Low-energy Intercept Orbits to NEO 2004 GU9 Offer a Compelling Opportunity for Long-duration Manned and Sample-return Missions

Crawl, Walk and Run towards Long Endurance Interplanetary Missions

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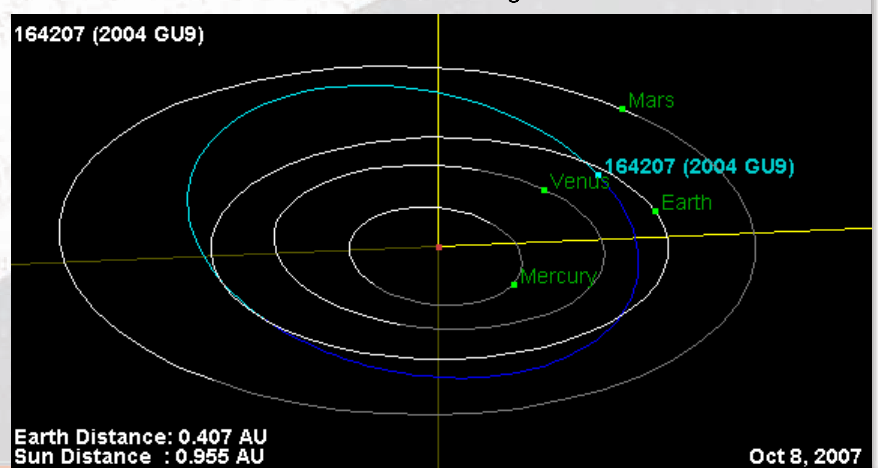
Mission Imagery Courtesy of
DIGITAL SPACE

WHY GU9?

- Sun centered orbit
    - GU9 orbits the sun at approximately the same distance as does Earth
- Orbit similar to that of Earth
    - While at a higher inclination and a longer eccentricity, GU9's orbit closely resembles that of Earth
- Frequency of potential launch and return dates
    - Because of these similarities, GU9 serves as a target which has frequent opportunities for visitation
    - Always visible from earth, assuring *line-of-sight* communications

Image Credit: NASA JPL

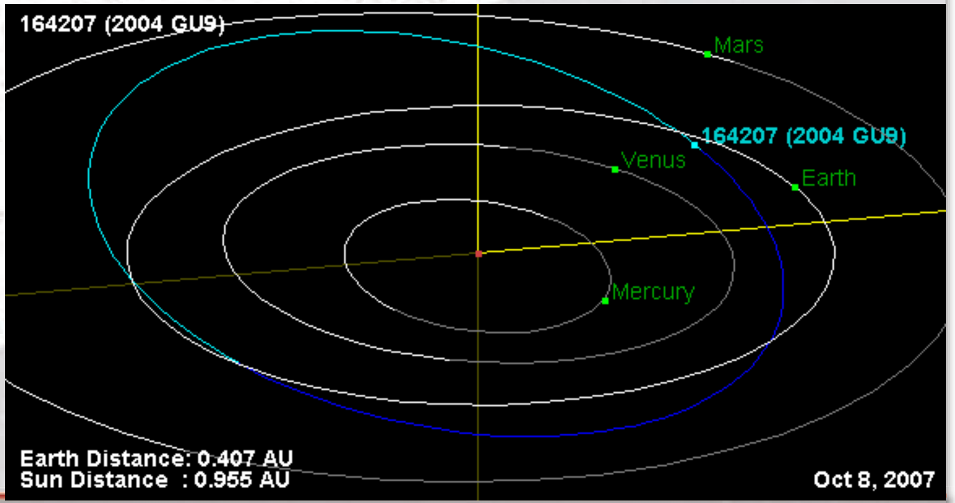


2004 GU9's Orbit

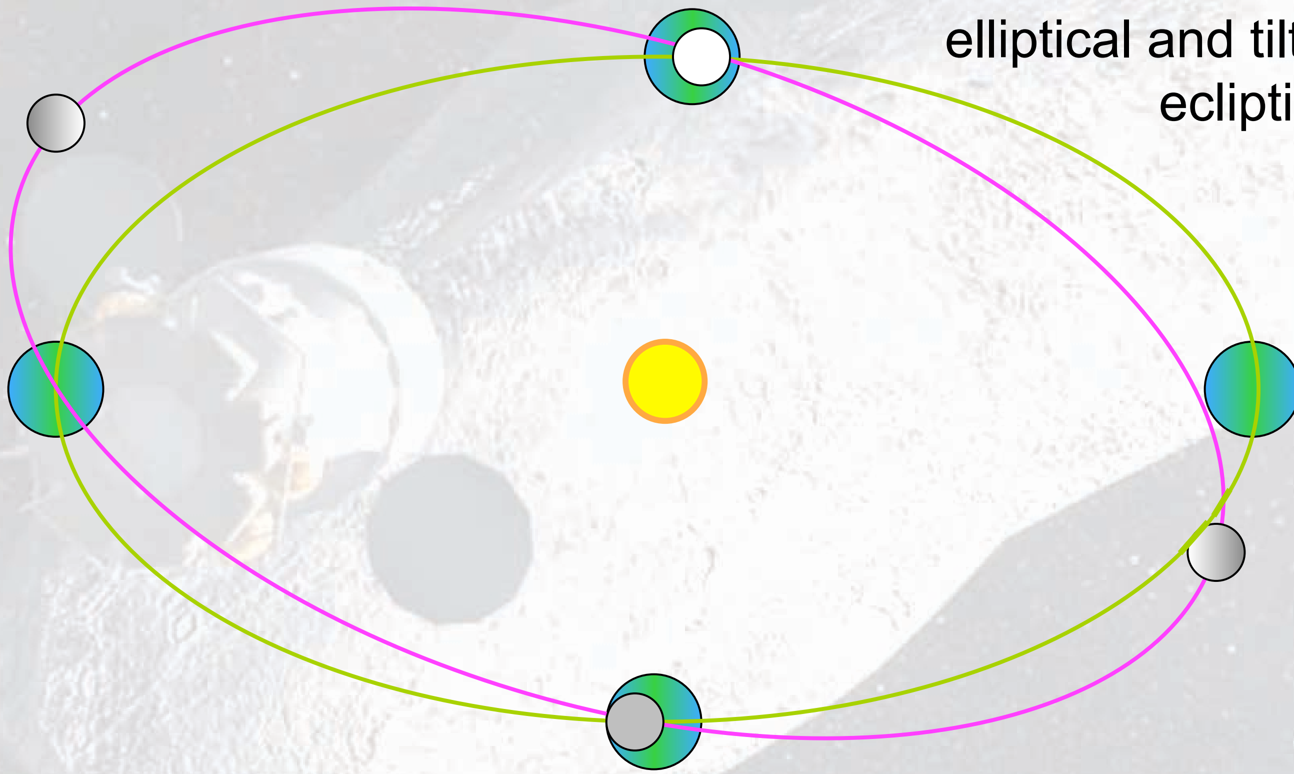
Due to their similar orbits about the Sun:

