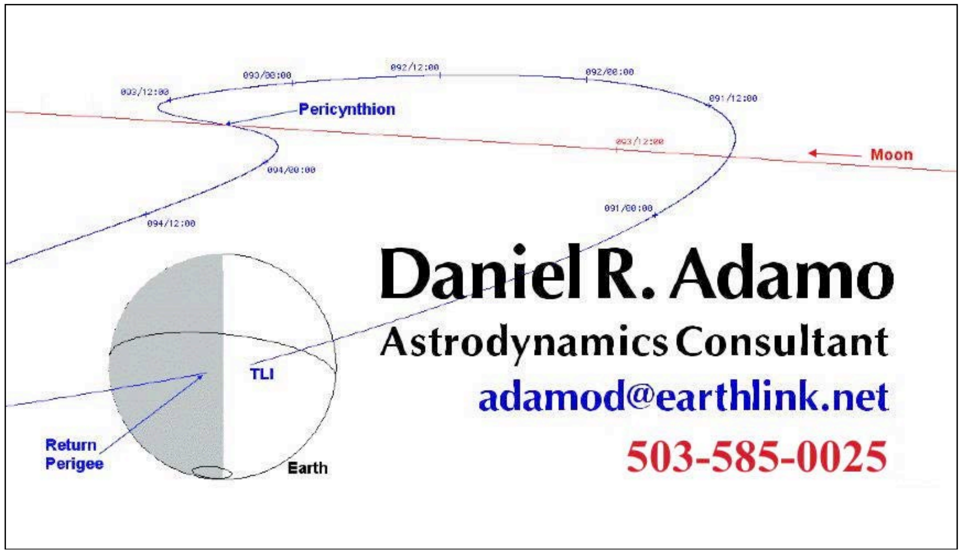
Potential Propellant Depot Locations
For Beyond-Low Earth Orbit (LEO) Human Transport



Orange County AIAA Section

17th Annual ASAT Conference

10 October 2020

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 cislunar 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!

---

[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.

Potential Propellant Depot Locations For Beyond-LEO Human Transport

Historic Examples From Earthly Transport

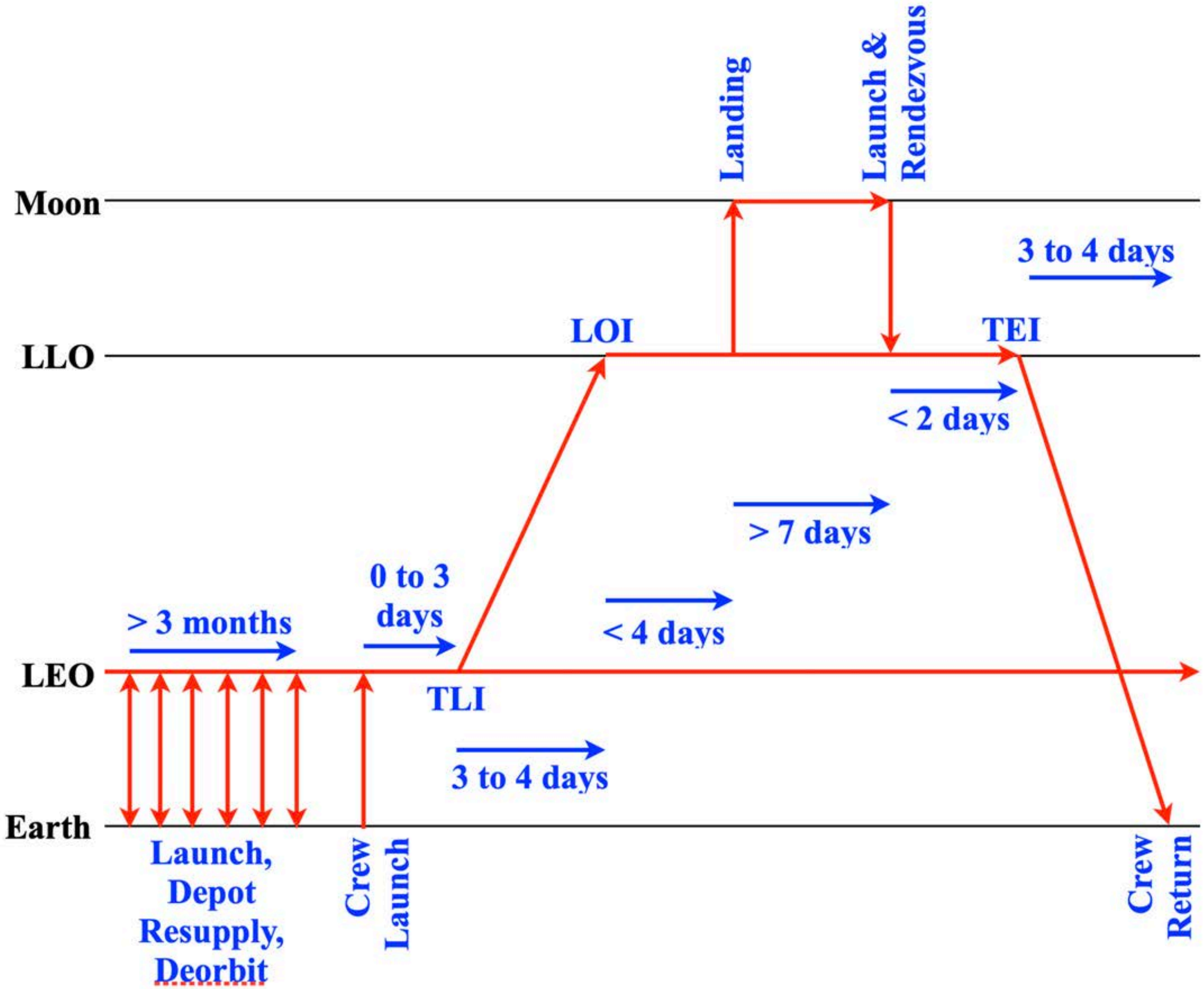
- Trucking, railroads, shipping, and airlines rarely carry all fuel needed for a round trip
- Even "milk runs" utilize refueling opportunities in a contingency or rerouting scenario

