Target Selection for a Hypervelocity Asteroid Intercept Vehicle Flight Validation Mission

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Outline

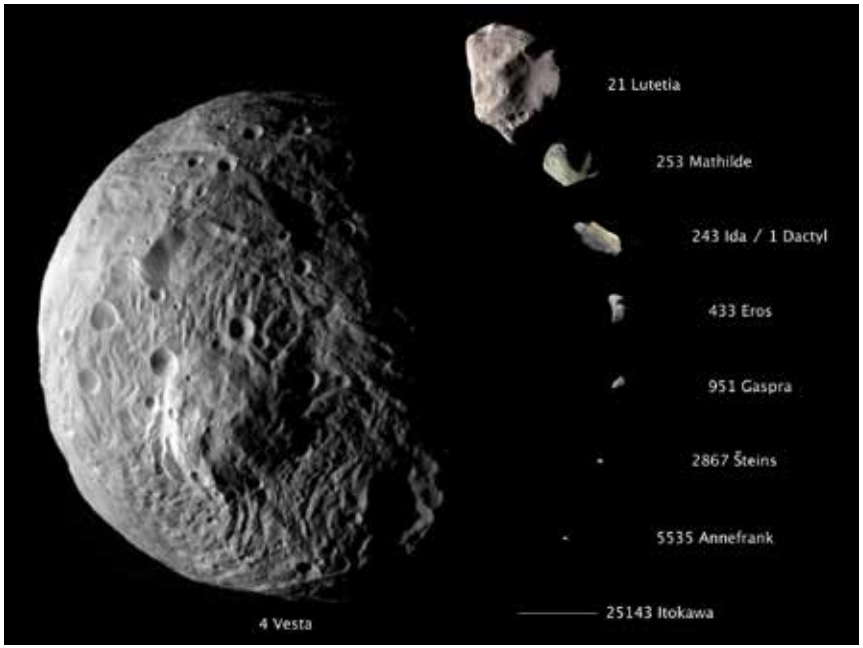


Image courtesy:
http://io9.com/5869960/is-vesta-a-giant-asteroid-or-a-protoplanet

- Introduction
- NEOs
- HAIV baseline S/C
- Problem formulation
  - Mission types and cost functions
- GA basics
- Results

Research Tasks

- **Determine targets for planetary defense demonstration mission**
  - **Baseline single hypervelocity impactor**
  - **Single launch observer s/c + impactor**
- **Utilize Hypervelocity Asteroid Intercept Vehicle (HAIV)**
  - **Being designed by ADRC and members at GSFC**
- **Develop mission design software**
- **Come up with list of target asteroids for each mission type considered**

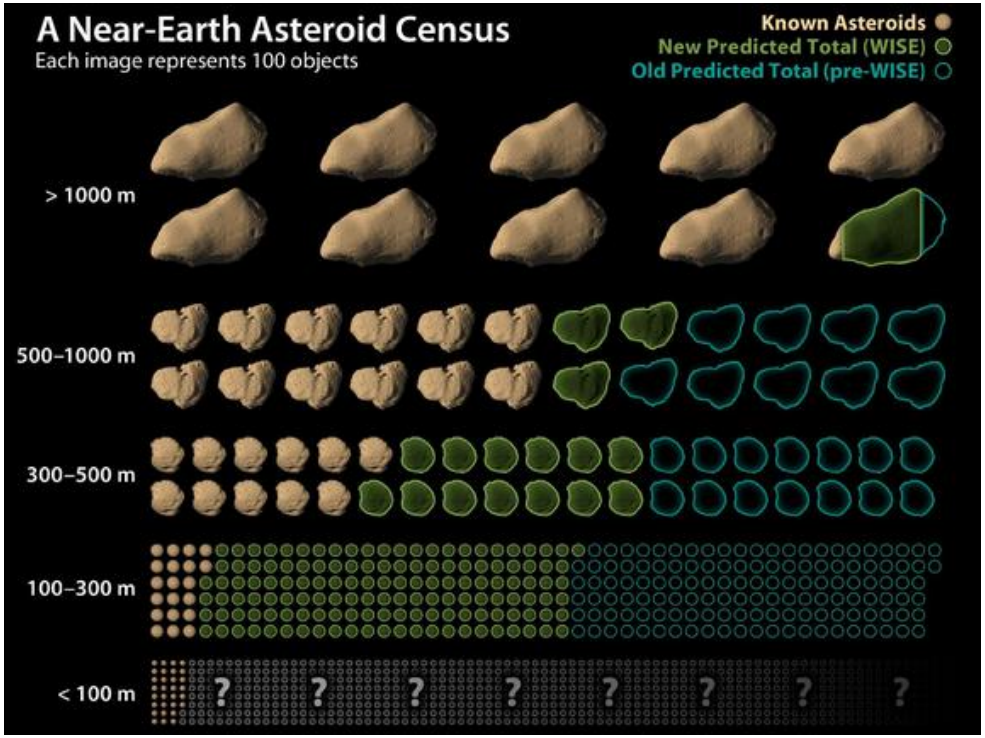
NEO Background

Past NEO Mission:

- NEAR-Shoemaker (NASA)
- Hayabusa (JAXA)
- Deep Impact (NASA)

Future NEO Missions:

