Solar Electric Propulsion (SEP) Benefits

- High-power SEP provides the highest $\Delta V$ capability of any near-term, in-space propulsion technology
- It offers real time mission flexibility (e.g. launch date, trajectory)
- ARM SEP component and system technologies are extensible to multiple future applications
  - Commercial communication satellites
  - Deep space cargo, including for Mars
  - Deep space science
SEP Enables High $\Delta V$ Missions

![Graph showing Delta-V Beyond Earth Escape for various missions with on-board propulsion and launch vehicle contributions.](image)
It’s All About Power
Space Solar Power History

- Vanguard
- SERT II
- Skylab
- Deep Space 1
- Dawn
- ISS
- ARM

Power doubles every four years
Representative Flight System Deployed Configurations

51 m

35 m
ARV Size Comparison

[Diagram showing various spacecraft and stations for comparison]
Mission Option A Overview

1) Launch direct to LGA (SLS, DIVH or Falcon Heavy) or to Earth Orbit (Atlas V 551)

2) Separation & S/A Deployment

3) Lunar Gravity Assist (if needed)

4) SEP low-thrust cruise to Asteroid
   ~3.8 km/s

5) Asteroid Operations: rendezvous, characterize, deploy capture mechanism, capture, and despin (60 days)

6) SEP redirect to Lunar orbit
   ~0.15 km/s

7) Lunar Gravity Assist

8) SEP transfer to safe DRO
   ~0.02 km/s

9) Orion rendezvous & crew operations

Mission Option A Diagram:

- Initial Earth Orbit (spiral only)
- Asteroid Orbit
- Moon’s Orbit

Key Numbers:
- ~4.7 km/s
- ~3.8 km/s
- ~0.15 km/s
- ~0.02 km/s
Option A: Proximity Operations Overview

1. **Orbit Refinement and Rendezvous**
   - *(Radio and Optical)*

2. **Pre-Capture**
   - Capture System Deploy

3. **Final Approach**

4. **Capture**
   - Capture Bag Retraction

5. **Characterize, Spin down, and Detumble**
Option B: Mission Timeline

1. Approach (14 Days)
   - 1,000 km to 100 km. Refine shape model, acquire landmarks, and update spin state.

2. Characterization (37 days)
   - Four fly-bys (~7.5 days each) with a week reserved for processing and gathering additional images as needed.

3-4. Dry-Runs and Boulder Collection (18 days)
   - Dry-Runs (x2): ~5.3 days each. ~6 hours to complete dry-run with 5 days of coast in-between for downlink and processing.
   - Boulder Collection Attempt: ~7.4 days with ~0.5 day for collection and 7 days for ascent and coast to allow for downlink and processing.

3-4. Contingency Dry-Run and Boulder Collection Attempts (51 days)
   - Reserve for complete dry-run sequences at two additional sites and four additional boulder collection attempts between the three sites to protect against failed collection due to boulder properties, system anomalies or other contingencies.

5. Orbit Determination (21 Days)
   - Hold for precise orbit determination prior to gravity tractor demonstration.

6. Gravity Tractor (90 Days)
   - Maintain orbit for at least 90 days. Resources reserved for 180 days.

6. Hold for Alignment (129 days)
   - Hold for to allow deflection to propagate and to achieve favorable orbital alignment for deflection verification.

7. Deflection Verification (21 Days)
   - Hold for precise orbit determination to verify orbit deflection.

Margin (19 days)
   - Unused margin in the 400 day stay-time allocation.

Operations heritage to prior robotic missions
Mission unique operations
Option B: Proximity Operations Overview

Proximity Operations Timeline (400 days)

1. Approach
2. Characterization Flybys (4)
3. Dry Runs (2 per site)
4. Boulder Collection
5. Pre-Gravity Tractor Orbit Refinement
6. Enhanced Gravity Tractor
7. Deflection Verification
8. Reserve (3 & 4)
9. Reserve (6) & Wait
10. Margin

Operations heritage to prior robotic missions
Mission unique operations

Approach, Flybys, & Characterization: 37 days to verify and refine shape, spin, and gravity models, and obtain ~cm imagery for majority of the surface.

Dry Runs: 2 dry runs at up to 3 sites refine local gravity, provide sub-cm imagery, and verify navigation performance.

Boulder Collection: Reserving for up to 5 boulder collection attempts provides contingency against surface and boulder anomalies.

Enhanced GT Demonstration: 260 days allows for operations and proper Earth-Itohikawa alignment to verify deflection.

Enhanced Gravity Tractor (EGT): 180 days reserved for EGT operations, 60 days required for measurable deflection.

Operations Margin: In addition to conservative operations profile, 19 days of unencumbered operations schedule reserve is provided in mission plan.

Proximity operations having a high heritage, along with a conservative operations strategy.
Option B: Boulder Collection

1. Dry Run (1 of 2): Refine local gravity and increase boulder characterization while in passively safe trajectory. Sufficient time allocated between dry runs to downlink data, process data, and update spacecraft.


3. Terminal Descent: No nominal thrusting toward asteroid to limit debris.

4. Surface Contact/Ascent: Contact arms allow controlled contact/ascent, provide stability, and limit debris. Thrusters provide attitude control and contingency ascent.

5. Boulder Collection: Conservative 120 minutes reserved, nominal ops estimated at 30 minutes.

6. Coast: Slow drift escape provides time to establish mass properties of the combined spacecraft/boulder system.

7. Subsequent Operations: As appropriate, transition to performing gravity tractor or subsequent capture attempt.

Conservative, high-heritage operations mitigate risks during boulder collection operations to increase probability of successful boulder capture.
Future Use of ARM Robotic Spacecraft and Solar Electric Propulsion

- Some assessments have shown that human Mars missions utilizing a single round-trip monolithic habitat + Orion requires a very high power SEP vehicle
  - Approaches 1 MW total power
  - An engineering and operational challenge

- Alternate architecture concepts enable ARM derived SEP to be used. As an example:
  - Pre-deploy crew mission assets to Mars utilizing high efficient SEP, such as
    - Orbit habitats: Supports crew while at Mars
    - Return Propulsion Stages or return habitats
    - Exploration equipment: Unique systems required for exploration at Mars.
  - High thrust chemical propulsion for crew
    - Low-thrust SEP too slow for crew missions
    - Crew travels on faster-transit, minimum energy missions: 1000-day class round-trip (all zero-g)
High-Power Hall Thrusters

- Hall thrusters have extraordinary performance and are extremely scalable
  - Isp’s from 1000 to 8000 s
  - Power levels from 200 W to >100 kW
- Magnetic shielding enables huge advances in the technology
- Nested Hall Thrusters may facilitate high-power operation and a very large throttle dynamic range
High-powered SEP Enables Multiple Applications

- Deep Space Human Exploration
- Satellite Servicing
- Payload Delivery
- Commercial Space Applications
- ISS Utilization
- Solar Electric Propulsion
- Orbital Debris Removal
- OGA Missions
- Space Science Missions
- Human Exploration
- Solar Electric Propulsion
- Space Science Missions
A DEEPER VISION, A BOLDER MISSION, ONE STEP AT A TIME

Step One: 2014