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.

Potential Propellant Depot Locations For Beyond-LEO Human Transport

Architecture With Refillable Propellant Depot Infrastructure In LEO



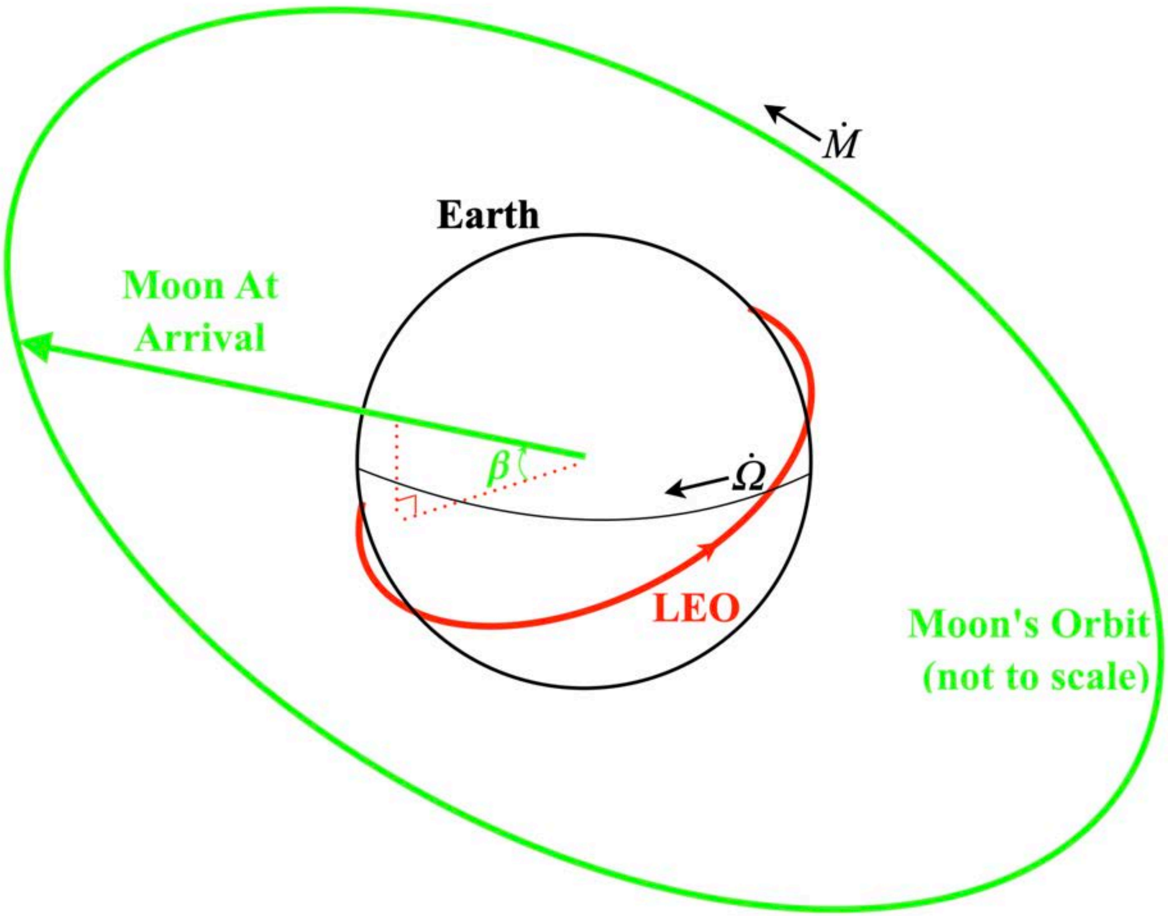
Potential Propellant Depot Locations For Beyond-LEO Human Transport