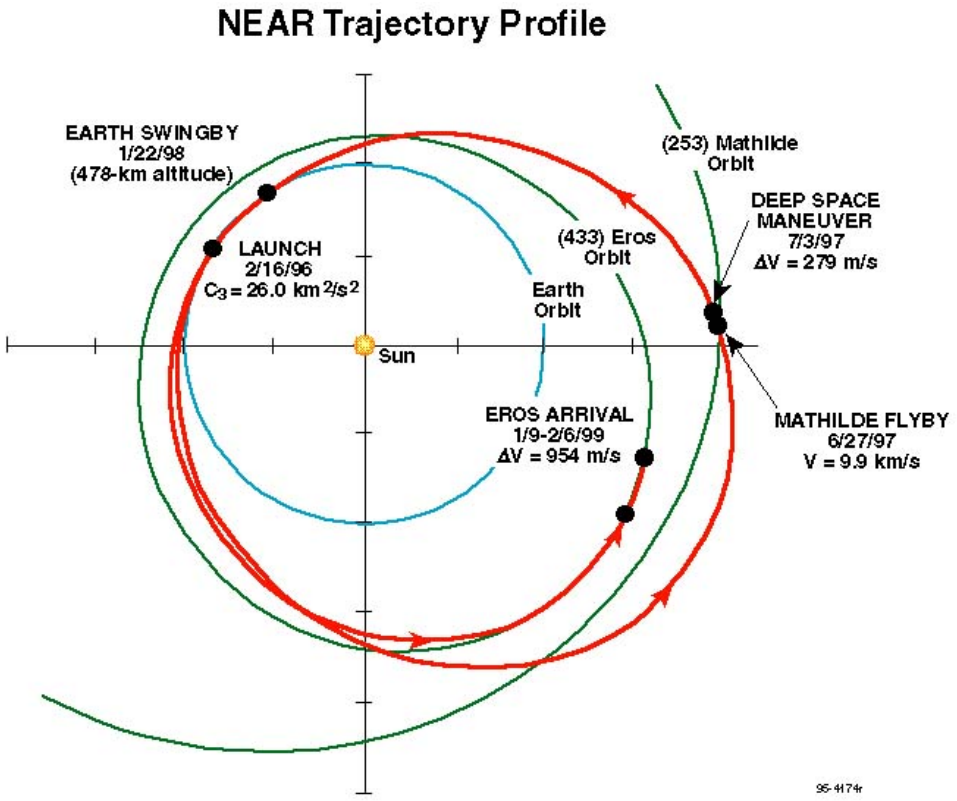
- OSIRIS-REx
- Proposed robotic and human exploration missions



NEO Background

NEAR Shoemaker

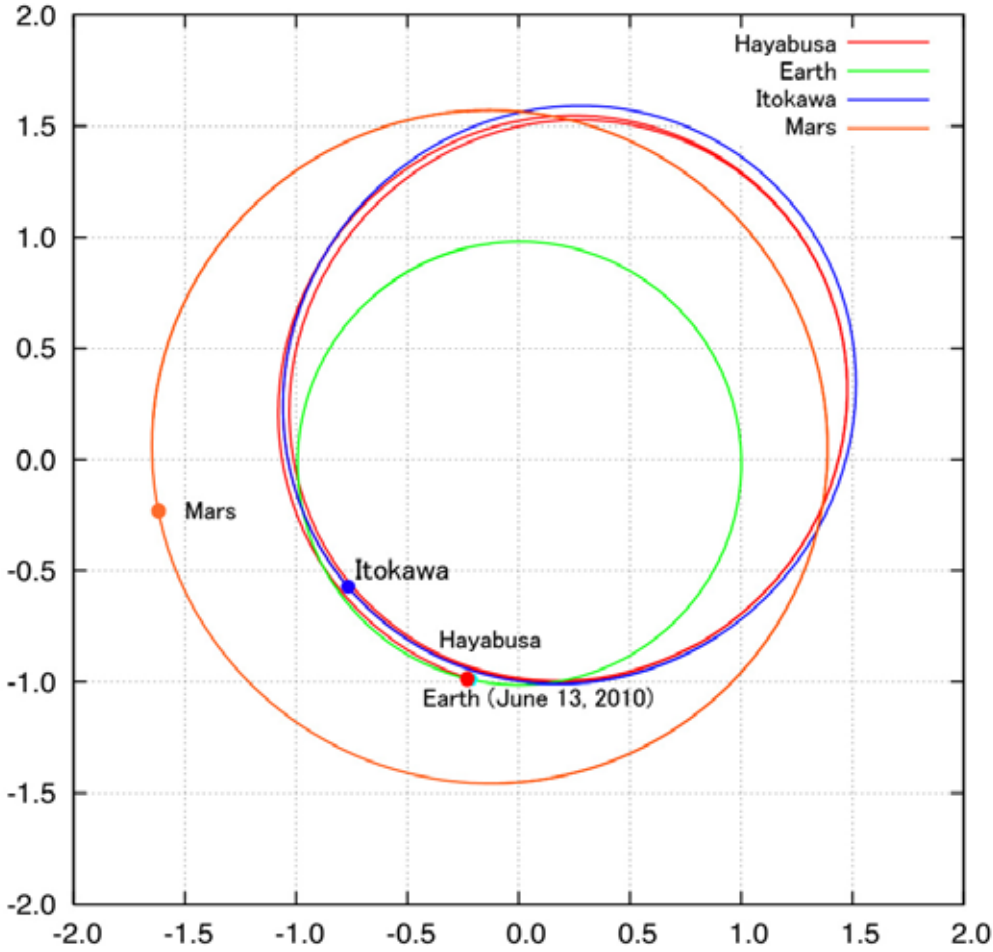
- Studied 433 Eros
- Launched Feb. 1996
- First to orbit and land on an asteroid
- Studied properties such as composition, magnetic field, etc.