- GU9's orbit being inclined *wrt* the plane of the ecliptic
- GU9's orbit being inside-then-outside of Earth's solar orbit
- 2004 GU9's orbit relative to earth appears to be a corkscrew about the Earth, with an interval of precisely one solar year
- 2004 GU9's orbital period is identical to Earth's – One Year!
- 2004 GU9 is always within a few degrees of Earth's solar radial

Image Credit: NASA JPL



2004 GU9's Orbit



The apparent orbit of 2004 GU9 around Earth is a result of its solar orbit being more elliptical and tilted *wrt* the ecliptic

Perhaps Earth serves to stabilize GU9's orbit

2004 GU9's Orbit

There are key locations in the orbit (the ascending and descending nodes) where:

- The relative velocity between the Earth and GU9 is at a minimum
- The range is at a minimum

Note two times when GU9's orbit crosses Earth's orbital plane

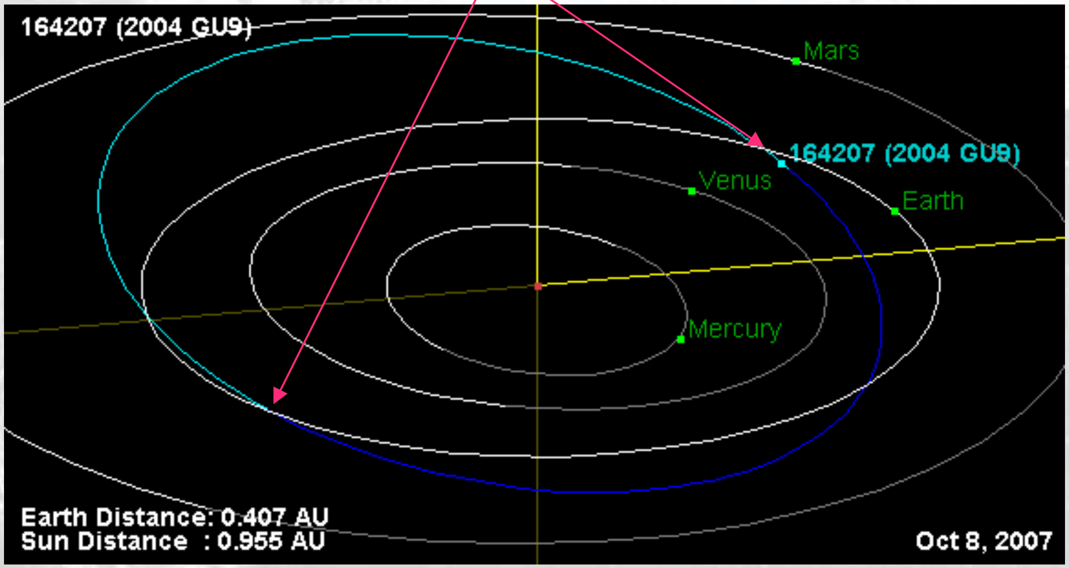
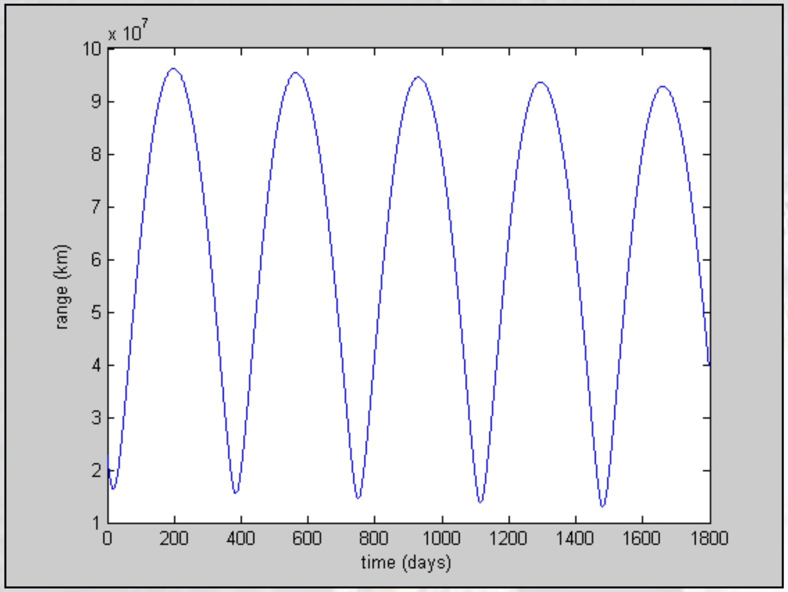
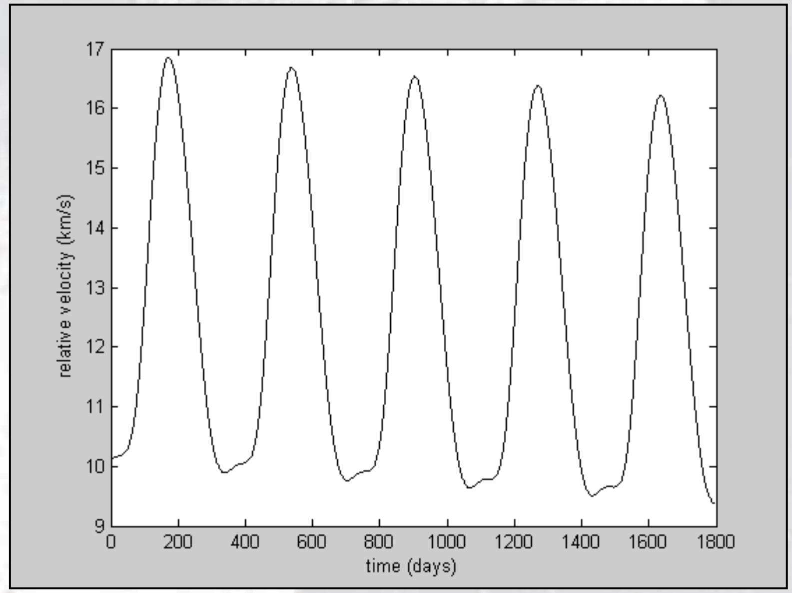


Image Credit: NASA JPL

2004 GU9's Orbit

2004 GU9's relative range and velocity to Earth over a 5 year period





The Mission Requirements

Depart from earth orbit (300 km)

- For the purposes of these simulations, it is assumed that the spacecraft is already parked in an orbit around the Earth
  - Earth launches to parking orbit are assumed, *a priori*
  - It is also assumed that the parking orbit is inclined as needed to perform the desired transfer maneuvers (inclination and phasing)

Arrive at asteroid safely

- In all cases, it is assumed that the spacecraft is meant to arrive at GU9 with no relative velocity
  - This does not account for a ‘soft’ landing on the surface of the asteroid nor does it determine the necessary velocities needed to orbit the asteroid as there is insufficient data available to perform such calculations

Flight Option 1

This method uses two orbital maneuvers:

- A Hohmann transfer matches the non-inclined orbit of the asteroid.
- A plane change is performed to match the orbits.