What LEO Is Best For A Depot Supporting Cislunar Logistics?

- Best inclination (i) depends on launch site latitude (ϕ)
  - 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.

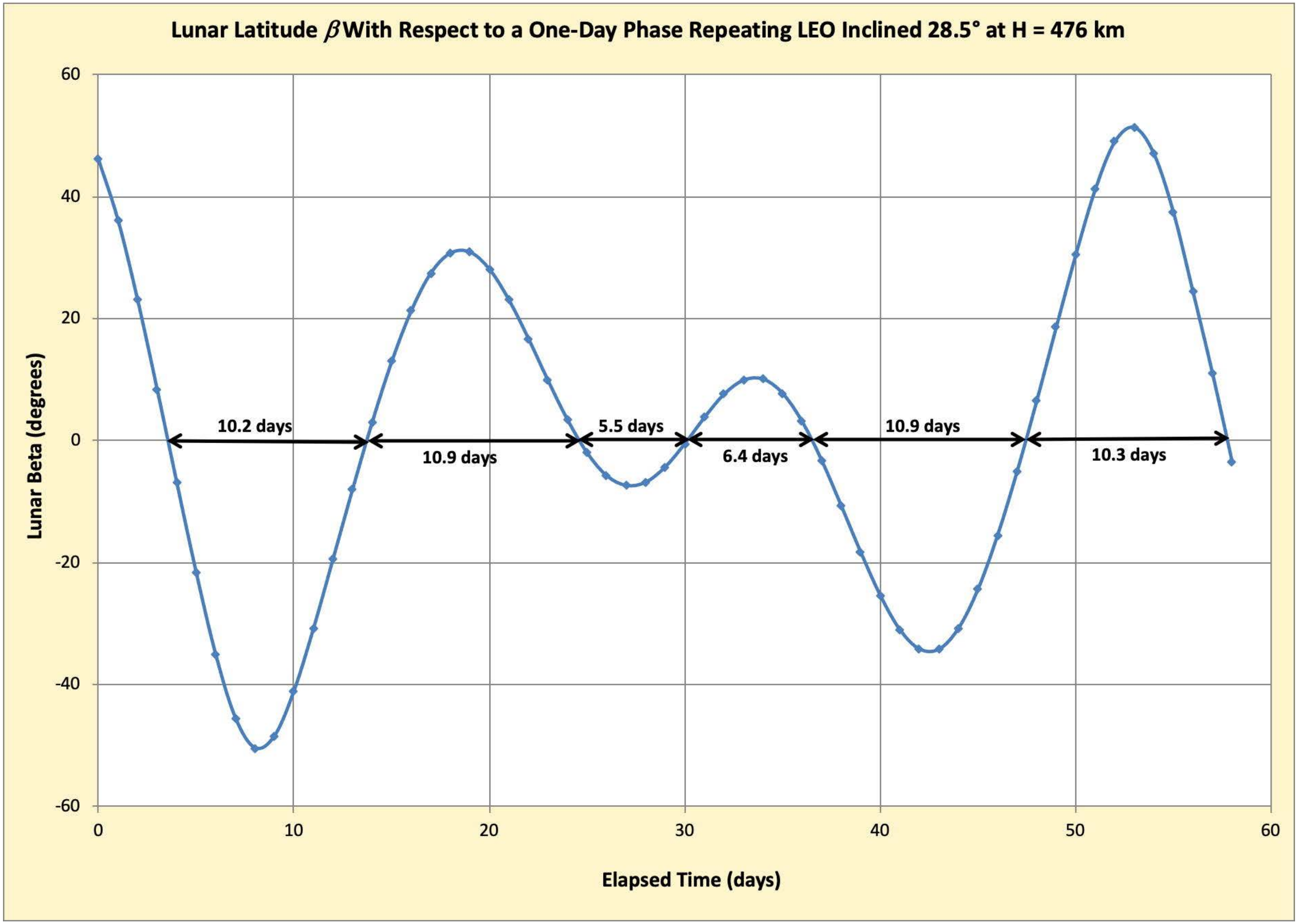
Potential Propellant Depot Locations For Beyond-LEO Human Transport