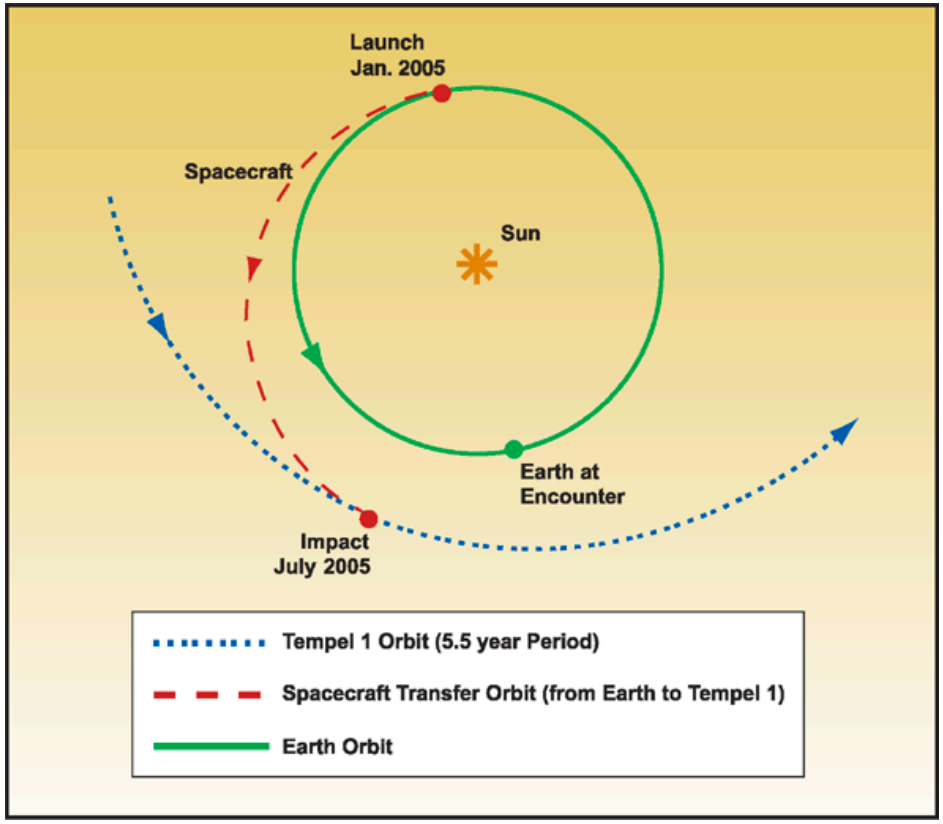
NEO Background

Hayabusa

- **Sample return mission to Itokawa**
  - **First ever sample return mission**
  - **MINERVA lander failed**
- **Launched May 2003**
- **Returned June 2010**



NEO Background



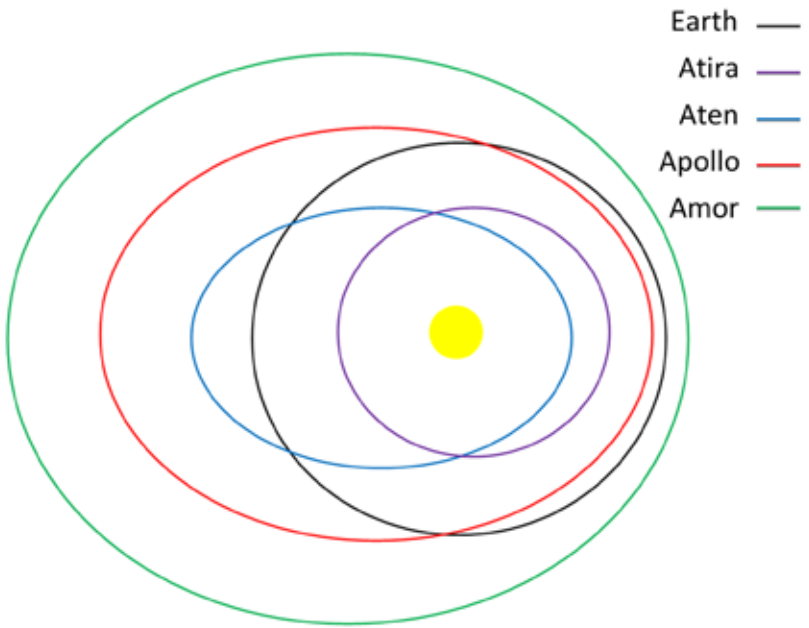
Deep Impact

- Launched Jan. 2005
- Tempel 1 impact on July 4th, 2005
- First hypervelocity impactor ~10 km/s
  - 5-km diameter
- Mission is still ongoing

NEO Background

NEO Groups

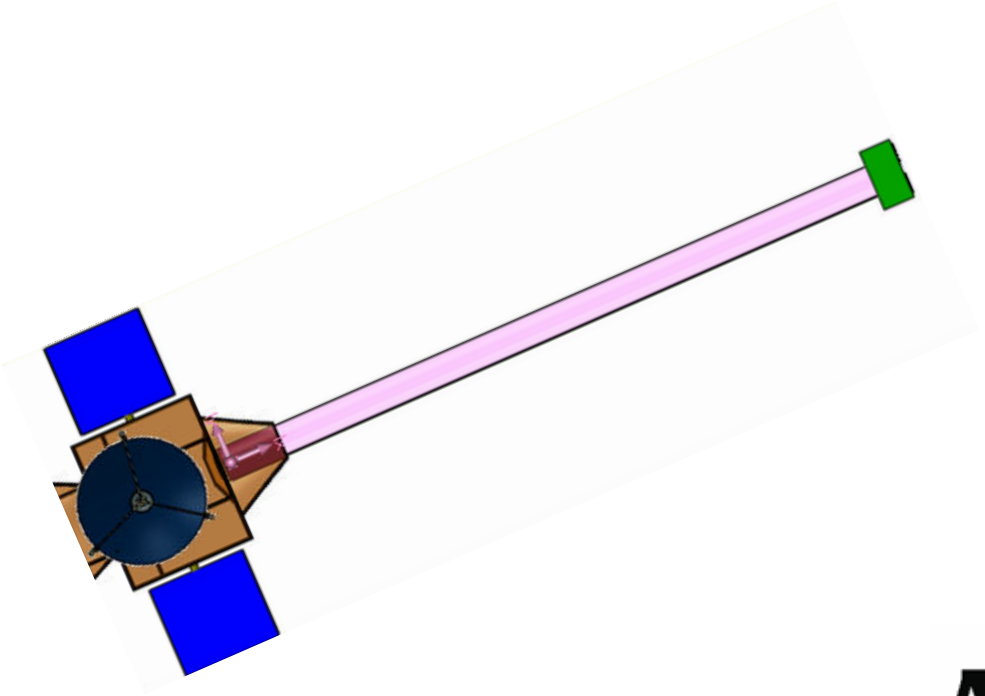
- Atira: a<1.0 AU, Q<0.983 AU
- Aten: a<1.0 AU, Q>0.983 AU
- Apollo : a>1.0 AU, q<1.017 AU
- Amor: a>1.0 AU, 1.017<q< 1.3