Pros

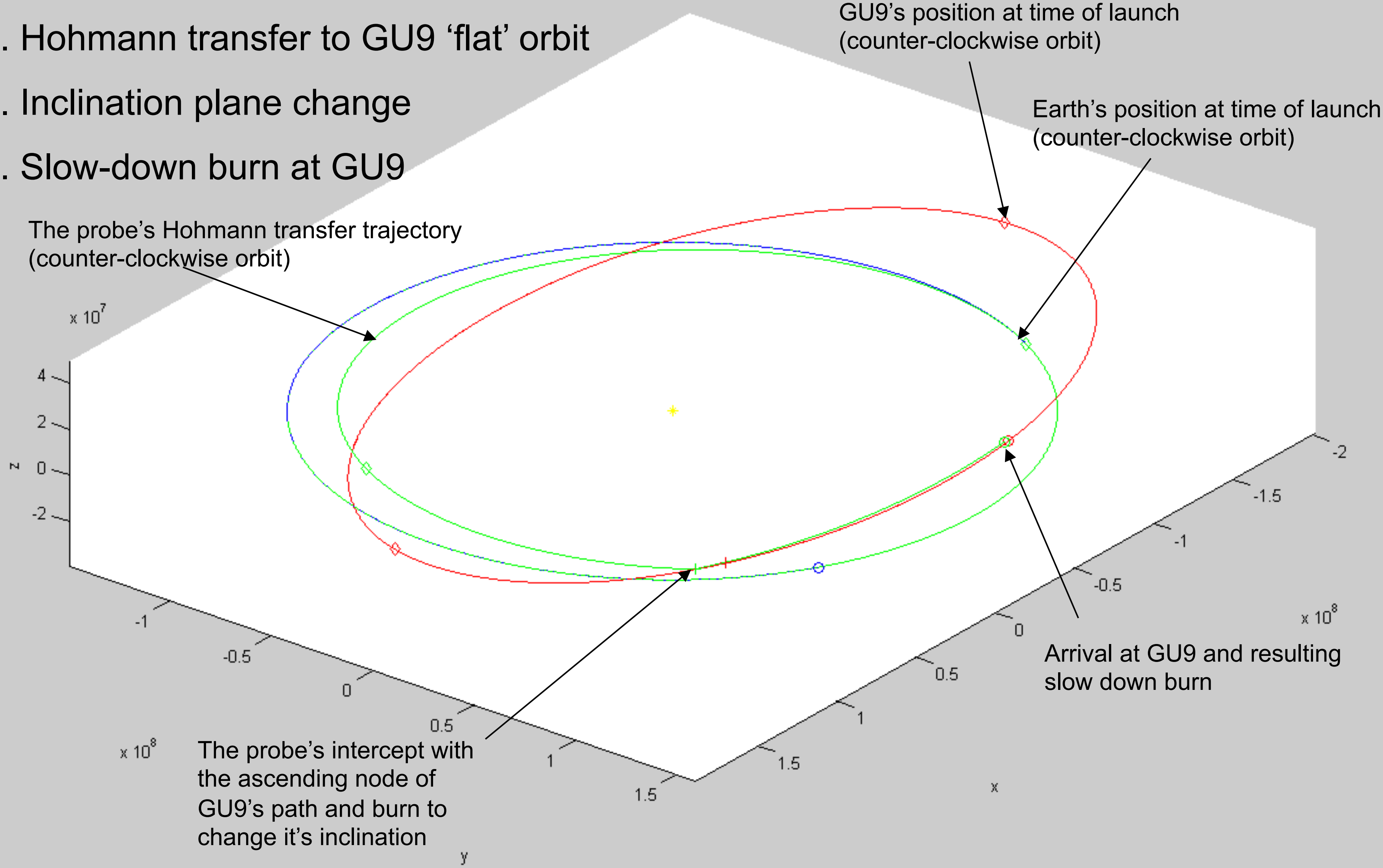
- This is a relatively ‘quick’ transfer at around 275 days (see following slides)
- The Hohmann transfer is highly fuel efficient and burning in the direction of Earth’s orbit will save even more fuel

Cons

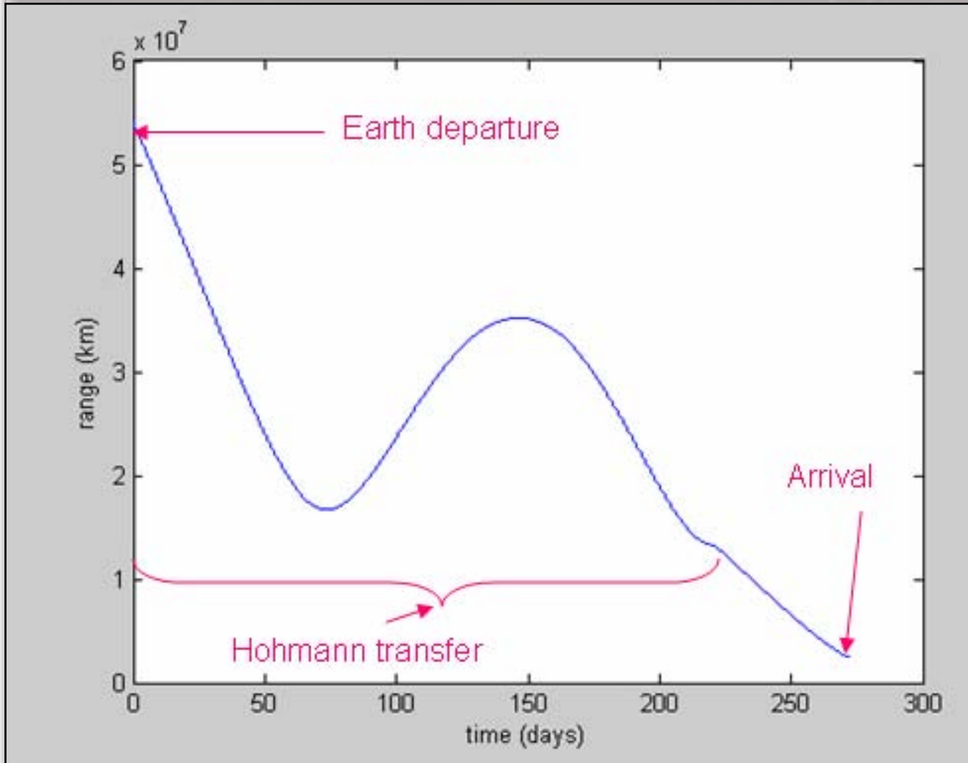
- The inclination change and following slow-down maneuvers are very expensive in terms of fuel (and therefore useable payload capacity)
- Decreased useful payload due to higher fuel requirements