Geometry Constrains When TLI Can Occur From A Reusable LEO Depot

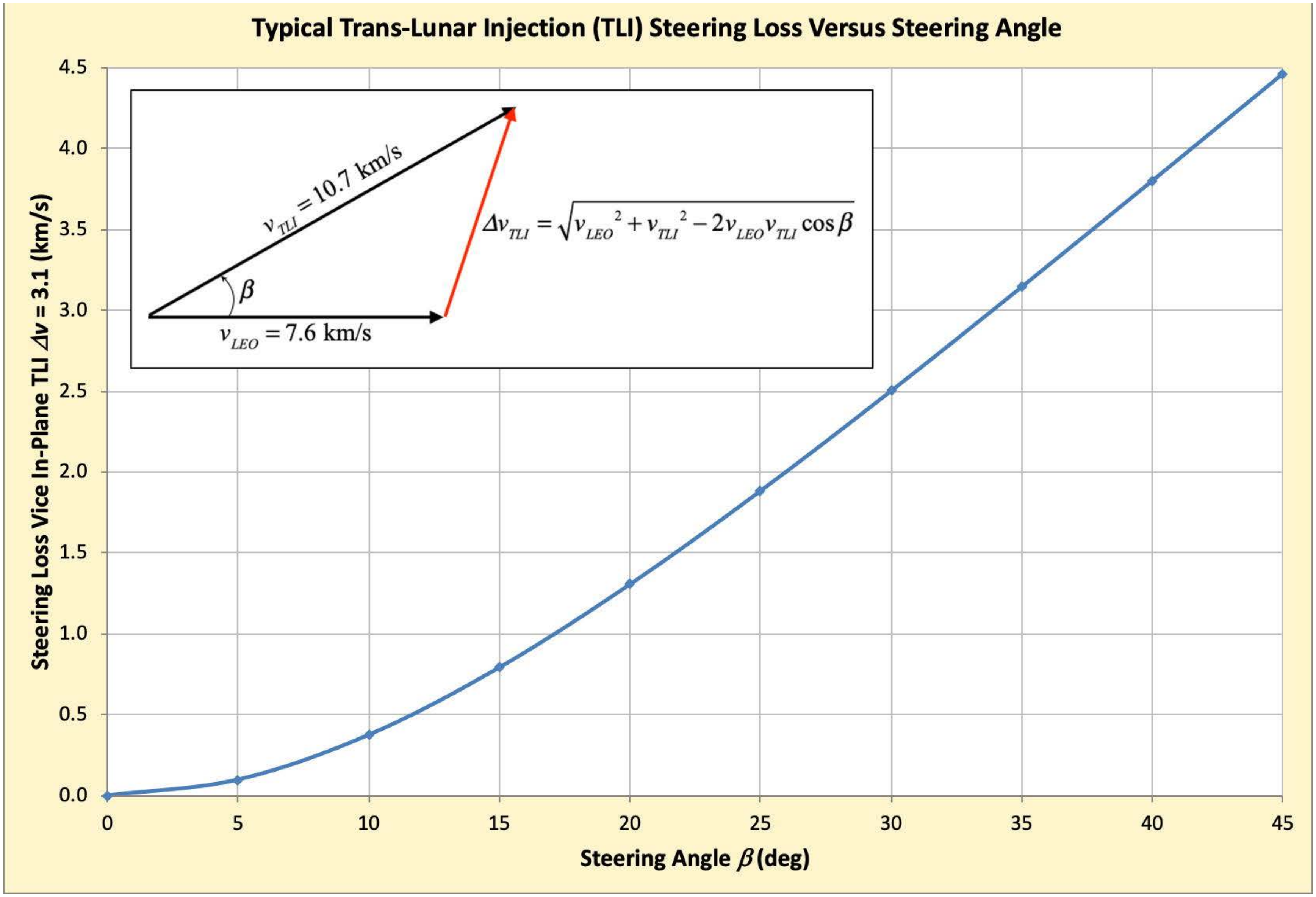


- The Moon at arrival must lie near the LEO plane when it was departed (β near zero)
- LEO ascending node precesses *westward* at $\dot{\Omega}$ = 6.8°/day
- Moon revolves *eastward* at $\dot{M}$ = 13.2°/day
- The ideal $\beta = 0$ condition arises every 180/(6.8 + 13.2) = 9.0 days