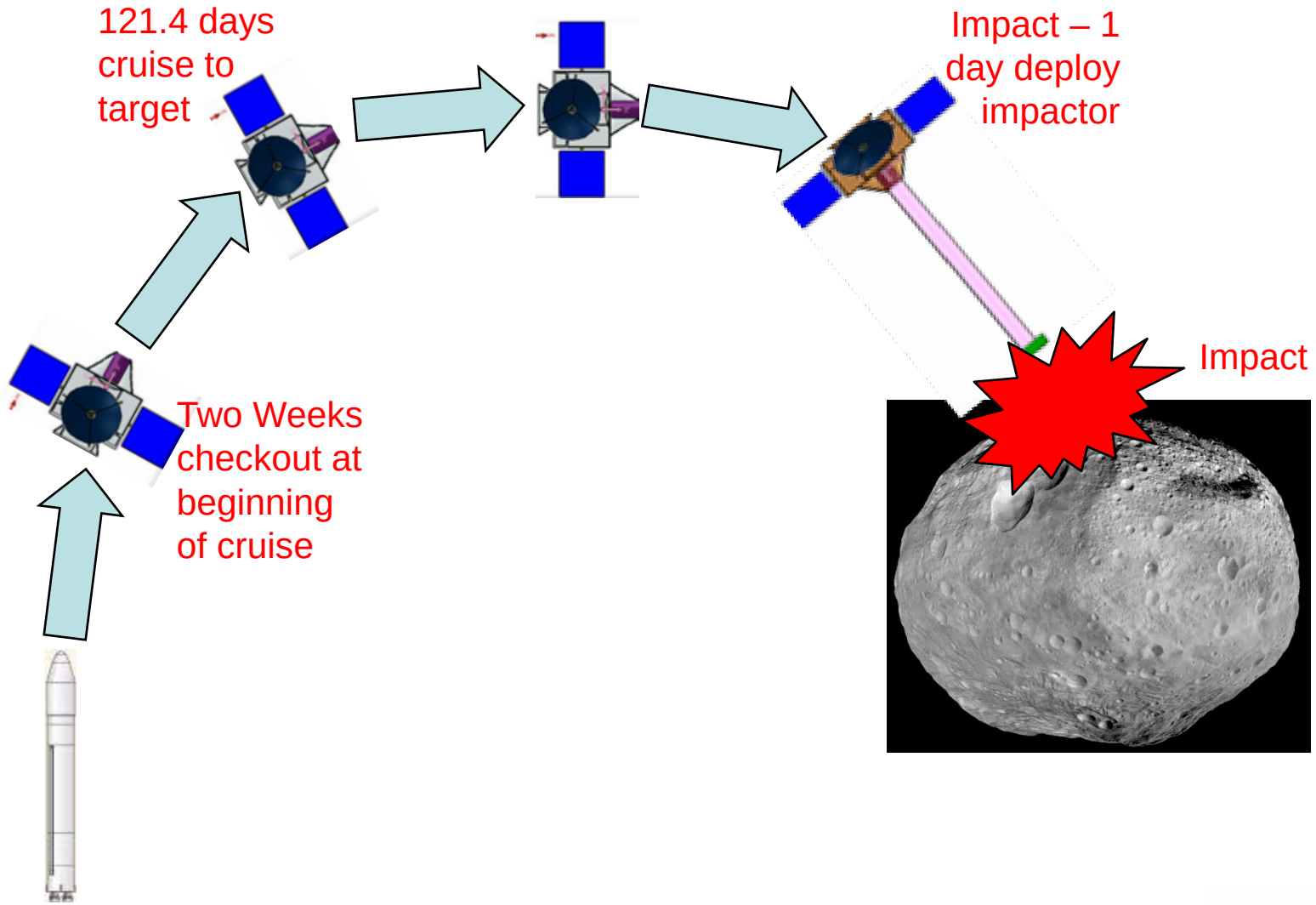
- Only Amor and Atira asteroids considered
  - No impact chance

HAIV

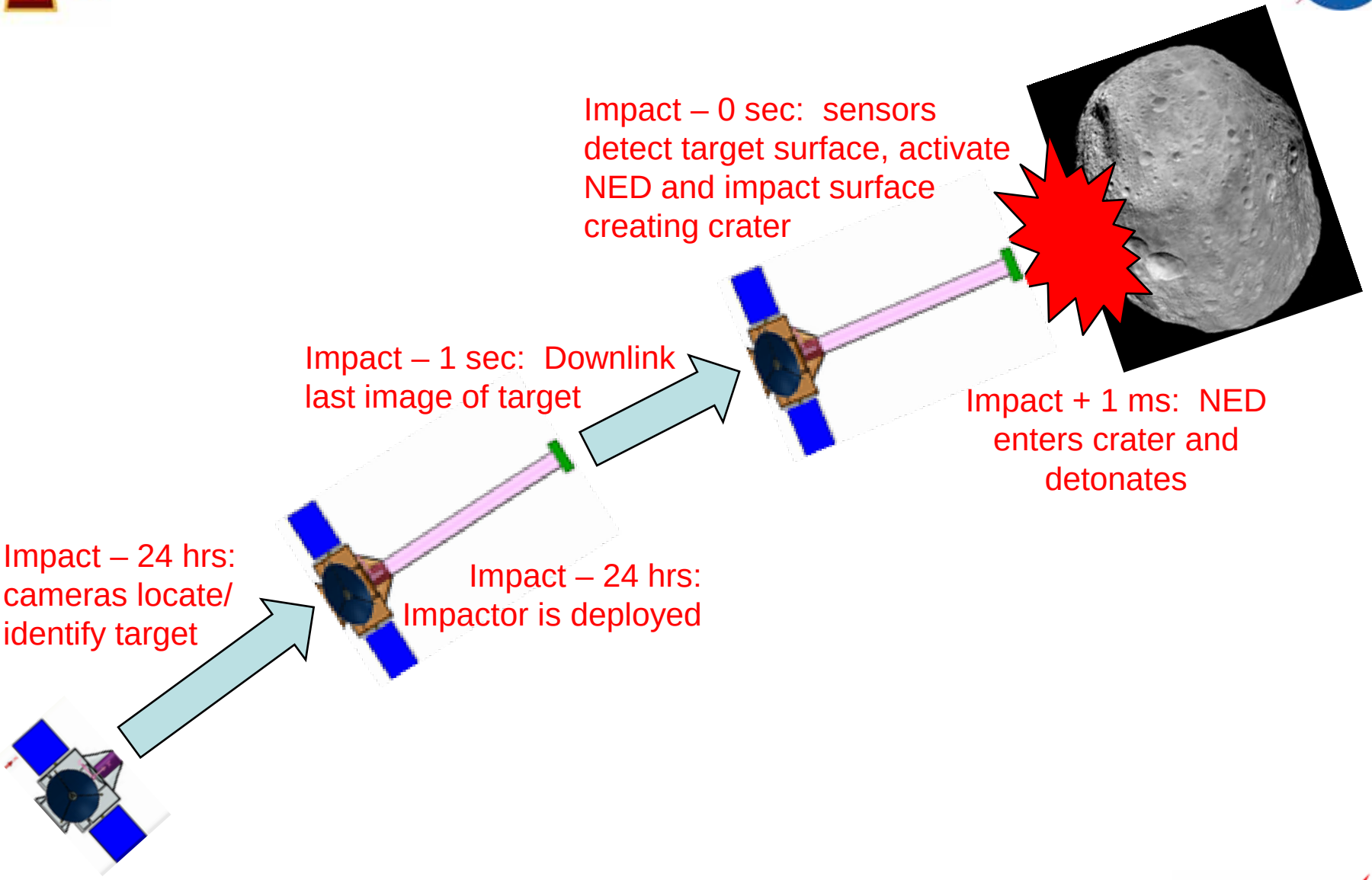
- Hypervelocity asteroid impact
- Assess the technical feasibility of a kinetic impactor (or HAIV) mission to hit an asteroid of diameter 50 m with desired accuracy