Maneuver diagram - Flight Option 1

1. Burn from Earth orbit
2. Hohmann transfer to GU9 ‘flat’ orbit
3. Inclination plane change
4. Slow-down burn at GU9

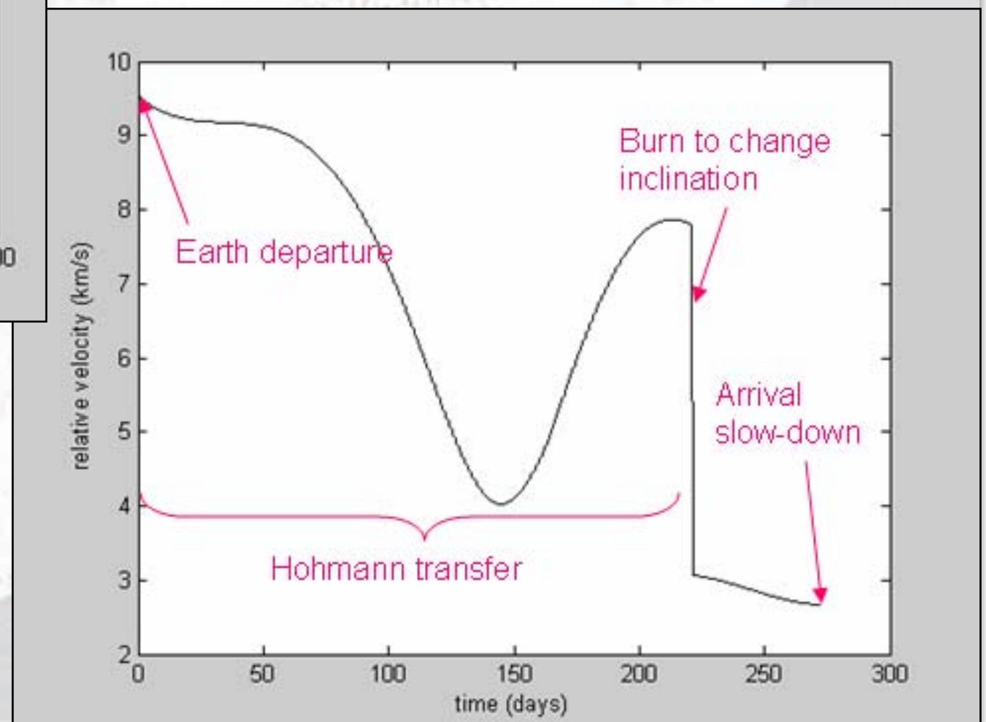


Flight Option 1 - Maneuver profiles



The spacecraft's range from GU9 during the course of the maneuvers

The spacecraft's relative velocity to GU9 during the course of the maneuvers



Viable Launch Dates

Dates that a departure could take place (launch windows)

Launch		Arrival		Travel Time (days)
Date	Time ± 1 hour	Date	Time ± 2 hours	
2/21/08	3:30 PM	11/20/08	4:29 PM	273.0415
2/21/09	6:30 AM	11/21/09	9:59 AM	273.1457
2/21/10	9:00 PM	11/22/10	2:59 AM	273.2498
2/22/11	12:00 PM	11/22/11	8:29 PM	273.354
2/23/12	2:30 AM	11/22/12	1:29 PM	273.4582
2/22/13	5:30 PM	11/23/13	6:59 AM	273.5623
2/23/14	8:00 AM	11/23/14	11:59 PM	273.6665
2/23/15	11:00 PM	11/24/15	5:29 PM	273.7707
2/24/16	1:30 PM	11/24/16	10:29 AM	273.8748
2/24/17	4:30 AM	11/25/17	3:59 AM	273.979
2/24/18	7:00 PM	11/25/18	8:59 PM	274.0832
2/25/19	10:00 AM	11/26/19	2:29 PM	274.1873
2/26/20	12:30 AM	11/26/20	7:29 AM	274.2915
2/25/21	3:30 PM	11/27/21	12:59 AM	274.3957
2/26/22	6:00 AM	11/27/22	5:59 PM	274.4998
2/26/23	9:00 PM	11/28/23	11:29 AM	274.604
2/27/24	11:30 AM	11/28/24	4:29 AM	274.7082
2/27/25	2:30 AM	11/28/25	9:59 PM	274.8123
2/27/26	5:30 PM	11/29/26	3:29 PM	274.9165
2/28/27	8:00 AM	11/30/27	7:59 AM	274.9998
2/28/28	11:00 PM	11/30/28	1:29 AM	275.104
2/28/29	1:30 PM	11/30/29	5:59 PM	275.1873
3/1/30	4:30 AM	12/1/30	11:29 AM	275.2915
3/1/31	7:00 PM	12/2/31	3:59 AM	275.3748
3/1/32	10:00 AM	12/1/32	9:29 PM	275.479
3/2/33	12:30 AM	12/2/33	1:59 PM	275.5623
3/2/34	3:30 PM	12/3/34	7:29 AM	275.6665
3/3/35	6:00 AM	12/3/35	11:59 PM	275.7498
3/2/36	9:00 PM	12/3/36	5:29 PM	275.854
3/3/37	11:30 AM	12/4/37	10:29 AM	275.9582

Flight Option 1 - Delta-V requirements

Burn number	Burn description	Delta-V (average)	Delta-V (% of total)
1	Earth departure into Hohmann transfer	1.1072 km/s	8.6%
2	Slow-down at end of Hohmann transfer to match projection of GU9's orbit onto a non-inclined orbit	0.9695 km/s	7.6%
3	Inclination change to match GU9's orbital inclination	8.1191 km/s	63.2%
4	Probe slow-down for arrival at GU9	2.6501 km/s	20.6%
	Total	**12.8459 km/s**	**100%**

Flight Option 2

This method also uses two orbital maneuvers and requires very precise timing. First, when Earth's orbit crosses the ascending or descending node of the asteroid, a burn is performed to inject the probe/spacecraft directly into the orbital plane of GU9. Secondly, a phase change maneuver is performed to help the spacecraft 'catch-up' with the asteroid, matching velocities.

Pros

- The lack of a plane change maneuver saves significant amounts of fuel
- Increased useful payload because of fuel savings
- The full momentum from Earth's rotation about the sun is under-utilized

Cons

- This is a slower transfer at around 360+ days (see following slides)
- May have implications on manned missions
- The full momentum from Earth's rotation about the sun can't be utilized to its maximum potential

