Identifying Accessible Near-Earth Objects for Crewed Missions with Solar Electric Propulsion

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Motivation

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- Growing interest in human exploration of Near-Earth Objects(NEOs)
- Crucial step in designing crewed missions to NEOs is identification of good targets
- Near-earth object Human space flight Accessible Targets Study (NHATS)
  - Only for chemical trajectories
  - Low thrust options were not considered because of computational cost
- This research lays some of the foundation for expanding the NHATS study with solar electric propulsion

Source: http://neo.ssa.esa.int/

NHATS background

- Identify all feasible trajectories to NEAs to all asteroids in time frame 2015-2040
- Requirements:
  - Total mission ΔV ≤ 12 km/s
  - Mission duration ≤ 450 days
  - Stay time ≥ 8 days
  - Re-entry velocity ≤ 12 km/s at 125 km
- Trajectory design: Lambert solver
- Highly automated system: automatically re-computes trajectories for asteroid when ephemeris of asteroid is updated, as well as automatically computing trajectories for newly discovered asteroids

Goal

- To identify attractive rendezvous missions with NEAs using solar electric propulsion

- Compare those attractive SEP rendezvous trajectories with the chemical trajectories
  - Comparison is complicated by different nature of chemical and SEP trajectories

Comparison considerations

- Chemical trajectories are ranked based on total mission ΔV
  - SEP operates on longer time scales → also at kinematically inefficient points (gravity losses) → higher ΔV
  - SEP has higher Isp → less propellant mass for same ΔV

➡ Unfair to only compare on total mission ΔV

- Comparison will be made based on initial mass in low-Earth orbit (IMLEO)

- For same payload mass, increasing IMLEO for chemical systems leads to higher achievable ΔV, increasing mission opportunities
  - SEP systems can only expel certain amount of propellant in certain time frame dependent on power of system
  - Increasing IMLEO / propellant mass does not always result in more mission opportunities

➡ Power largely influences the comparisons

Method

- Use chemical trajectories to estimate lower bound on required power for each SEP trajectory
  - Use this information as filter for SEP trajectories to avoid running clearly infeasible trajectories
- Implement SEP & optimize trajectories
  - Using chemical trajectory design variables as initial guess
- Compute IMLEO for both SEP and chemical trajectories and compute their difference