Potential Propellant Depot Locations For Beyond-LEO Human Transport



Potential Propellant Depot Locations For Beyond-LEO Human Transport



Potential Propellant Depot Locations For Beyond-LEO Human Transport

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 $i = 51.6°$ and possibly from a recoverable Falcon 9 first stage.

---

[2] Orloff & Harland, *Apollo: The Definitive Sourcebook*, p. 592.

[3] Reference https://www.spacex.com/vehicles/falcon-9/ (accessed 5 October 2020).

[4] Reference https://www.spacex.com/vehicles/dragon/ (accessed 5 October 2020).

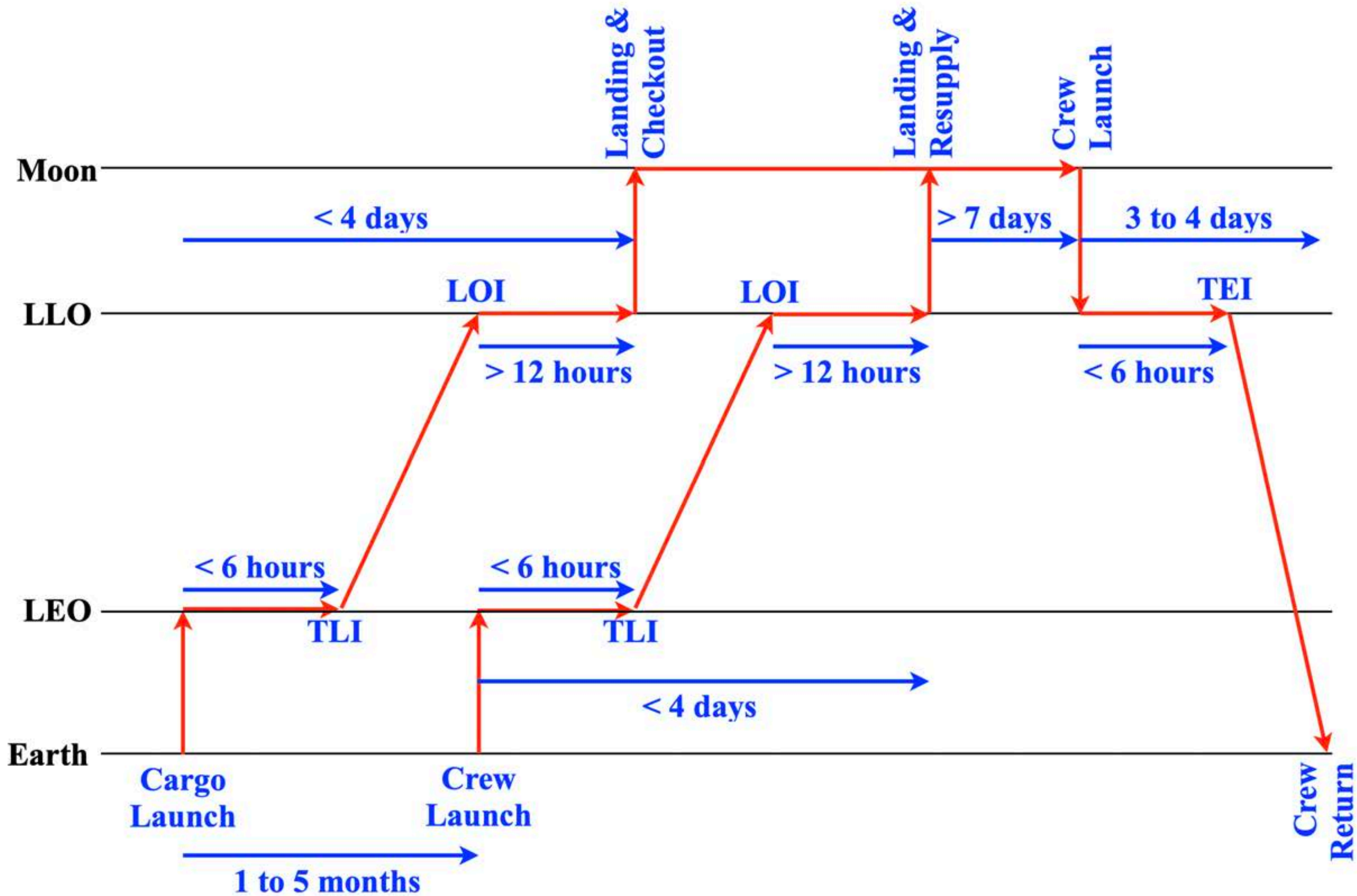
Potential Propellant Depot Locations For Beyond-LEO Human Transport