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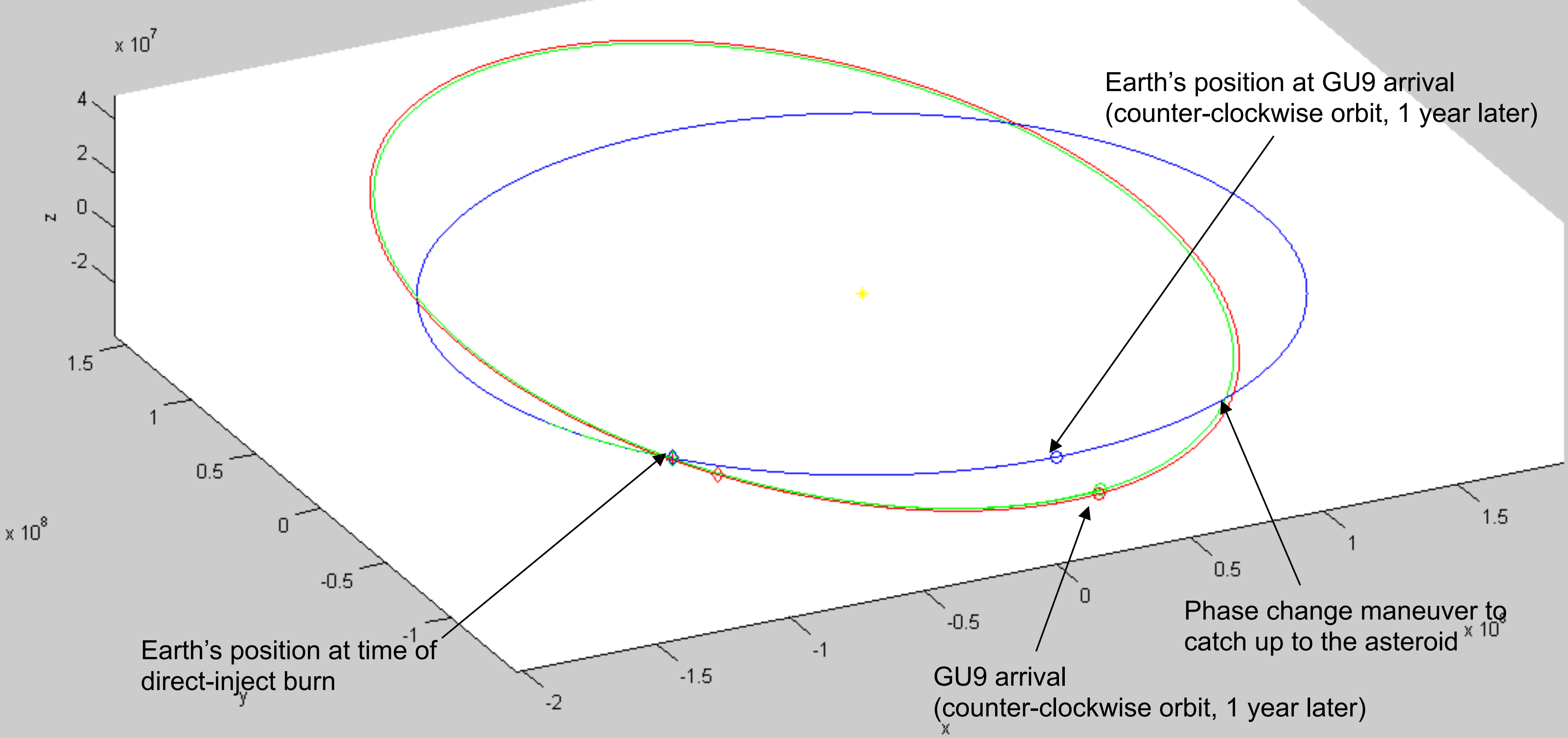
Maneuver diagram - Flight Option 2

- Burn from inclined Earth orbit
- Direct insertion into GU9 heliocentric orbit
- Phase correction to adjust for intercept
- Braking burn at GU9



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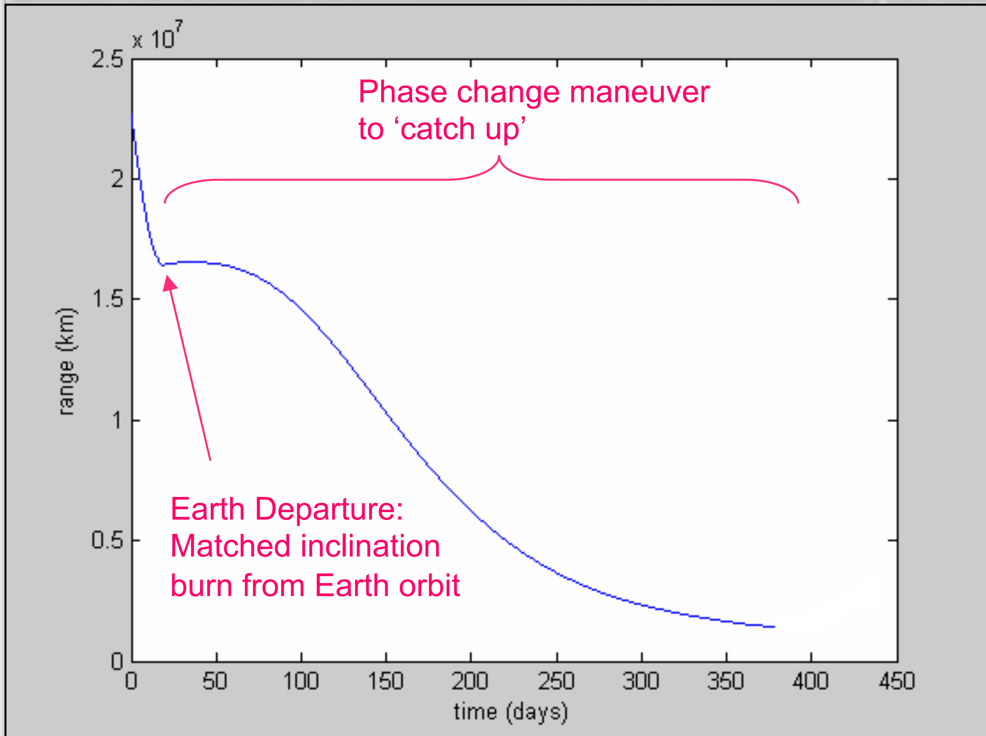
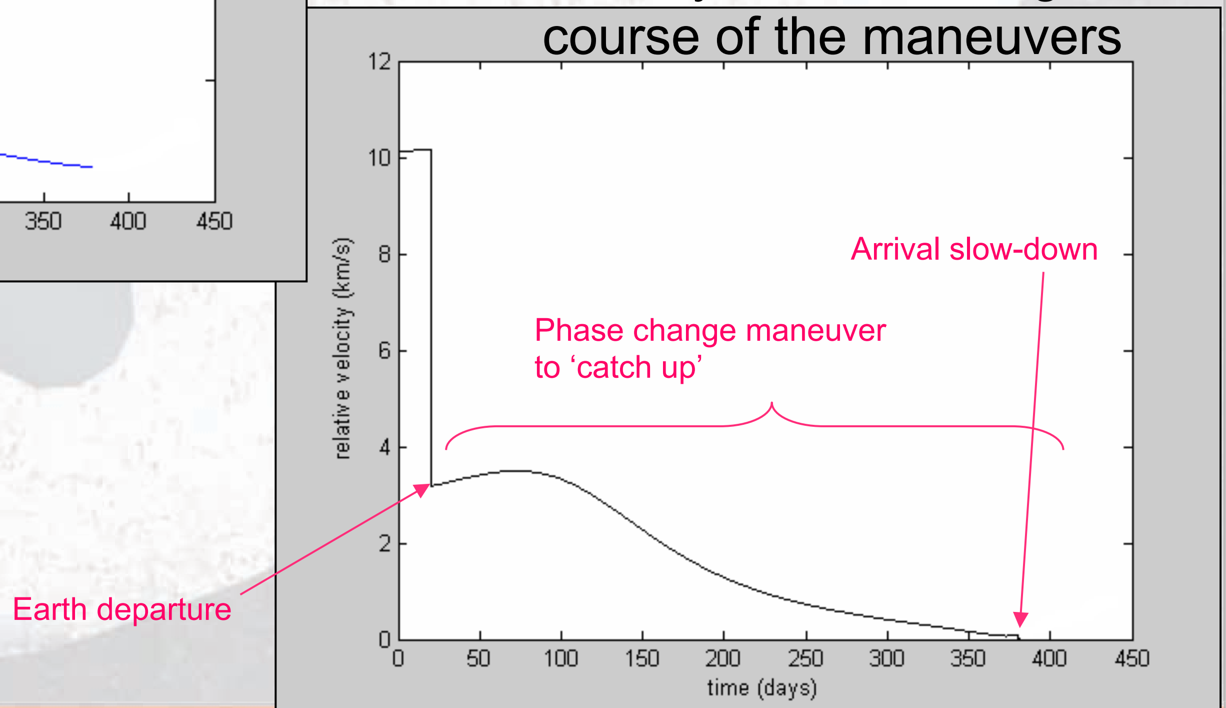
Flight Option 2 - Maneuver profiles