Method – filtering of 2000 SG344

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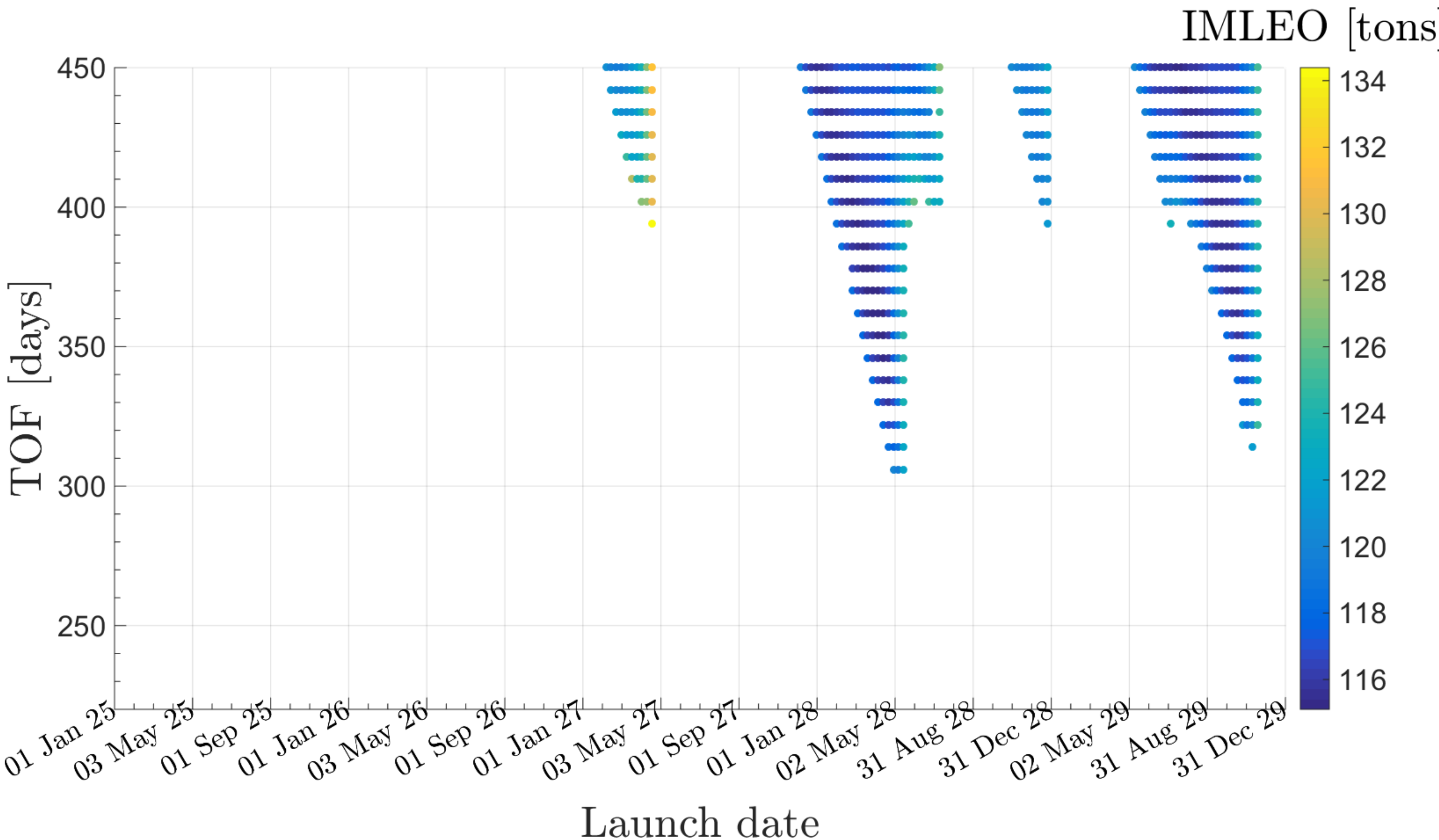
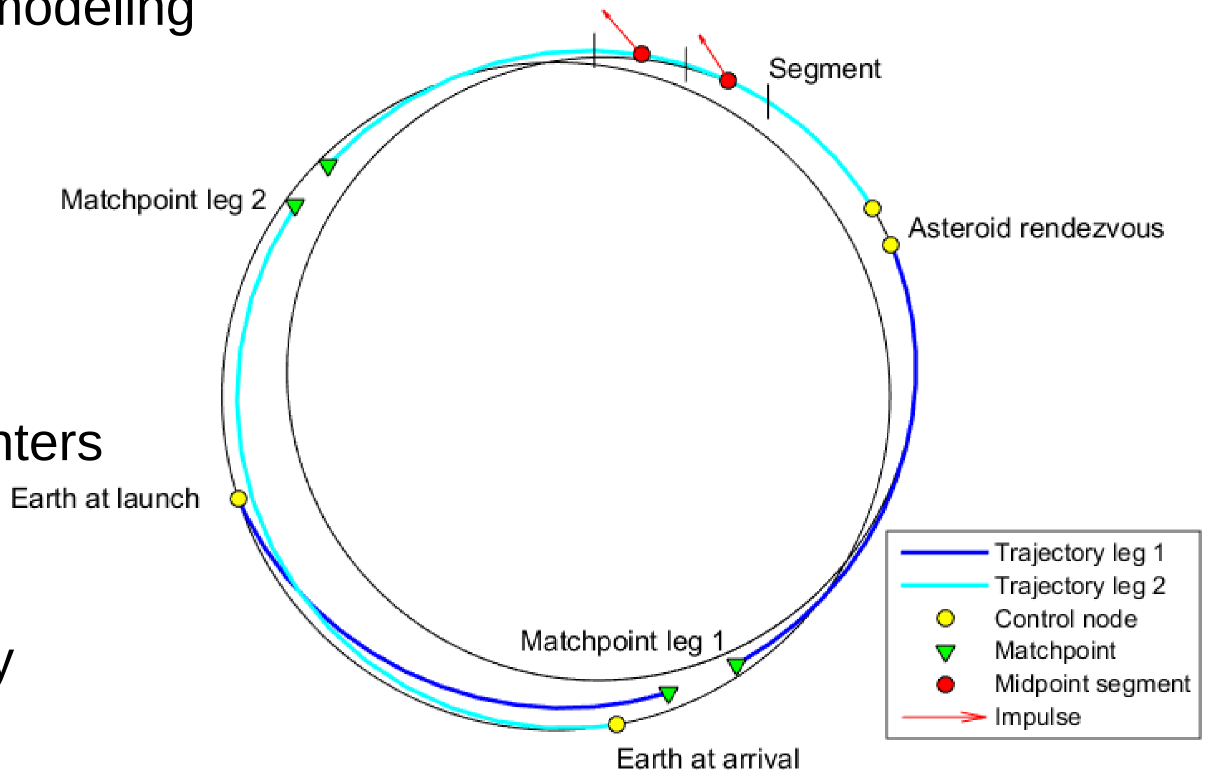


Method – trajectory optimization

- Sims-Flanagan based modeling
- Model low-thrust by small impulsive burns
- Control nodes at planetary / NEO encounters
- Matchpoint constraints for continuous trajectory
- Solved using SNOPT