HAIV Mission Overview



HAIV Mission Overview



Problem Formulation

- **HAIV intercepts a target at 5-30 km/s**
- **Alternate single launch missions with observer and impactor**
  - **Rendezvous observer s/c must arrive prior to impactor**
- **Approximately 1500 asteroids searched for each mission type**

Earliest Launch Date	1-Jan-2018
Latest Launch Date	31-Dec-2022
Impact V (km/s)	5-30
H Magnitude Range	20.75-23.62
Impact Phase Angle	As close to 0 deg as possible
Communication LOS	>185 and <175
Max C_3 km^2/s^2	12.5, 30

Problem Formulation

- **Mission Problem Formulations**
- Single valued cost function
- Cost function typically consist of mission ΔV's, departure v_∞, and mission constraints
- 2 body dynamics
  - Lambert solution for main s/c
  - DSMs: Kepler's eqn.+Lambert solution

$$[R_{mid}, V_{mid-1}] = kepler(R_0, V_0, \epsilon T_1)$$

$$[V_{mid-2}, V_1] = lambert(R_{mid}, R_1, T_2)$$

$$\Delta V_{DSM} = |V_{mid-1} - V_{mid-2}|$$

Problem Formulation

Gravity Assist Model Basics

- Patch 2 Lambert Solutions
- Iterate to find eccentricity
- ΔV required by the gravity-assist can be determined

$$a_{in} = -\frac{\mu_p}{v_{\infty-in}^2}$$

$$a_{out} = -\frac{\mu_p}{v_{\infty-out}^2}$$

$$r_p = a_{in}(1 - e_{in}) = a_{out}(1 - e_{out})$$

$$\Delta V_{GA} = \left| \sqrt{v_{\infty-in}^2 + \frac{2\mu_p}{r_p}} - \sqrt{v_{\infty-out}^2 + \frac{2\mu_p}{r_p}} \right|$$

Problem Formulation

Mission Constraint Implementation (6)

- **Check radius for gravity-assists**

$$g_1 = -2 \log \frac{r_p}{1.1 R_p}$$

- **Time penalty**

$$g_2 = \begin{cases} 0.1(T_{s/c-arr} - T_{imp}) & T_{imp} < T_{s/c-arr} \\ 0 & T_{\frac{s}{c}-arr} \leq T_{imp} \end{cases}$$

- **Impact velocity limits (30 km/s max also checked)**
  - $g_3 = \begin{cases} 5 - v_{\infty-ast-arr} & v_{\infty-ast-arr} < 5.0 \\ 0 & v_{\infty-ast-arr} \geq 5.0 \end{cases}$

Problem Formulation

Mission Constraint Implementation

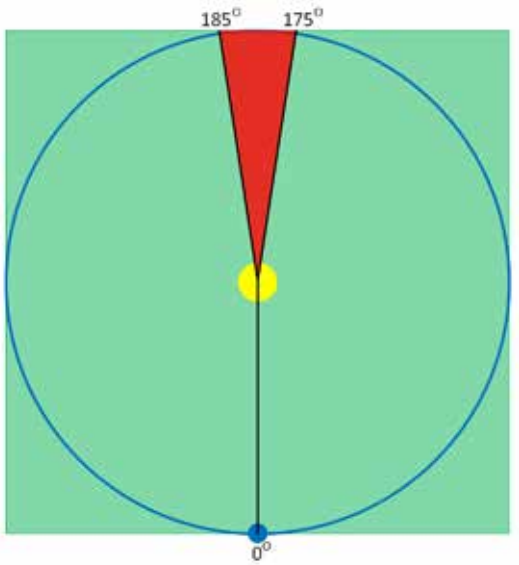
- Departure C_3 limit

$$g_4 = \begin{cases} v_\infty - \sqrt{C_{3max}} & v_\infty > \sqrt{C_{3max}} \\ 0 & v_\infty \leq \sqrt{C_{3max}} \end{cases}$$

- Approach phase angle

$$\theta_A = \cos^{-1}(\hat{e}_r \cdot \hat{e}_v)$$

$$g_5 = \frac{1}{\pi}\theta_A$$



- LOS communication angle

$$g_6 = \begin{cases} e^{-1/(1-(LOS-180^o)^2)} & 175^o \leq LOS \leq 185^o \\ 0 & all\ other\ angle \end{cases}$$

Problem Formulation

- **Final cost functions consist of all necessary penalties and DSMs**

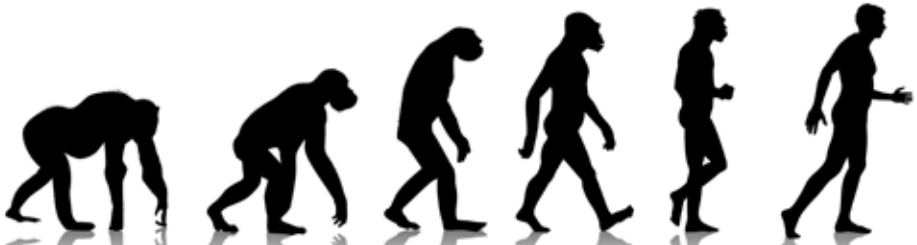
$$C = \sum g_i + \sum \Delta V_{DSM-i} + \sum \Delta V_{GA-i}$$

- **More advanced mission types were tested, but require long run times for a search of 1500+ asteroids**
  - **In the future a GPU implementation of the search will enable more complex mission searches**

Genetic Algorithm: Basics

- One Class of evolutionary algorithms
  - No initial guess required
- Traditionally not used for mission design
  - No proof of convergence
  - Not designed for unconstrained minimization
  - NLP solvers are gradient based
- Other mission design groups have recently begun to use evolutionary algorithms
  - As mission complexity increases exhaustive searches become prohibitive