The spacecraft's range from GU9 during the course of the maneuvers

The spacecraft's relative velocity to GU9 during the course of the maneuvers



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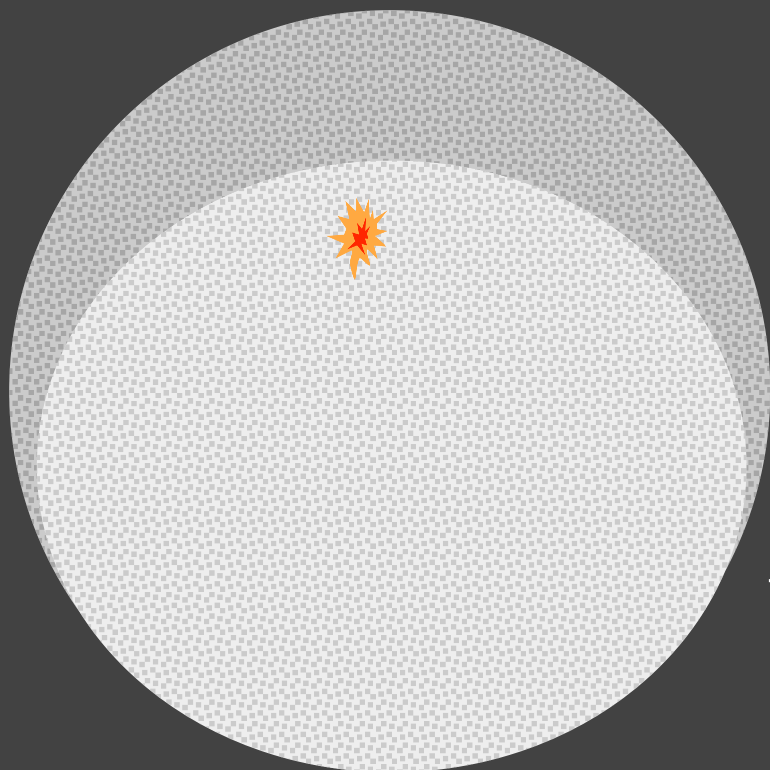
Viable Launch Dates

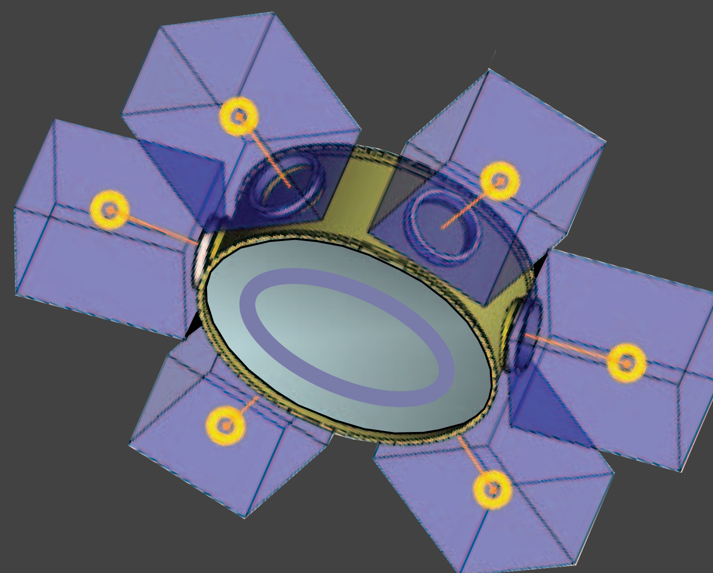
Dates that a departure could take place (launch windows)

Launch		Arrival		Travel Time (days)
Date	Time ± 1 hour	Date	Time ± 2 hours	
4/30/07	5:30 PM	4/24/08	2:29 AM	359.374611
4/29/08	11:30 PM	4/24/09	4:38 PM	359.714051
4/30/09	6:00 AM	4/25/10	7:16 AM	360.053437
4/30/10	12:30 PM	4/25/11	9:54 PM	360.392258
4/30/11	7:00 PM	4/25/12	12:31 PM	360.730514
4/30/12	1:30 AM	4/26/13	3:08 AM	361.068211
4/30/13	7:30 AM	4/26/14	5:12 PM	361.404629
4/30/14	2:00 PM	4/27/15	7:47 AM	361.741182
4/30/15	8:30 PM	4/26/16	10:21 PM	362.077183
4/30/16	3:00 AM	4/27/17	12:54 PM	362.412638
4/30/17	9:00 AM	4/28/18	2:55 AM	362.746690
4/30/18	3:30 PM	4/28/19	5:26 PM	363.081026
4/30/19	10:00 PM	4/28/20	7:57 AM	363.414822
4/30/20	4:30 AM	4/28/21	10:27 PM	363.748084
4/30/21	10:30 AM	4/29/22	12:24 PM	364.079824
4/30/22	5:00 PM	4/30/23	2:53 AM	364.411992
4/30/23	11:30 PM	4/29/24	5:20 PM	364.743634
4/30/24	6:00 AM	4/30/25	7:47 AM	365.074753
4/30/25	12:00 PM	4/30/26	9:42 PM	365.404235
4/30/26	6:30 PM	5/1/27	12:07 PM	365.734286
5/1/27	1:00 AM	5/1/28	2:31 AM	366.063823
4/30/28	7:30 AM	5/1/29	4:55 PM	366.392849
4/30/29	1:30 PM	5/2/30	6:46 AM	366.720125
4/30/30	8:00 PM	5/2/31	9:09 PM	367.048109
5/1/31	2:30 AM	5/2/32	11:30 AM	367.375591
4/30/32	9:00 AM	5/3/33	1:51 AM	367.702575
4/30/33	3:30 PM	5/3/34	4:11 PM	368.029063
4/30/34	9:30 PM	5/4/35	5:59 AM	368.353663
5/1/35	4:00 AM	5/3/36	8:17 PM	368.679139
4/30/36	10:30 AM	5/4/37	10:35 AM	369.004130

