Potential Propellant Depot Locations
For Beyond-Low Earth Orbit (LEO) Human Transport

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Potential Propellant Depot Locations For Beyond-LEO Human Transport

Agenda

• Provide some historic perspective on transportation depots
• Provide operational and trajectory-driven insight into LEO-based propellant depots
• Compare two propellant depot options supporting transport to cis-lunar space from LEO
  - Departure via LEO depot supported by Falcon 9 launches (22.8 metric tons \{t\} IMLEO\(^1\) each)
  - Immediate LEO departure supported by one "heavy lift" Saturn 5 launch (140.3 t IMLEO)
• Visualize example LEO geometries for departures targeting near-Earth objects (NEOs) and Mars
• Ensuing charts intended to provoke dialogue, so by all means engage
• Critical thinking is necessary to discriminate between competing depot-based architectures, and this lecture is intended to stimulate it. Players beware: this is a complex celestial shell game!

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\(^1\) IMLEO = initial mass in low Earth orbit. This parameter is arguably the most objective measure of cost/effort required to initiate a mission under any architecture. Some architectures require multiple launches to achieve the required IMLEO.
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Historic Examples From Earthly Transport

• Trucking, railroads, shipping, and airlines rarely carry all fuel needed for a round trip
• Even "milk runs" utilize refueling opportunities in a contingency or rerouting scenario

ISS: Our Current LEO Propellant Depot

• Progress cargo carriers cache some of their propellant aboard the ISS Russian Segment
• Progress can interconnect with and burn cached propellant to reboost ISS
• If the ISS "aft" docking port is unoccupied, Zvezda engines can reboost ISS
• Hard to conceive of a better architecture, assuming ISS is the end destination
• Russia has considered ISS to be a possible node for cislunar transport
  - Upside: ISS already exists, and propellant-optimal departure from it to cislunar space is no more expensive than from any other LEO of comparable height
  - Downside: the Moon's inclination never exceeds 28.6°, but ISS inclination is 51.6°. Every launch to ISS from low latitude sites like Cape Canaveral or Korou gives up IMLEO it could have delivered to inclinations lower than 51.6°. Propellant-optimal departures from ISS recur only about once every 10 days. Cislunar arrival time cannot be freely chosen.
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Architecture With Refillable Propellant Depot Infrastructure In LEO
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What LEO Is Best For A Depot Supporting Cislunar Logistics?

• Best inclination \( (i) \) depends on launch site latitude \( (\phi) \)
  - Maximize IMLEO by launching due east such that \( i = |\phi| \)
  - Since the Moon's inclination never exceeds 28.6°, \( i = \phi = 28.5° \) is selected

• Best height \( (H) \) depends on multiple factors
  - To minimize aero drag losses and orbit lifetime maintenance propellant, \( H > 400 \) km
  - A one-day phase repetition condition at \( i = 28.5° \) occurs near \( H = 476 \) km. This height is therefore selected to standardize depot rendezvous transit times and procedures. Similar phase repetition conditions have greatly contributed to successful and efficient rendezvous operations during Shuttle, \( Mir \), and ISS programs.
• The Moon at arrival must lie near the LEO plane when it was departed ($\beta$ near zero)

• LEO ascending node precesses westward at $\dot{\Omega} = 6.8^\circ$/day

• Moon revolves eastward at $\dot{M} = 13.2^\circ$/day

• The ideal $\beta = 0$ condition arises every $180/(6.8 + 13.2) = 9.0$ days
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Lunar Latitude $\beta$ With Respect to a One-Day Phase Repeating LEO Inclined 28.5° at H = 476 km

- Elapsed Time (days)
- Lunar Beta (degrees)

10.2 days
10.9 days
5.5 days
6.4 days
10.9 days
10.3 days

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![Graph showing Typical Trans-Lunar Injection (TLI) Steering Loss Versus Steering Angle](image)

\[ \Delta v_{TLI} = \sqrt{v_{LEO}^2 + v_{TLI}^2 - 2v_{LEO}v_{TLI}\cos\beta} \]

- \( v_{TLI} = 10.7 \text{ km/s} \)
- \( v_{LEO} = 7.6 \text{ km/s} \)
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Historic Heavy Lift Versus Current Private Enterprise Launch Capability