Adapted from Sims et al., 2006

Optimization parameters

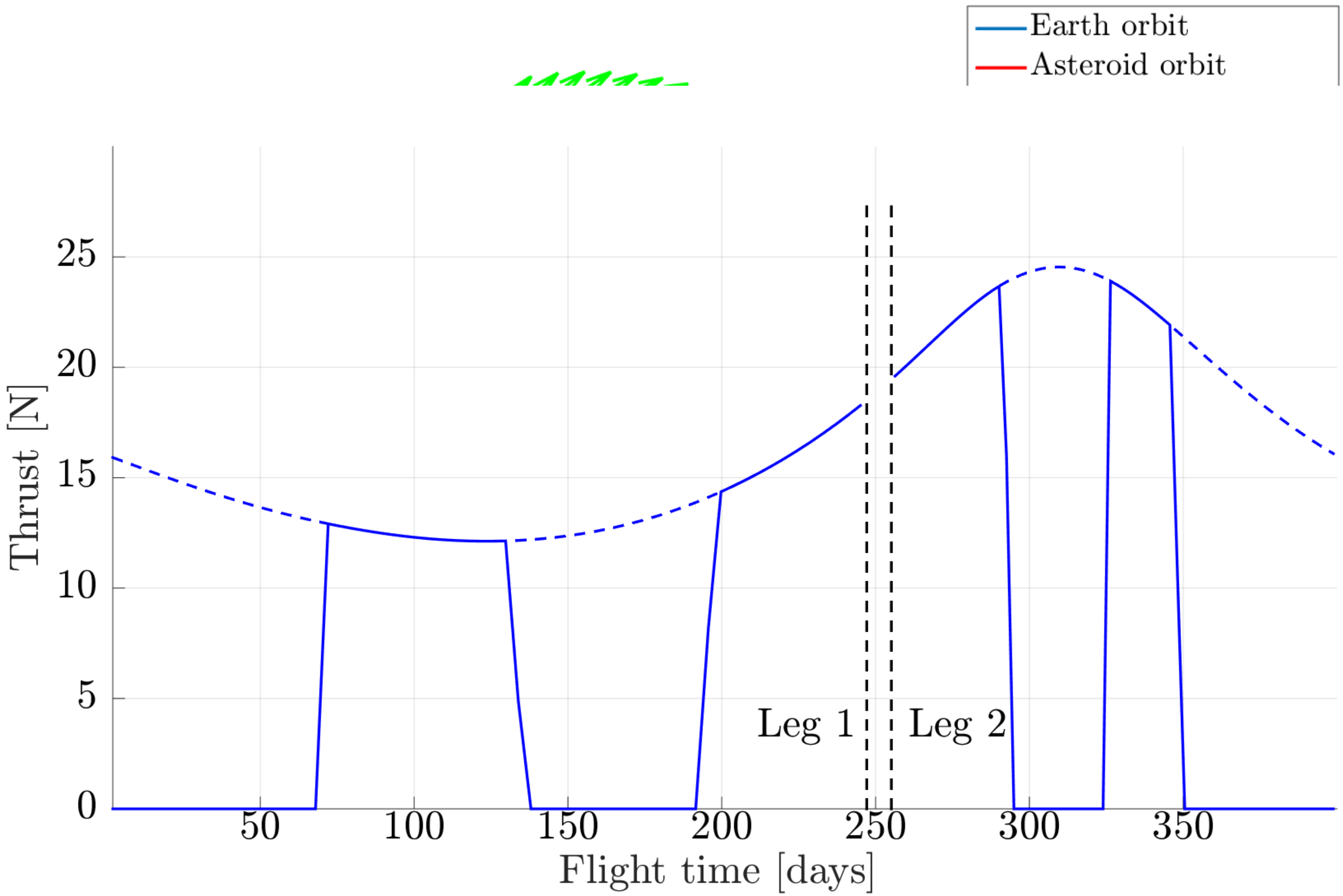
Assumptions for SEP

Mass-to-power ratio	30 kg/kW
Jet efficiency	60%
Duty cycle	90%
Chemical specific impulse	450 s
Specific Impulse	2000 s