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 ⇒

Potential Propellant Depot Locations For Beyond-LEO Human Transport

Lunar Surface Rendezvous (LSR) Architecture[5]



[5] Reference http://www.nasa.gov/pdf/373994main_036%20-%2020090608.17.LSRvirtuesR6.pdf (accessed 5 October 2020).

Potential Propellant Depot Locations For Beyond-LEO Human Transport

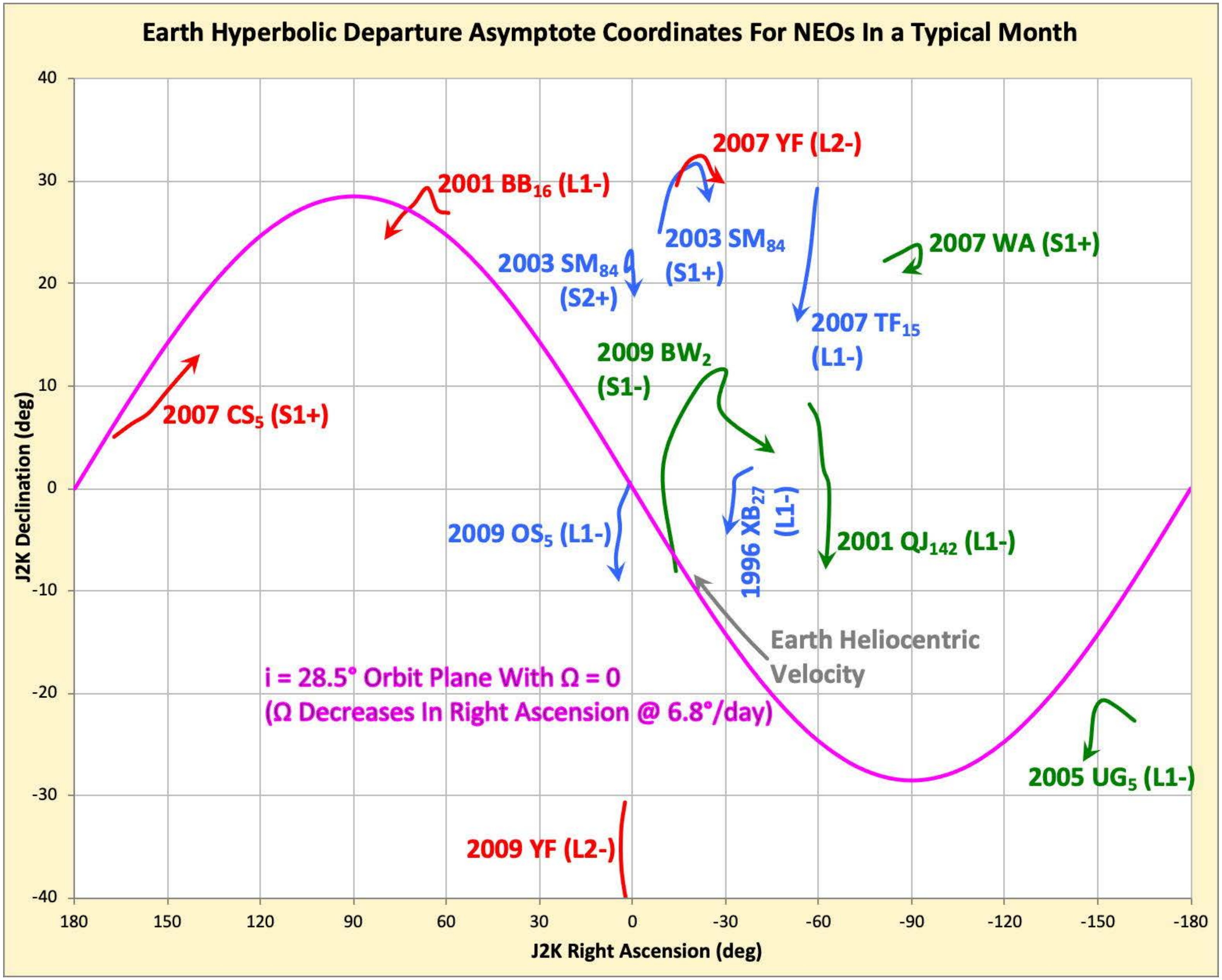
Depot Support To NEO Destinations & Interplanetary Launch "Seasons"

