Material Collection Analysis for Solar Power Satellite - ALPHA

ENAE788T

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Overview

This paper analyzed several methods of material gathering/harvesting, processing, and transportation for the purpose of the construction of Solar Power Satellite - ALPHA (SPS-ALPHA).

These methods, evaluated on the bases of energy expenditure, finances, and logistics, include:

- Surface-to-orbit launches
- Space junk reprocessing/recycling
- Asteroid capture + mining
- Lunar surface mining

Surface-to-Orbit Launch: Logistics/Costs

- Cheapest commercially available option: SpaceX Falcon Heavy
  - Cost per kilogram: $3370/kg
- SPS-ALPHA, as currently designed, has a total mass of approximately 26 million kilograms
  - Excludes required construction infrastructure
  - Total financial cost: approximately **$87.6 billion**
- Requires **900 separate launches**
  - One launch a week ⇒ more than **17 years**

Berger, E., Bongle, & Utc. (2018, October 25). SpaceX's Falcon Heavy rocket seems to be a hit with satellite companies. Retrieved from https://arstechnica.com/science/2018/10/spacexs-falcon-heavy-rocket-seems-to-be-a-hit-with-satellite-companies/

Surface-to-Orbit Launch: Energy Expenditure

The vis-viva equation relates an object's speed and radial distance to its total energy with respect to a body. This equation is shown below:

$$\varepsilon = (1/2)v^2 - \mu/r = -\mu/2a$$

With:

- ε = specific total energy (MJ/kg)
- r = orbital radius (km)
- v = magnitude of velocity with respect to the Earth's surface (km/s)
- μ = Earth gravitational constant = 398600 km^3/s^2

Surface-to-Orbit Launch: Energy Expenditure

Solved out, we can find the energy required to transport 26 million kilograms to an orbital radius of 42,164 km (geosynchronous orbit).

This energy cost will be approximately **1.3 petajoules (on the order of 10^{15} joules)**.

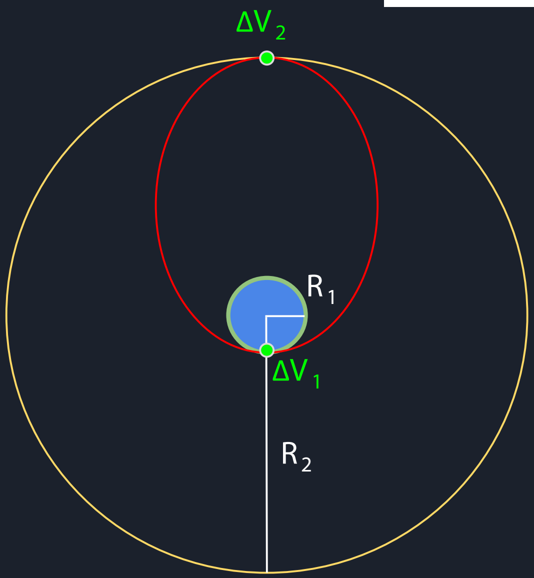
However, comparison of energy expenditure is useless with different points of reference. Therefore, we'll use ΔV to compare between operations.

Surface-to-Orbit Launch: ΔV Requirement

A “stationary” object on Earth’s surface has a linear velocity of approx. 0.46 km/s. For an elliptical Hohmann transfer orbit, the semimajor axis will be:

$$a = (R_1+R_2)/2 = (6378 + 42164)/2 = 24271 \text{ km}$$

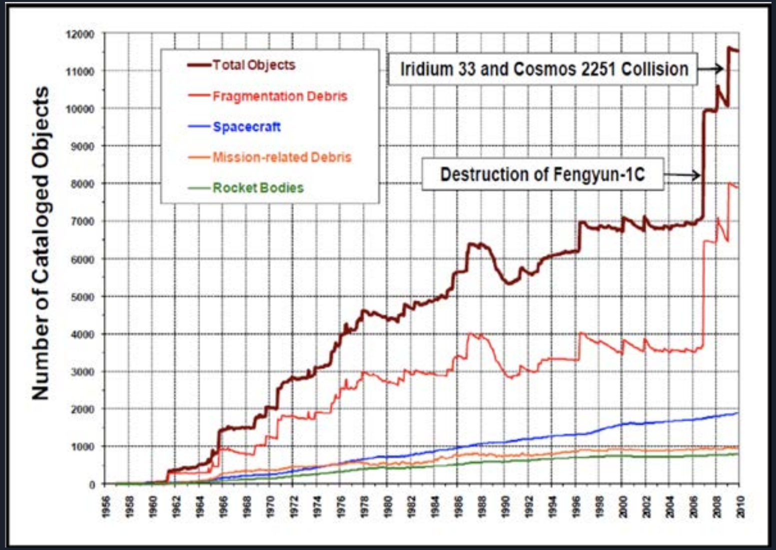
Using the vis-viva equation, ΔV_1 will be 9.96 km/s and ΔV_2 will be 1.5 km/s, resulting in a total **ΔV = 11.46 km/s.**



Hohmann Transfer --------
GEO --------
R_1 = 6378 km
R_2 = 42164 km

Space Junk Recycling: Orbital Debris Transformed

- According to European Space Agency: 7,500 tonnes of space debris in orbit around the earth ⇒ 7.5 million kg
  - ≈1/3 of required mass for SPS ALPHA
- Salvagable parts are pre-processed, similar component makeup
  - Components broken beyond repair can be ground down to feed for zero-G additive manufacturing
- Existing debris propagates over time: exponential growth, long-term issue



Catcher's Mitt Final Report, Defense Advanced Research Projects Agency, Arlington, VA, 30 August 2011.

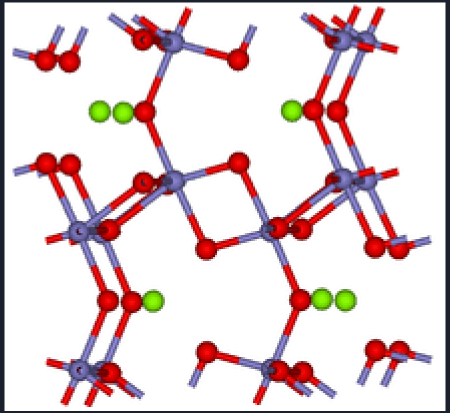
Space Junk Recycling: "Catcher's Mitt"

- DARPA 2011 space junk analysis dubbed "Catcher's Mitt"
  - Planned clean-up of 242 largest objects in orbit totaling 1,000,000 kg
  - ΔV to put into *de-orbit* is 377 km/s total effort
- Why spend 377 km/s in ΔV to remove one million kg from orbit, just to turn around and spend an enormous amount of ΔV to put one million kg back into orbit?
- Recycling has the potential to be a more efficient effort
  - We know the material in orbit is already the type needed for spacecraft
  - How much is useful, how much is not?
  - Future study to classify the types of material available warranted
- Space Debris is an international problem
  - Recycling space junk would be funded as the expense of cleaning the orbital planes and not the construction of satellite systems
  - Offset costs through sale of in-orbit construction material

Lunar Surface Mining: Resources/Uses

Minerals for possible exploitation on the moon for use in SPS-ALPHA construction:

- Feldspar
  - $KAlSi_3O_8$ (Potassium)
  - $NaAlSi_3O_8$ (Sodium)
  - $CaAl_2Si_2O_8$ (Calcium)
- Olivine
  - $(Mg^{2+}, Fe^{2+})_2SiO_4$ (Magnesium)
- Ilmenite and Armalcolite
  - $FeTiO_8$ (Titanium)
  - $(Mg, Fe^{2+})Ti_2O_5$ (Iron, Titanium)
- Corundum
- Spinel
- KREEP – Rare Earth Elements
- Other Metallic Minerals
  - Fe, Ni, Co



WikiVisually.com. (n.d.). Retrieved from https://wikivisually.com/wiki/Armalcolite

Lunar Surface Mining: Logistics/Costs

Recent developments in perovskite-structured PV technology give lunar mining the potential to be much more useful.

- Perovskite PV highest conversion efficiency to date of **30.2%** is from Pb (lead) based structure in combination with silicon PV ...however
- Titanium has been shown to create perovskite structures, which can be found in abundance on the lunar surface
  - Increasing breakthroughs with titanium based perovskites show promise of tech
- Extra benefits include high oxygen content, can be captured from the processing of lunar compounds such as ilmenite and feldspars
  - Used for life support systems / fuel

Using patched conics method, we approximate the lunar surface-to-GEO ΔV as 6.92 km/s - less than half the cost of Earth surface launch.