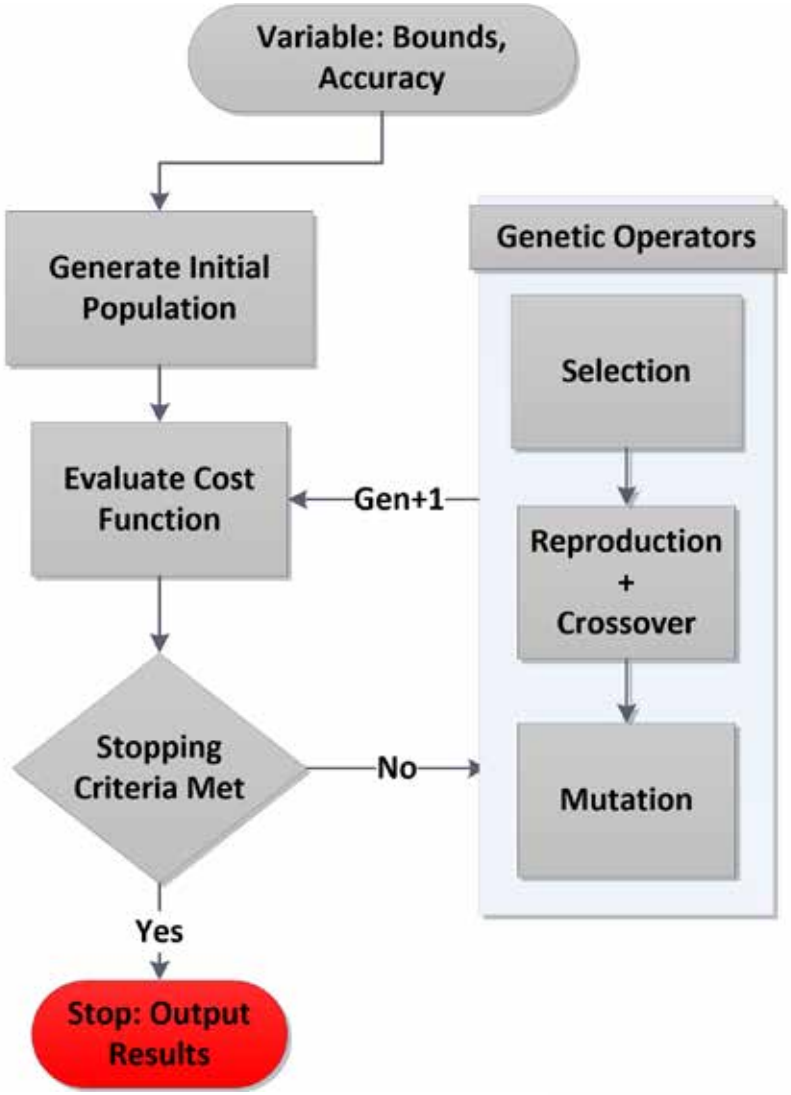
Genetic Algorithm: Basics



- **Based on Darwin's theory of evolution**
  - **Natural selection**
  - **Biological reproduction**
  - **Random genetic mutations**
  - **Elitism**
- **An initial population is randomly generated and "evolved" to more fit solutions**
  - **Selection, reproduction, crossover, mutations**

Genetic Algorithm: Basics

- **Genetic algorithm inputs:**
  - Variable bounds, accuracy
  - Population size
  - Number of generations
  - Reproduction, crossover, and mutation probabilities, type
- **Possible stopping criterion**
  - Max # of generations
  - Stagnation of best solution
  - Average cost approaches best solution
- **Initial population randomly generated**



Genetic Algorithm: Performance

Mutation Type

Crossover Type	Flip Bit		Uniform		Boundary		Inversion	
	Cost (km/s)	Time (sec)	Cost (km/s)	Time (sec)	Cost (km/s)	Time (sec)	Cost (km/s)	Time (sec)
Uniform	*6.51*	*816.814*	*6.938*	*830.543*	*6.805*	*924.832*	*6.536*	*857.554*
Uniform Gene	*4.903*	*830.455*	*5.05*	*896.438*	*5.626*	*827.157*	*5.368*	*854.672*
Single Point	*5.182*	*823.98*	*4.148*	*895.148*	*4.636*	*827.59*	*4.687*	*856.197*
Double Point	*4.389*	*816.464*	*3.731*	*915.24*	*5.137*	*846.842*	*3.363*	*827.83*

- **What crossover/mutation types work best**
  - **Cassini mission**
  - **Population size of 20,000**
  - **200 generations**
- **Best combination is double point crossover and inversion mutation**

Results: Direct Intercept

- Single launch
- No rendezvous S/C
- 1500 asteroids searched

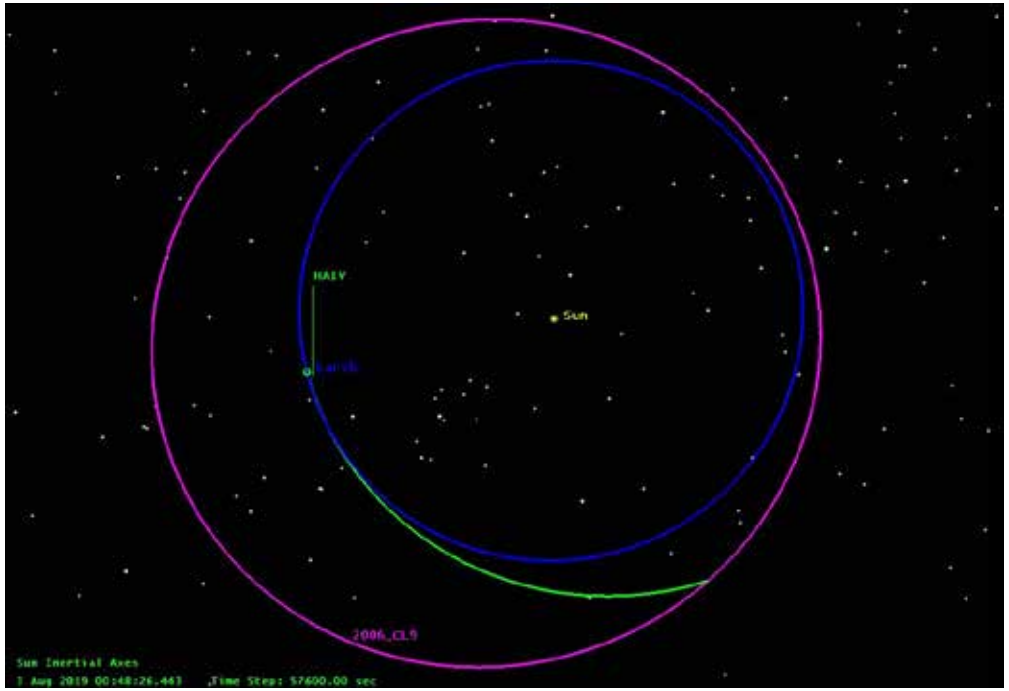
- C_3 limit of 12.5 used
  - Allow smaller (cheaper) launch vehicle
- 100's of asteroids require no ΔV
  - Except small TCMs