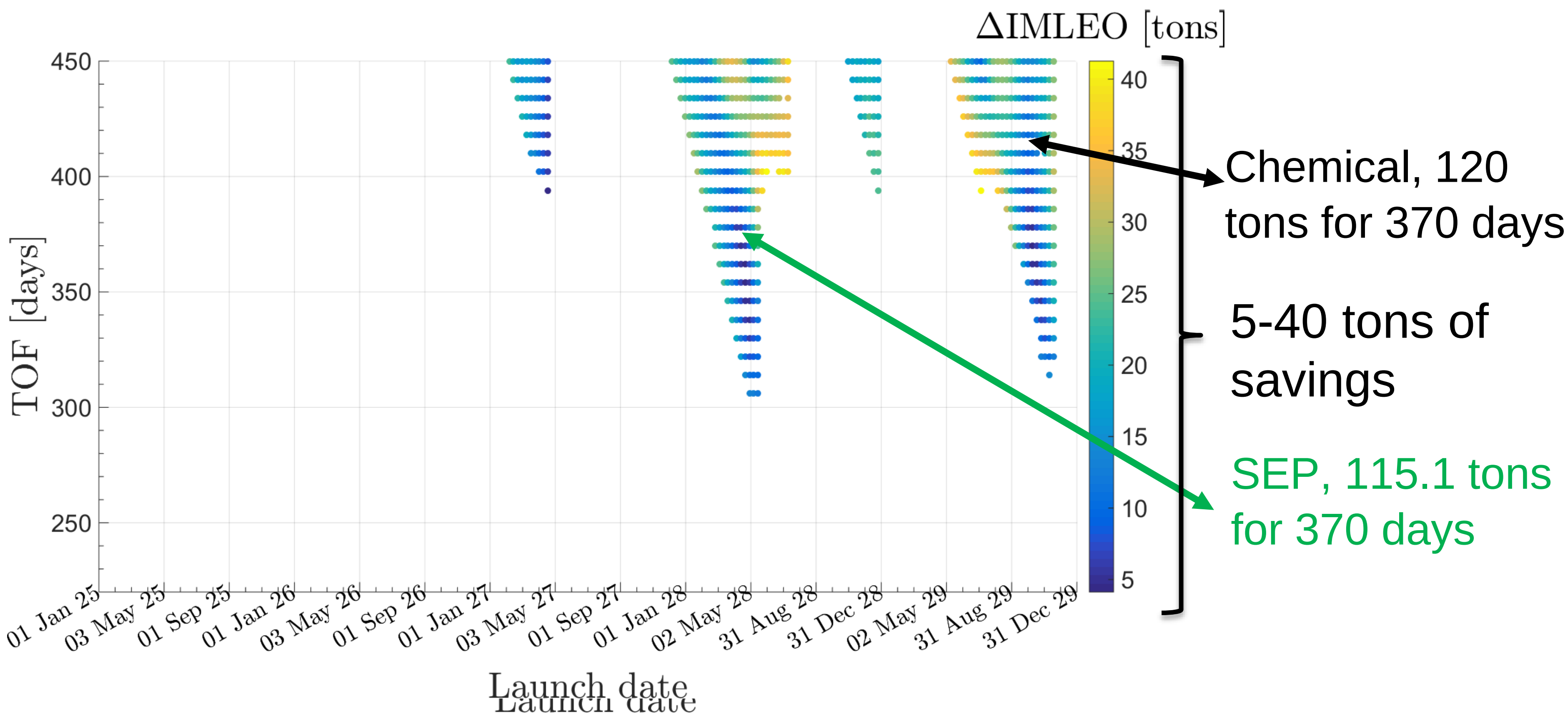
Derived from NHATS

Maximum re-entry velocity	12 km/s
Maximum total mission duration	450 days

Trajectory example



Results



Asteroid	2000 SG344
Power:	50 kW

Results

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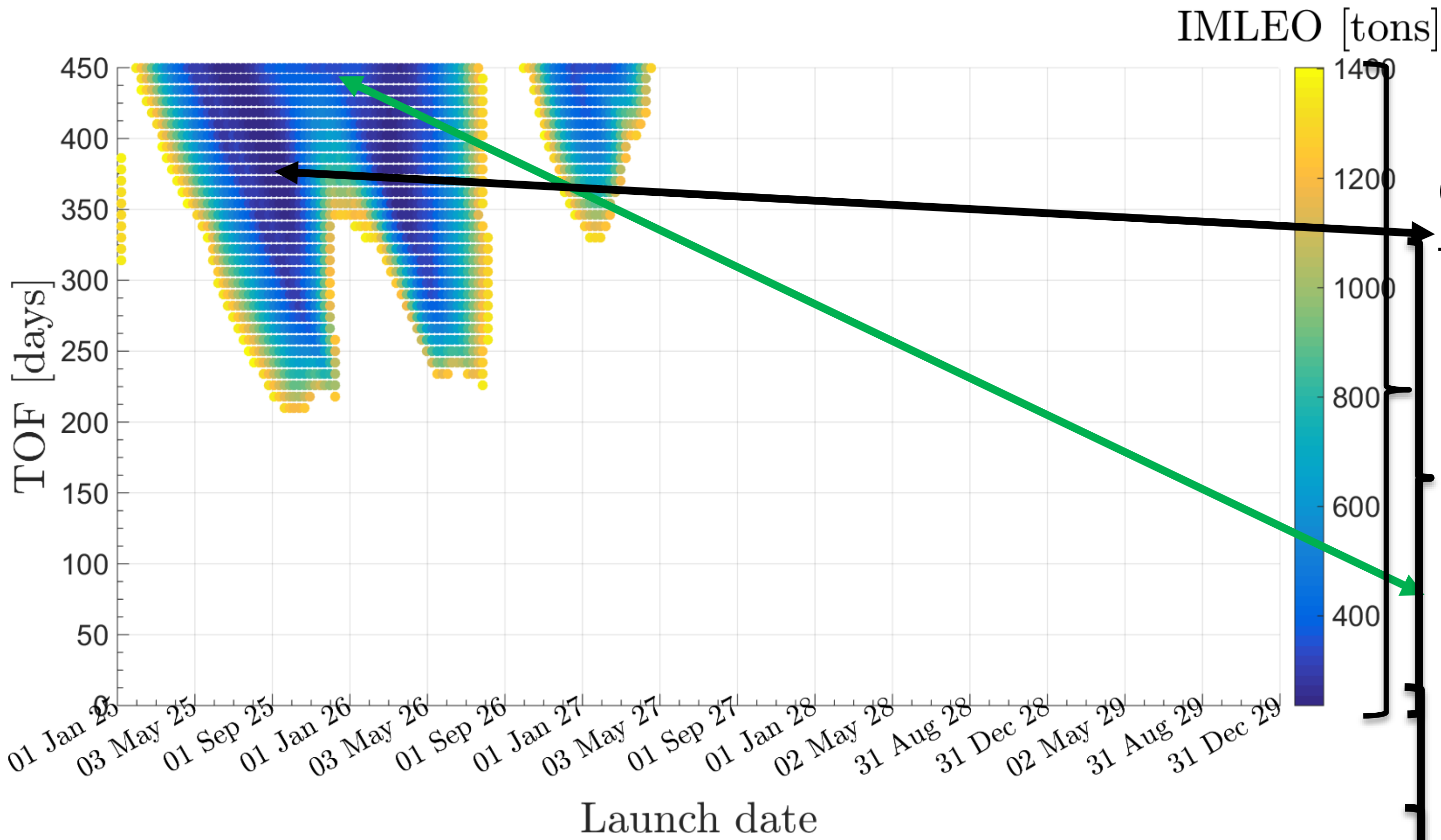

Chemical, 236 tons for 386 days

180-270 tons of savings

2 SLS 4xRL LEO capability

SEP, 151.1 tons for 450 days

3 SLS 4xRL LEO capability

2 SLS 4xRL LEO capability

Asteroid:	2015 BM510
Power:	150 kW

Additional results

- 2004 VJ1 - 150 kW: similar to 2015 BM510: could be launched with 2 SLS 4xRL10, its chemical counterpart needs at least 3 SLS 4xRL10

- Also scenarios with 300 kW have been investigated
  - Launch window for 3 SLS 4xRL10 with SEP allows for smaller TOF's than chemical

Conclusion on research

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- SEP can be used to significantly enhance crewed NEO rendezvous missions
  - Initial mass in LEO can be reduced
  - Launch periods can be extended
  - Additional mission opportunities become available
  - TOFs can be reduced
