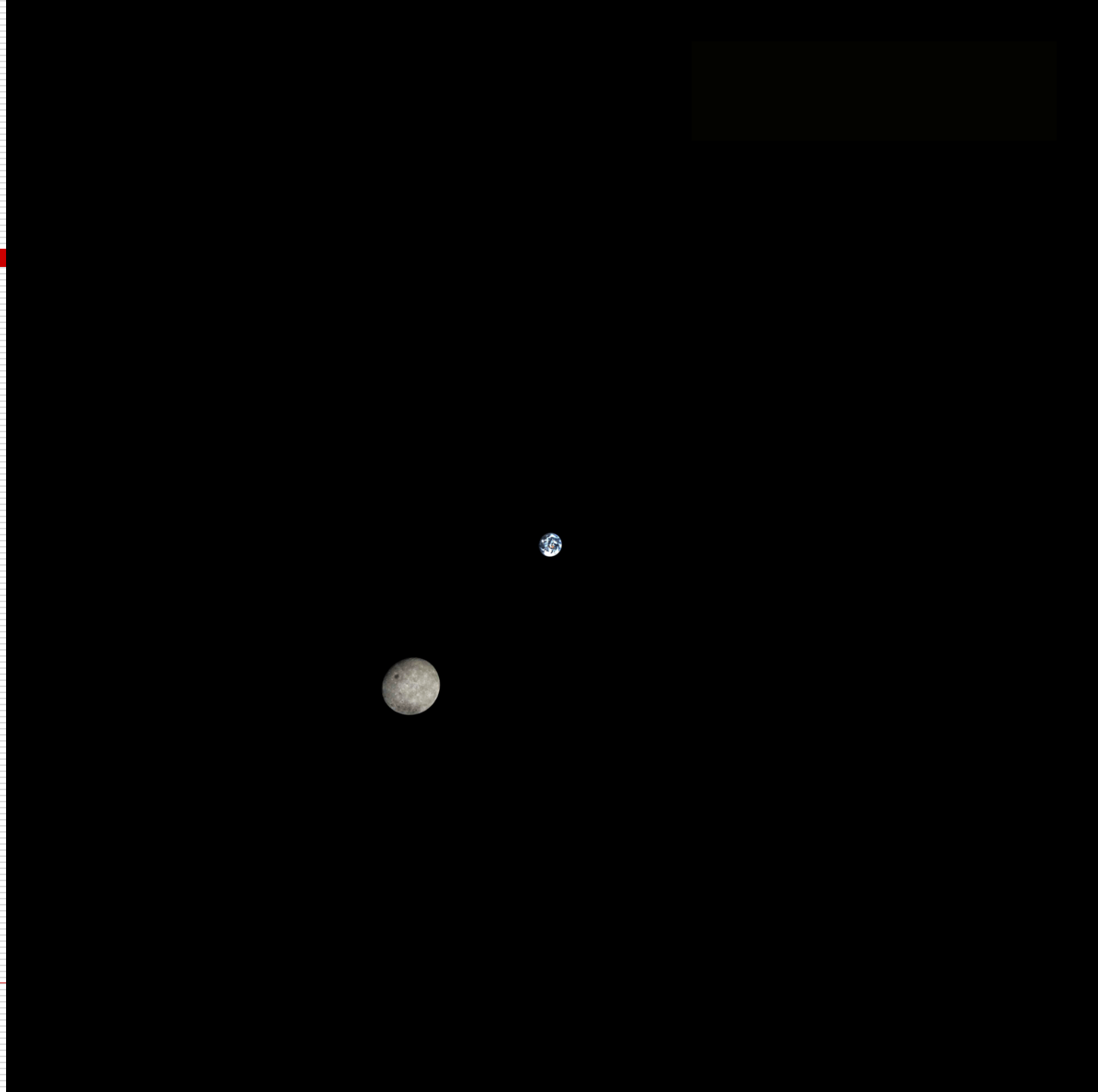
Thanks!