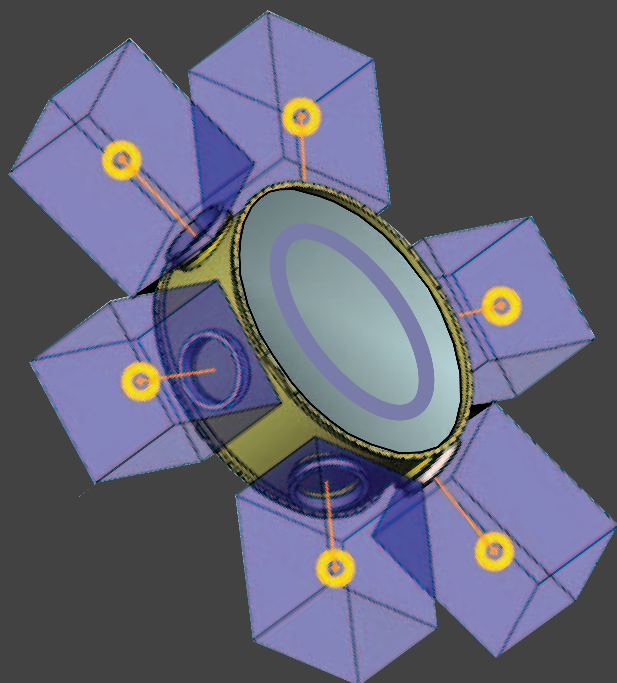
Flight Option 2 - Delta-V requirements

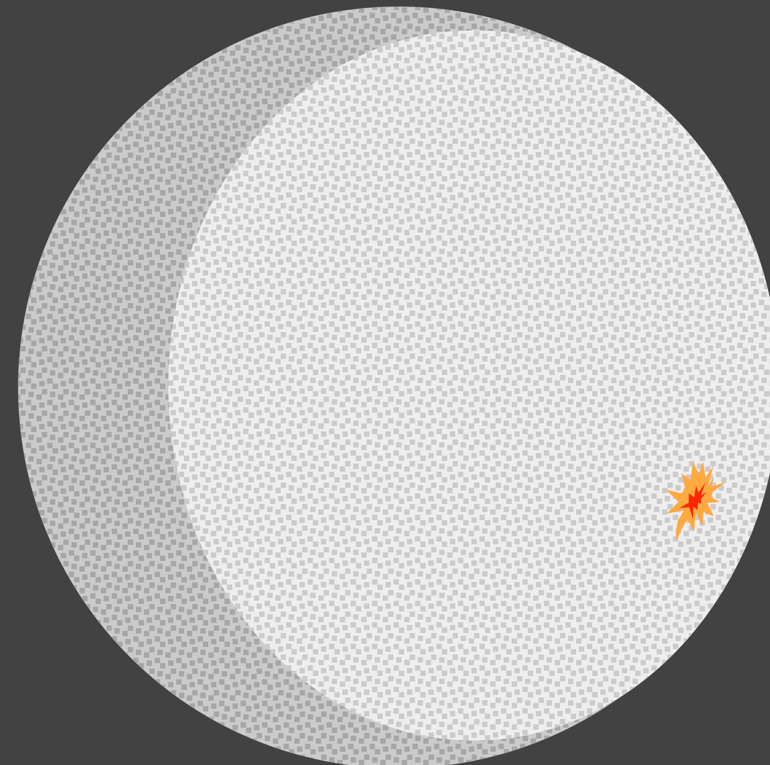
Burn number	Burn description	Delta-V (average)	Delta-V (% of total)
1	Earth departure directly into inclined 2004 GU9 orbital plane	8.1745 km/s	98.0%
2	Velocity increase to accelerate probe into a smaller orbit for phase change	0.08262 km/s	1%
3	Velocity decrease to slow spacecraft to match GU9 orbital rate & arrival	0.08262 km/s	1%
	Total	**8.3397 km/s**	**100%**