- These benefits are not achievable with traditional impulsive maneuvers
- Results presented here suggest that many other targets in the asteroid population would enjoy similar performance improvements through the use of SEP

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Extra slides

- Extra slides

Method - filtering

- Rough guess for required spacecraft power is

$$P_0 = \frac{\Delta V \cdot m_{\text{avg}} \cdot I_{\text{sp}} \cdot g_0}{2\Delta t \cdot \eta_{\text{jet}} \cdot \varepsilon_T}$$

- Average mass is the average of the mass after the chemical departure burn and the mass at Earth return

$$m_{\text{avg}} = \frac{m_{0,\text{SEP}} + M_{\text{Earth return}}}{2} = \frac{M_{\text{Earth return}}}{2} \cdot \left(1 + \exp\left(\frac{\Delta V}{I_{\text{sp}} \cdot g_0}\right)\right)$$

- This gives

$$P_0 = \frac{\Delta V \cdot m_{\text{PL}} \cdot \left(1 + \exp\left(\frac{\Delta V}{I_{\text{sp}} \cdot g_0}\right)\right) \cdot I_{\text{sp}} \cdot g_0}{4\Delta t \cdot \eta_{\text{jet}} \cdot \varepsilon_T - k_{P_0} \cdot \Delta V \cdot I_{\text{sp}} \cdot g_0 \left(1 + \exp\left(\frac{\Delta V}{I_{\text{sp}} \cdot g_0}\right)\right)}$$