Asteroid	2006 CL9	2009 QO5	2004 BW18
a (au)	1.35	1.59	1.37
e	0.24	0.24	0.25
Diameter (m)	104.85	105.82	97.40
Departure C3 (km^2/s^2)	11.99	12.50	12.49
Require S/C Δ-V (km/s)	**0.00**	**0.00**	**0.00**
LOS Angle	349.01	349.33	333.17
Sun Approach Angle	3.04	28.05	34.21
Departure Date	2-Aug-19	27-Mar-19	7-Apr-19
TOF (days)	121.41	124.38	268.45
OCC	5	1	5
Arrival Velocity	**11.53**	**9.22**	**6.57**

Results: Direct Intercept

2006 CL 9

- Target Body: 2006 CL9
- Launch Date: August 2, 2019
  - Nominal Launch Case
    - C3: 11.99 km^2/s^2
    - Outgoing Asymptote RA = 52.4°
    - Outgoing Asymptote Dec = -12.0°
- Departure Date: August 2, 2019
- TOF: 121.41 days
- Arrival Date: December 1, 2019
- Intercept Velocity: 11.5 km/s
- Approach phase angle: 3°
- Max. Dist. from Earth: 0.36 AU
- Max. Dist. from Sun: 1.28 AU
- Total DV: 37.1 m/s



Results: Advanced Missions

- Rend. S/C+ HAIV
- Single launch vehicle
- Utilize DSMs and GAs
- 4 Final mission types
- Other mission types considered

– **Type 1:**
  - **Rend. S/C direct injection + HAIV DSM**

– **Type 2:**
  - **HAIV direct injection + Rend. S/C DSM**

– **Type 3:**
  - **Rend. S/C direct injection + HAIV DSM/GA**

– **Type 4:**
  - **Rend S/C direct injection + HAIV DSM/2xGA**

Results: Type 1 Missions

Asteroid	2010 KU7	2012 JX11	2001 CK42	2009 CR4	2000 RD53
a (au)	1.67	1.97	1.42	1.75	1.79
e	0.381	0.475	0.281	0.419	0.428
Diameter (m)	94.74	58.42	265.80	122.62	279.61
Total DV	**3.299**	**3.518**	**3.711**	**3.737**	**3.755**
Launch Date	14-Jul-21	7-Jun-18	18-May-18	28-Apr-21	19-Oct-22
Impactor TOF (days)	668.356	801.317	542.820	676.738	651.854
Rend. TOF (Days)	381.743	472.330	329.512	405.902	365.241
C3	25.584	33.860	16.815	33.803	24.088
Imp. DSM (km/s)	2.387	1.990	3.258	2.153	2.030
Rend. Arr. DV (km/s)	0.912	1.186	0.453	1.247	1.725
LOS (deg)	26.164	257.769	128.765	19.857	39.917
Sun Angle (deg)	97.820	102.315	92.953	94.386	106.090
Imp. Vel. (km/s)	**5.001**	**5.001**	**5.000**	**5.000**	**5.000**

Results: Type 2 Missions

Asteroid	2000 WO148	2009 TV4	1998 UM1	1996 FO3	2008 XB
a (au)	1.64	1.69	1.7	1.44	1.51
e	0.376	0.37	0.402	0.29	0.313
Diameter (m)	198.9	59.2	60.1	212.1	81.4
Total DV	**2.603**	**2.657**	**2.709**	**2.926**	**2.942**
Launch Date2	19-Jan-20	27-Sep-20	20-Sep-18	11-Feb-22	2-Dec-21
Rend TOF (days)	515.347	335.871	404.795	353.638	395.915
Impactor TOF (days)	373.451	550.537	488.660	362.521	404.855
C3	26.636	29.154	33.104	16.800	24.198
Rendezvous DSM (km/s)	1.265	0.562	1.448	0.951	1.632
Rend. Arr. DV (km/s)	1.338	2.095	0.976	1.975	1.310
LOS (Deg)	64.029	198.157	149.624	202.840	163.150
Sun Angle (deg)	91.704	100.956	60.920	90.103	100.676
Imp. Vel (km/s)	**5.047**	**5.000**	**4.992**	**5.004**	**5.000**

Results: Type 3 Missions

Asteroid	2012 OO	2008 XB	2000 WO148	2009 CO5	1996 FO3
Diameter (albedo=0.25)	214.07	81.39	198.86	119.83	212.11
Total ΔV	**1.145**	**1.322**	**1.410**	**1.430**	**1.539**
Launch Date	3-Sep-21	13-Dec-21	15-Jan-20	14-Mar-22	21-Feb-22
Rend. TOF (days)	627.812	231.753	569.599	553.895	245.288
Imp. TOF Leg 1 (days)	625.840	685.350	626.402	630.144	699.471
Imp. TOF Leg 2 (days)	70.945	226.789	156.689	716.637	275.928
C3	34.509	29.678	27.570	30.354	30.460
Impactor ΔV (km/s)	0.546	0.764	0.264	0.496	1.094
Rend. Arrival ΔV (km/s)	0.599	0.558	1.146	0.934	0.445
GA Planet	Earth	Earth	Earth	Earth	Earth
GA Perigee Rad (km)	7397.560	17249.044	8032.784	30908.181	13097.549
LOS (deg)	348.472	289.519	316.493	332.860	281.732
Sun Angle (deg)	134.721	6.243	156.973	164.746	4.909
Imp. Arr. Vel. (km/s)	**5.798**	**5.118**	**6.149**	**5.016**	**5.601**