- 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[6]
  - More mature destination depots rely on in-situ resource utilization to a greater degree
  - What profitable airline *wouldn't* operate this way?

---

[6] Reference http://www.nasa.gov/exploration/library/esmd_documents.html (accessed 5 October 2020).

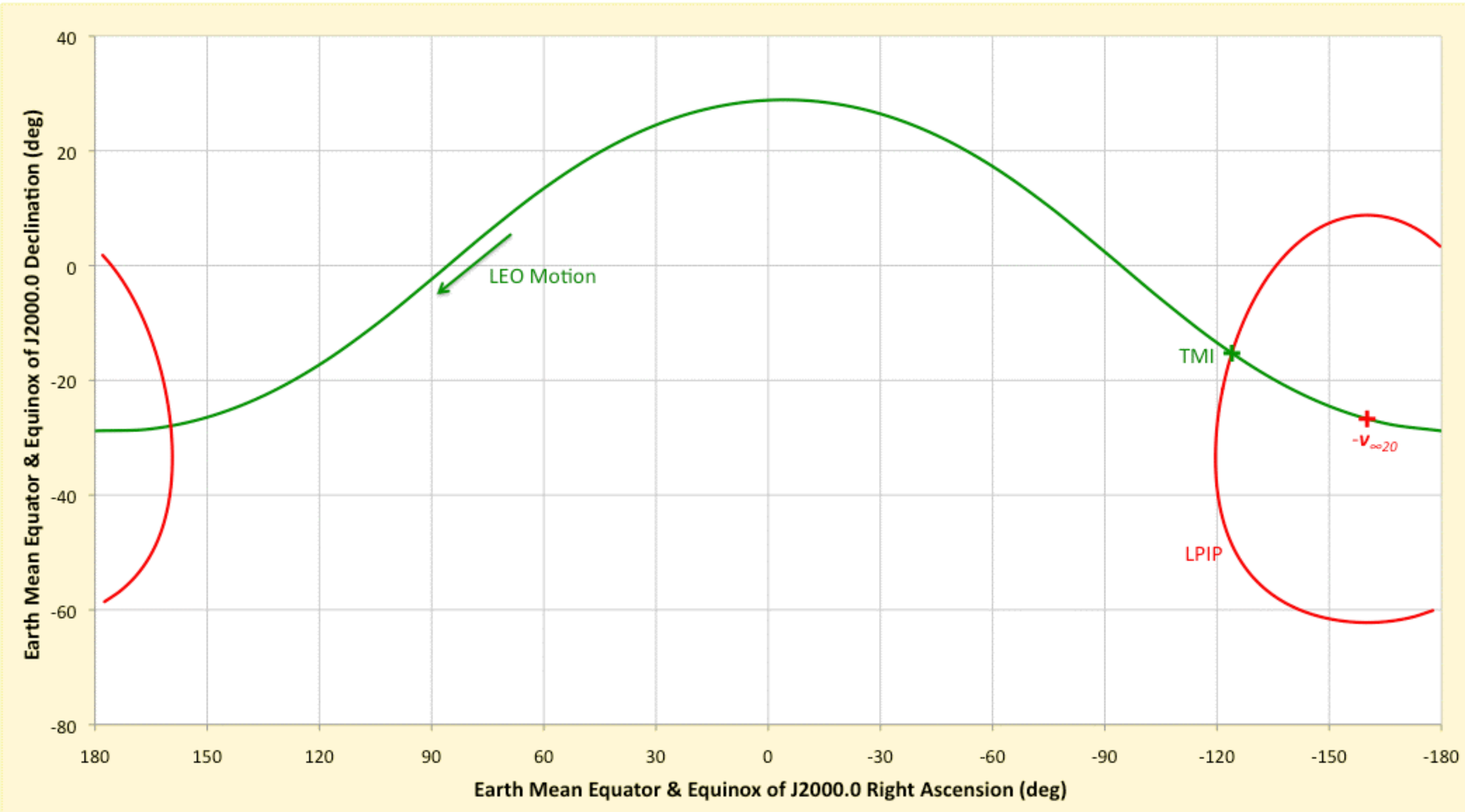
Potential Propellant Depot Locations For Beyond-LEO Human Transport