IMLEO formulation

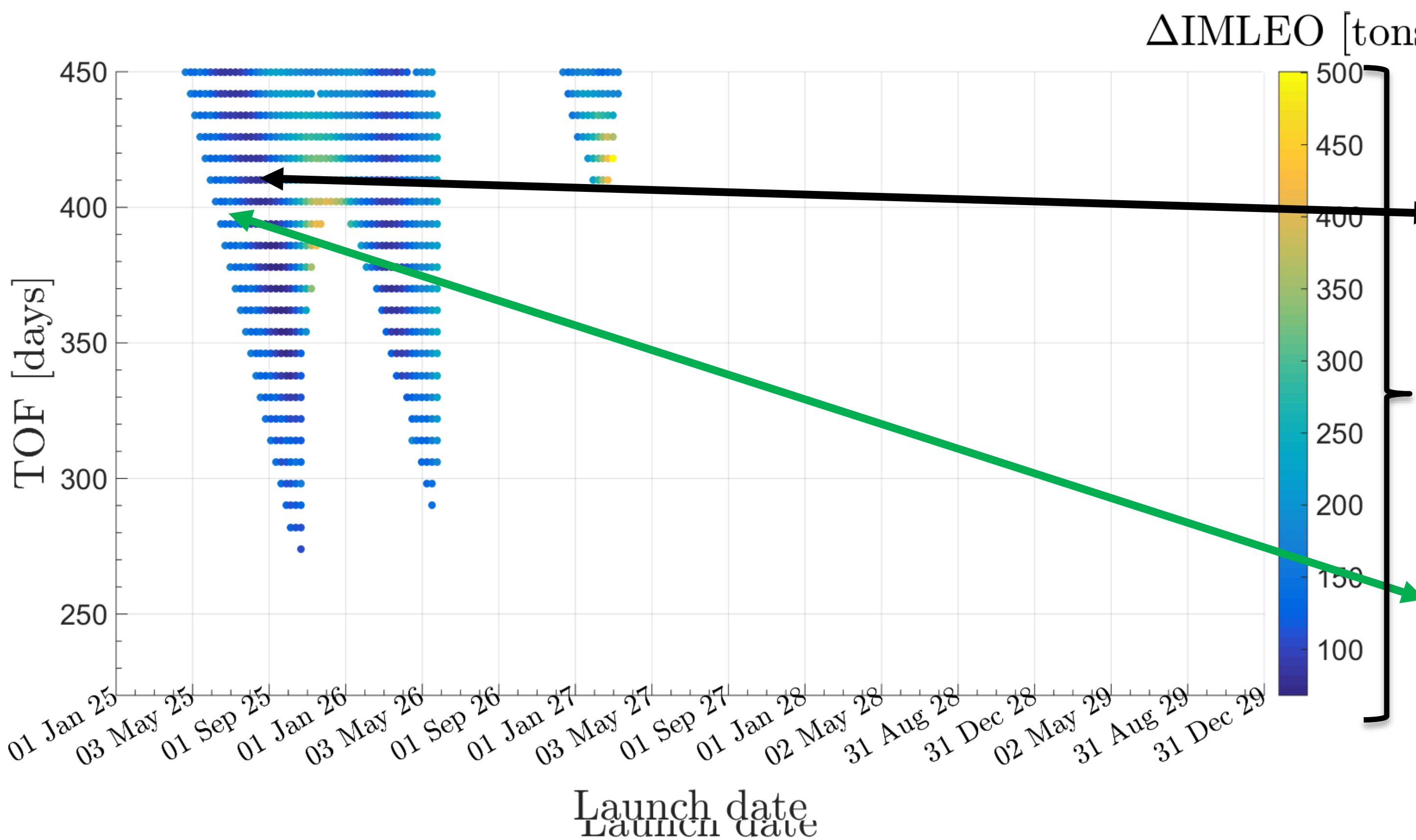
- Chemical

$$\begin{aligned}
\text{IMLEO} &= M_{\text{PL}} + M_{\text{chem prop}} + M_{\text{chem prop, esc}} + M_{\text{kick stage}} \\
&= M_{\text{PL}} + M_{\text{chem prop}} + (1 + k_{\text{KS}}) \cdot M_{\text{chem prop, esc}} \\
&= M_{\text{PL}} \cdot \exp\left(\frac{\Delta V_{\text{tot}} - \Delta V_{\text{esc}}}{I_{\text{sp},2} \cdot g_0}\right) \cdot \left((1 + k_{\text{KS}}) \cdot \exp\left(\frac{\Delta V_{\text{esc}}}{I_{\text{sp},1} \cdot g_0}\right) - k_{\text{KS}}\right)
\end{aligned}$$

- SEP

$$\begin{aligned}
\text{IMLEO} &= M_{\text{Earth ret}} + M_{\text{SEP prop}} + M_{\text{chem prop, esc}} + M_{\text{kick stage}} \\
&= M_{\text{Earth ret}} + M_{\text{SEP prop}} + (1 + k_{\text{KS}}) \cdot M_{\text{chem prop, esc}} \\
&= \left(M_{\text{Earth ret}} + M_{\text{SEP prop}}\right) \cdot \left((1 + k_{\text{KS}}) \cdot \exp\left(\frac{\Delta V_{\text{esc}}}{I_{\text{sp},1} \cdot g_0}\right) - k_{\text{KS}}\right)
\end{aligned}$$