• Apollo 17's Saturn 5 delivered 140.3 t IMLEO, including 78.3 t of LOX/LH2 TLI propellant
  ²
• Falcon 9 delivers 22.8 t of payload mass to LEO
  ³, but Dragon cargo capacity is 6.0 t
  ⁴
• Assuming Dragon could be modified to deliver LOX/LH2 to a LEO depot, 78.3/6.0 = 13
  launches would be required to deliver the propellant mass Apollo 17 needed for TLI
• Note that 6.0 t of Dragon deliverable propellant mass is optimistic because it neglects:
  - Losses due to depot rendezvous/docking maneuvers and propellant transfer system mass,
  - Losses due to depot orbit maintenance propellant consumption,
  - Losses due to cryogenic boiloff (or from added Dragon insulation mass), and
  - Undocking/separation from depot and deorbit for reuse or atmospheric incineration
• Note that Dragon's ISS cargo mission in April 2016 only delivered a payload mass of 3.2 t,
  including the Bigelow Expandable Activity Module (BEAM). The delivery mass shortfall vice
  6.0 t is likely due to ISS \( i = 51.6^\circ \) and possibly from a recoverable Falcon 9 first stage.

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² Orloff & Harland, Apollo: The Definitive Sourcebook, p. 592.
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So What? It Probably Depends On Your Perspective...

• If you're trying to sell rockets with IMLEO << 140 t, depots are great for high launch rate, but…
  - How dependable are 7 launches per TLI, each followed by complex depot events?
  - How is the cislunar spacecraft launched and assembled prior to depot tanking and TLI?
  - How are TLI times imposed by acceptable steering losses accommodated?
  - What if a time-critical cislunar emergency develops requiring TLI be performed ASAP?
  - How are timely maintenance and repairs performed on a robotic depot?
  - Is recovery and reuse of many small first stage components sustainable and profitable?

• If you're trying to sell heavy-lift with IMLEO >> 25 t, achieving TLI is straightforward, but…
  - What about development costs for the launch vehicle and launch site infrastructure?
  - Can the launch vehicle be human-rated at reasonable cost?
  - Will launch frequency be sufficient to realize economic and safety/reliability payoffs?
  - What if a time-critical cislunar emergency develops requiring TLI be performed ASAP?

• If we go the heavy-lift route, a propellant depot on the lunar surface makes more sense in the context of "land anywhere; leave anytime" lunar exploration →
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Lunar Surface Rendezvous (LSR) Architecture


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Depot Support To NEO Destinations & Interplanetary Launch "Seasons"

- A launch season is driven by heliocentric motion and typically lasts a few weeks
- Heliocentric motion is slow vice lunar geocentric motion: seasons require years to recur
- A LEO plane must contain the Earth departure asymptote, or steering losses arise
- Season duration is rarely sufficient to adequately align a reusable LEO depot's plane with a departure asymptote of interest. When they arise, these alignments are fleeting, typically lasting less than a day.
- A depot in cislunar space requires the Moon to be in the proper geocentric position to manage departure steering losses, a condition satisfied only for a day or so each month
- A depot near a Sun-Earth libration point can support departures throughout the launch season, but propellant-efficient transits between Earth and SEL1/SEL2 can require weeks or months
- The most efficient depot for human missions is pre-emplaced near the destination
  - This is a strategy partially adopted by NASA's Mars Design Reference Architecture 5.0
  - More mature destination depots rely on in-situ resource utilization to a greater degree
  - What profitable airline wouldn't operate this way?

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Prograde Earth Departure For Mars On 14.0 July 2020 UT At $i = 29^\circ$

- LPIP = "locus of possible injection points" centered on departure asymptote's antipode $-\mathbf{v}_\infty$20
- TMI = trans-Mars injection point
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Prograde Earth Departure For Mars On 9.0 September 2022 UT At $i = 45^\circ$
Conclusions

• For cislunar destinations, there may be a commercial case for LEO depot infrastructure
  - Operationally, this is an unattractive alternative to heavy-lift with IMLEO ~140 t
  - Challenges to current range safety and LEO space traffic control capabilities posed by dozens of launches per year to the same asset are formidable compared to ISS
  - Greatest technical challenges for a LEO depot are in space (robotic depot operations, cryo boiloff, etc.); greatest technical challenges for heavy-lift launch are on the ground (vehicle development, infrastructure modification, etc.)
  - Any potential for in-situ resource utilization at a LEO depot is unforeseeable
  - Depot locations near or on the Moon provide more logistic efficiency

• Pre-emplace consumables or production facilities near an interplanetary destination
  - Launch seasons at Earth are too brief and infrequent to tolerate steering losses typically imposed by reusable depot infrastructure in LEO
  - For Earth-to-Mars transits, place depot on the outer moon Deimos. For Mars-to-Earth transits, place depot in stable lunar orbit with period < 2 days to support "any day" Earth logistics.