Asteroid Capture + Mining: Resources/Uses

- Near Earth Asteroids (NEAs)
  - Millions of kilograms of raw materials, useful for structures, electronics, fuel, etc
- Minerals and metallics
  - Construction
    - Gold, platinum, magnesium, and nickel-iron could be used to construct SPS-ALPHA after they are processed
  - Life support/Fuel
    - Hydrogen, oxygen, water and nitrogen for on-site construction workers and crew members in nearby habitats
- Modern mining techniques in zero-gee
  - Magnetic separation
  - Thermal extraction
  - Electrostatic beneficiation, etc

Kettley, S. (2019, May 10). NASA asteroid tracker: A BUS-SIZED asteroid will pass Earth TODAY dangerously close. Retrieved from https://www.express.co.uk/news/science/1125345/NASA-asteroid-tracker-bus-size-Asteroid-2019-JJ3-Earth-Close-Approach

Asteroid Capture + Mining: Logistics/Costs

- 2010 NASA study
  - 40kW electric propulsion system
  - 1 million kg body potential
  - Nudge into high Earth orbit, let Sun gravity pull into Earth-Moon L2
- Required Infrastructure
  - Standardized approach to nudging into HEO
  - On-orbit processing facility/resource depot
    - Lunar Gateway
  - Communications/sensing array
    - 69 NEAs in the past 110 years within one lunar distance (384,400 km)
      - Only 4 were detected more than a week beforehand
    - Solar system-wide satellite array
      - Also essential for tracking solar weather, other phenomena
- Potential to become the largest industry in existence after constructing SPS-ALPHA
  - Expand to asteroid belt in future

Asteroid Capture + Mining: Logistics/Costs: 2012 KZ41 Example

- June 3, 2019 at 2300 Universal Standard Time
    - 1.451 million km from Earth
    - 12.027 km/s relative velocity
- NASA Jet Propulsion Laboratory's Small-Body Mission-Design Tool helps to design mission parameters: minimum ΔV departs 7/13/26 and arrives 2/22/29
    - $\Delta V_{dep} = 7.7$ km/s
    - $\Delta V_{arr} = 0.9$ km/s
    - $\Rightarrow \Delta V_{total} = 8.6$ km/s

Since this mission only includes the trip to the asteroid, not the return, we can assume a much larger ΔV value and TOF for the return trip due to the asteroid's progress on its orbit.

Conclusions:
Launches & Lunar Mining

With each resource allocation method comes positives and negatives.

- Surface-to-Orbit Launches:
  - Reliable process
  - Availability of certain materials on Earth
  - SPS-ALPHA will require at least some launches - possible combination with other method(s)
  - Total ΔV required is **11.46 km/s per launch**
- Lunar Mining:
  - Significantly lower ΔV at **6.92 km/s**
  - Needs investment in infrastructure
    - Mining, processing, lunar-to-GEO launches
  - Most useful in future
  - Less so for SPS-ALPHA in short term, at current TRL

Conclusions:
Orbital Recycling & Asteroid Capture

With each resource allocation method comes positives and negatives.

- Orbital Recycling:
  - Ongoing international effort to clean/prevent propagation of space junk
  - Incentive for private effort as well
    - Helps prevent damage to essential infrastructure + secures valuable materials
  - Lower total ΔV required if keeping in orbit instead of pushing to deorbit and relaunching
    - Ops will require less propellant for same ΔV with electric propulsion - less impact

- Asteroid Capture/Processing:
  - Long term potential for major industry
  - Requires significant infrastructure
  - Example required ΔV = **8.6 km/s** + needed ΔV for long return trip; much more than launch ΔV

Conclusions

Based on our analyses, there is no one best method for material collection; a combination will be most useful.

- Future Work
  - Long term tech development
  - Infrastructural investment, economic incentives
  - Lunar Mining / Asteroid Capture will become more viable for other large-scale projects

- Short-Term Best Options for SPS-ALPHA
  - Orbital Recycling and Surface-to-Orbit
  - Most likely to garner international support

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