Results



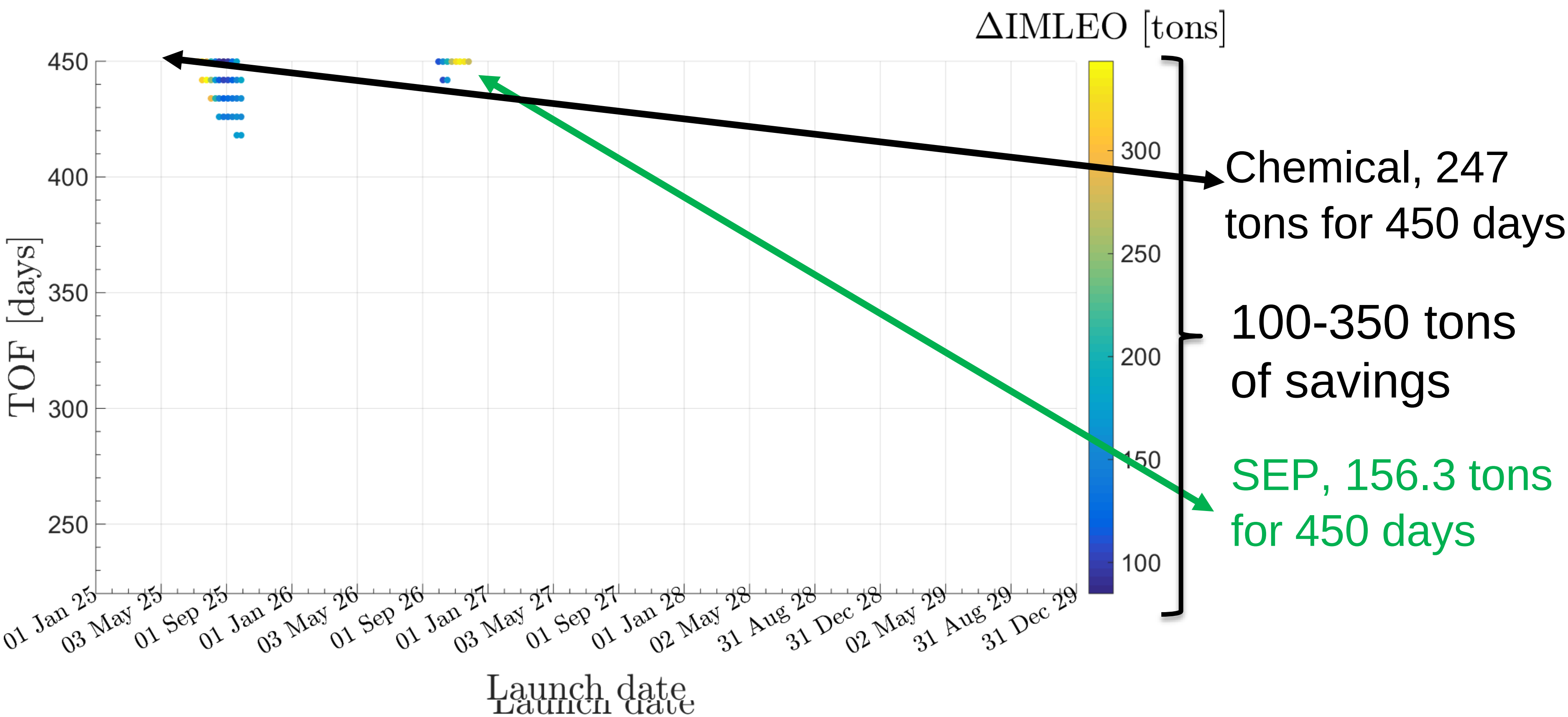
Chemical, 236 tons for 386 days

80-500 tons of savings

SEP, 152.1 tons for 402 days

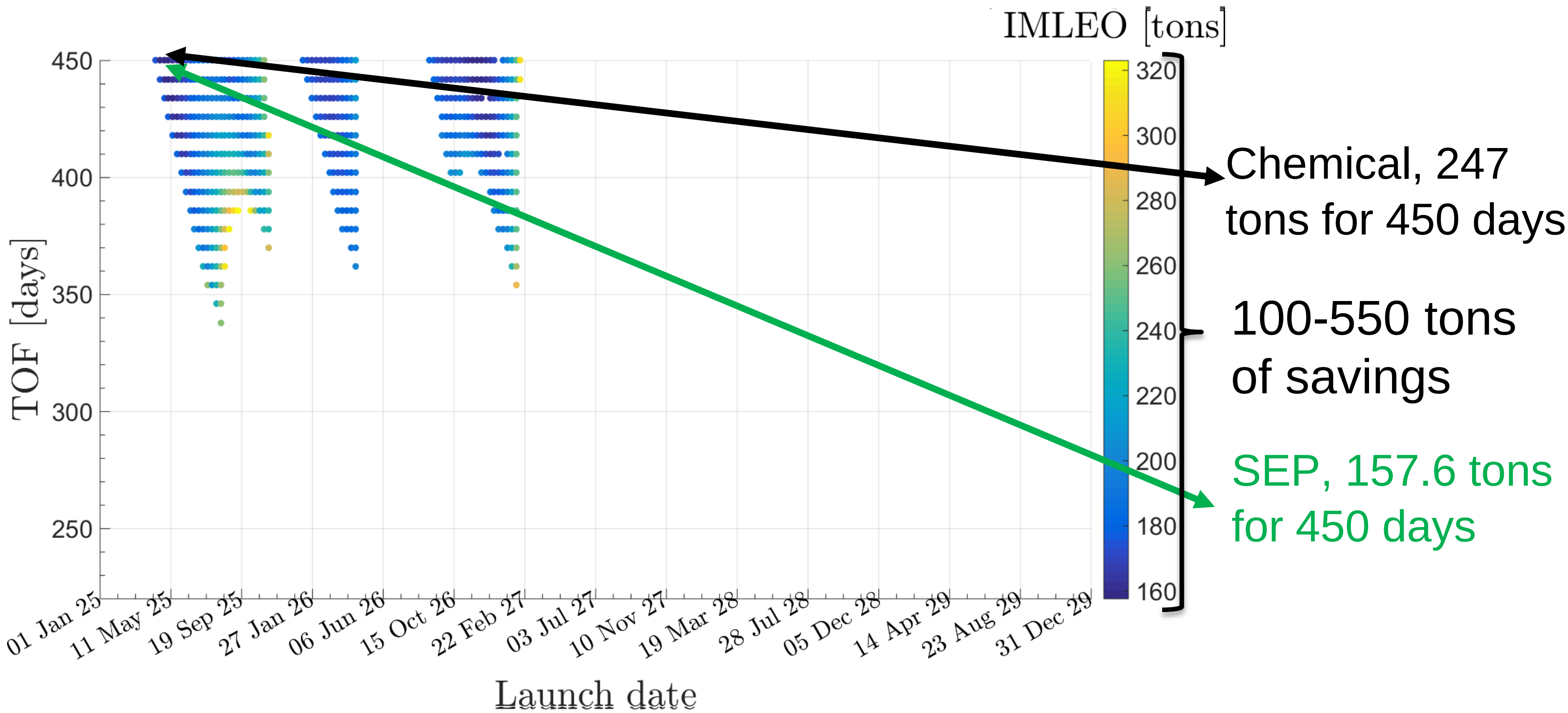
Asteroid	2015 BM510
Power:	300 kW

Results



Asteroid	2004 VJ1
Power:	150 kW

Results



Asteroid	2004 VJ1
Power:	300 kW

Summary results

Table 3: Minimal IMLEO for the different scenarios

Asteroid	Case	Minimal IMLEO [tons]	Launch date [mm-dd-yyyy]	TOF [days]
2000 SG344	50 kW	115.1	03-29-2028	370
	chemical	120	10-10-2029	370
2015 BM510	150 kW	151.1	12-18-2025	450
	300 kW	152.1	06-25-2025	402
	chemical	236	09-05-2025	386
2004 VJ1	150 kW	156.3	11-19-2026	450
	300 kW	157.6	04-30-2025	450
	chemical	247	05-16-2025	450

Summary results

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Table 4: Launcher analysis

Launchers required	Asteroid	Case	Launch season [days]	Minimal TOF [days]
2 SLS 1xRL (140 tons)	2000 SG344	50 kW	568	306
		chemical	488	298
	2015 BM510	N.A.	N.A.	N.A.
	2004 VJ1	N.A.	N.A.	N.A.

Summary results

Table 4: Launcher analysis

Launchers required	Asteroid	Case	Launch season [days]	Minimal TOF [days]
2 SLS 4xRL (186.2 tons)	2000 SG344	50 kW	568	306
		chemical	994	146
	2015 BM510	150 kW	136	418
		300 kW	448	290
		chemical	N.A.	N.A.
	2004 VJ1	150 kW	136	434
		300 kW	408	378
		chemical	N.A.	N.A.

Summary results

Table 4: Launcher analysis

Launchers required	Asteroid	Case	Launch season [days]	Minimal TOF [days]
3 SLS 4xRL (279.3 tons)	2000 SG344	50 kW	568	306
		chemical	1232	106
	2015 BM510	150 kW	136	418
		300 kW	496	274
		chemical	200	306
	2004 VJ1	150 kW	152	418
		300 kW	488	338
		chemical	120	402