Results: Type 4 Missions

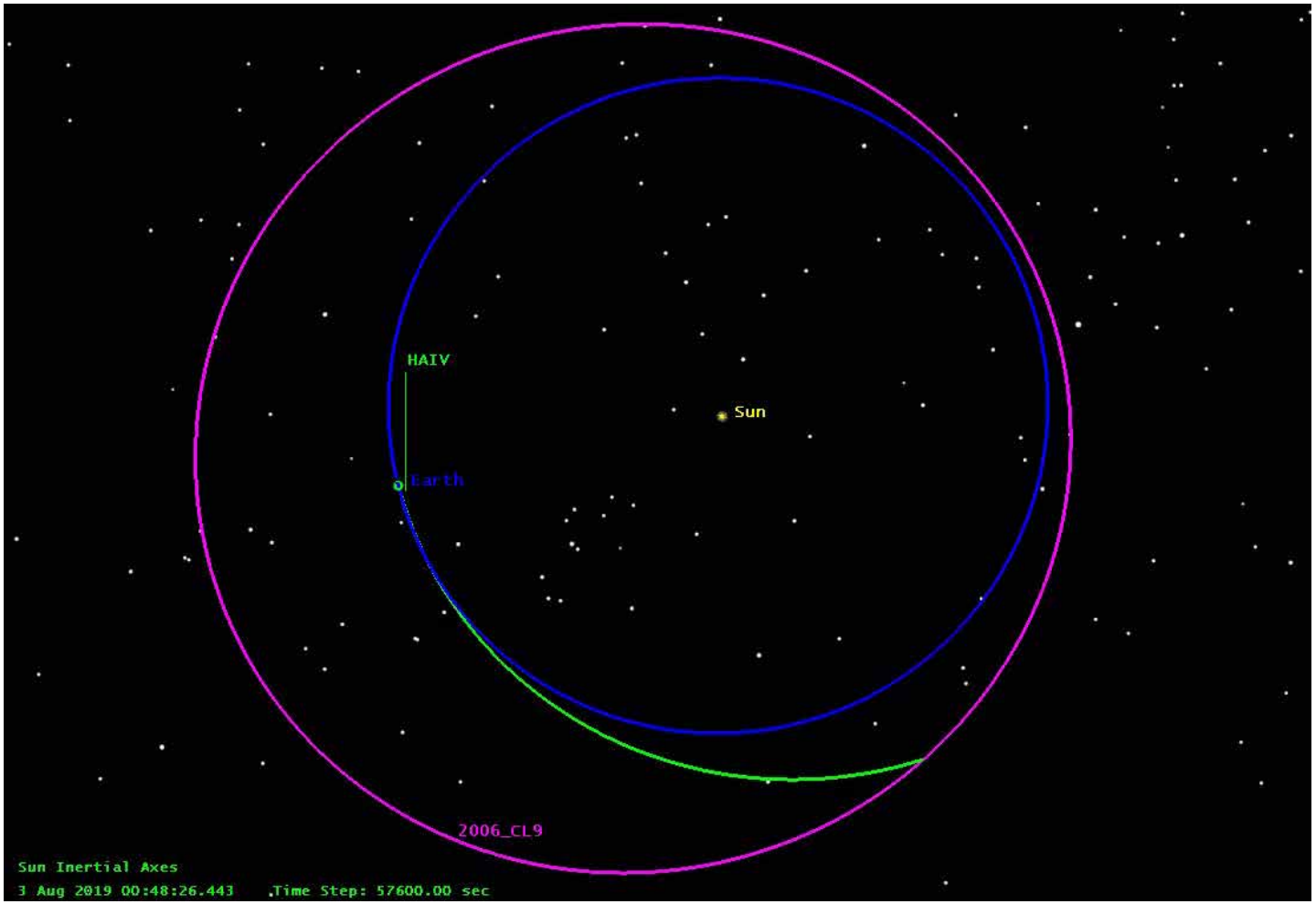
Asteroid	2012 CR	2011 FR17	2010 XB73	2010 GZ33	2011 AL24
Diameter (km)	120.38	55.53	102.46	90.90	91.32
Total Delta-V	**0.608**	**1.005**	**1.218**	**1.254**	**1.306**
Launch Date	25-Feb-19	10-Mar-22	30-Nov-19	3-Apr-18	10-Jan-20
Rendezvous TOF (days)	366.722	405.961	351.305	325.152	391.061
Impactor TOF Leg 1 (days)	692.292	702.523	694.408	682.899	692.473
Impactor TOF Leg 2 (days)	44.823	569.094	351.721	1223.708	1126.003
Impactor TOF Leg 3 (days)	605.125	533.076	540.387	767.832	565.256
C3	26.788	29.499	30.623	30.008	32.096
Impactor S/C Delta-V	0.461	0.303	0.230	1.150	0.373
Rendezvous S/C Delta-V	0.147	0.702	0.988	0.104	0.933
Perigee Radius 1	34570.970	32342.255	40987.783	7151.113	19785.661
Peridgee Radius 2	28356.505	87771.992	21174.207	20645.644	91586.652
LOS Angle (deg)	341.415	54.077	30.175	201.362	26.862
Sun Angle (deg)	175.912	168.543	167.575	174.940	167.531
Impactor Velocity	**12.271**	**9.541**	**7.213**	**19.394**	**10.213**

Summary

Asteroid	Mission Type	Delta-V (km/s)	Diameter (m)
2006 CL9	Direct	0	105
2010 KU7	Type 1	3.3	95
2000 WO148	Type 2	2.6	199
2012 OO	Type 3	1.15	214
2012 CR	Type 4	0.6	120

- **Baseline mission require no ΔV**
- **Utilizing 2 gravity-assists brings required ΔV to approximately 600 m/s**
- **Once GPU version is mature additional advanced mission types can be analyzed**

Questions


HAIV
Sun
Earth
2006_CL9
Sun Inertial Axes
3 Aug 2019 00:48:26.443 .Time Step: 57600.00 sec

HAIV Flight Demo Mission

Baseline Mission

- Target Body: 2006 CL9
- Launch Date: August 2, 2019
- Launch Vehicle: Atlas V 401
  - Nominal Launch Case
    - C3: 11.99 km^2/s^2
    - Outgoing Asymptote RA = 52.4°
    - Outgoing Asymptote Dec = -12.0°
- Time at Injection: August 2, 2019 08:47:26.443 UTCG
- Elapsed Time of Flight: 121.41 days
- Time of Intercept: December 1, 2019 18:37:50.443 UTCG
- Target relative velocity at intercept: 11.5 km/s
- Approach phase angle at intercept: 3°
- Total Mission DV: 37.1 m/s