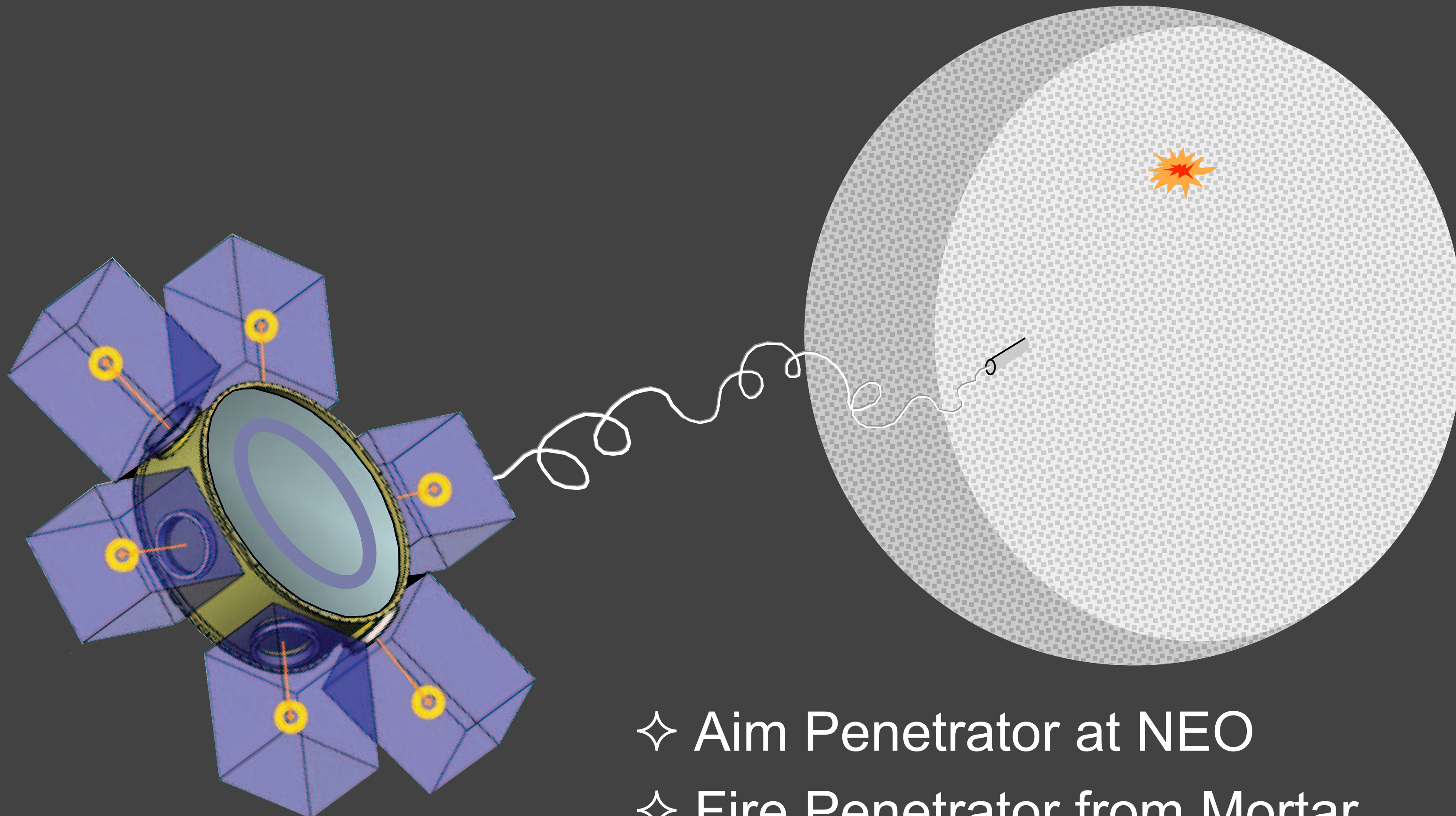


- Mark surface with a reference index point – *Cosmic Paintballs*

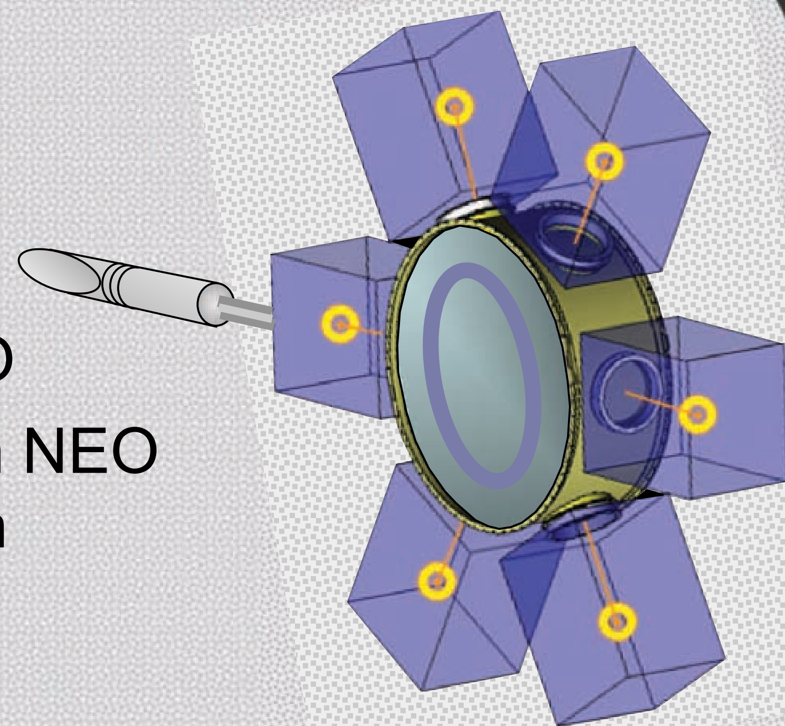




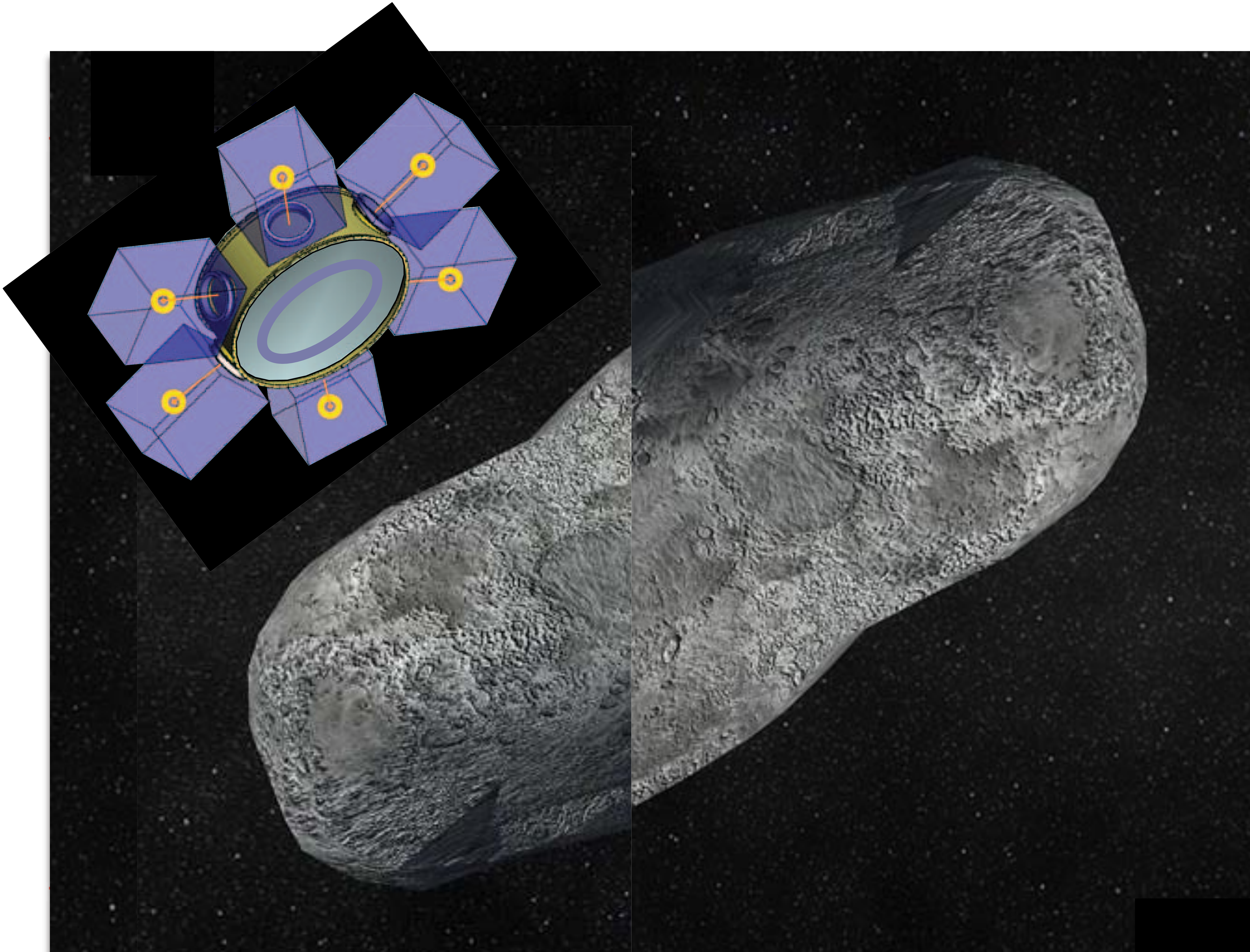
- ✧ Perform Optical Imaging
- ✧ Perform Ground Penetrating RADAR Imaging (GPR)
- ✧ Perform Electromagnetic and Electrostatic Measurements



- ✧ Aim Penetrator at NEO
- ✧ Fire Penetrator from Mortar
- ✧ Allow line slack to settle
- ✧ Reel in slack until the spacecraft moors with the NEO



- Fly Penetrator into NEO
- Retract Penetrator from NEO while pushing back with manipulator arm
- Push off from NEO with manipulator arm

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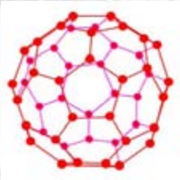
A Sketch of *sys*RAND



- Incorporated 14 Dec 1989 in Colorado
- Started as a systems consultancy, work with oil, industrial, avionics and systems manufacturers
- 1998 downturn: product development increasingly moved offshore along with manufacturing (the IT bust)
- 2001: entered space industry with a paper on ISRU applications of Silicon
- 2004: assembled and managed a winning $14.3M NASA ISRU contract for Colorado School of Mines
- 2006: awarded existing NASA and AF SBIRs, where both advanced to Phase 2
- Today, we actively develop technologies in two domains:
  - Foundational Systems and Tools
  - Translating Low-Energy Industrial Processes to Space-based ISRU
- Our new facility at Centennial Airport combines our offices and laboratory facilities into a suite which includes an integration bay and technical library