Potential Propellant Depot Locations For Beyond-LEO Human Transport

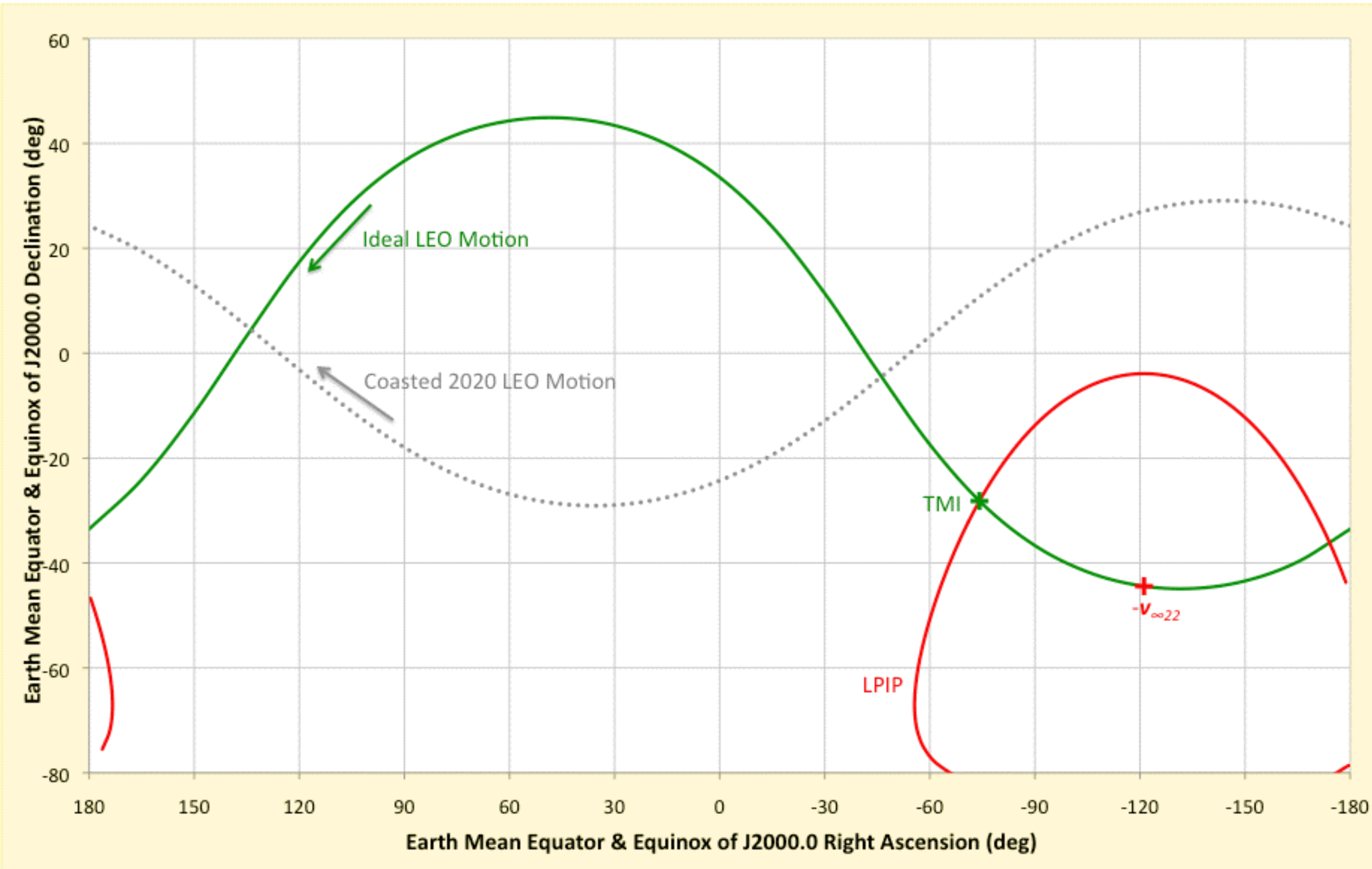
Prograde Earth Departure For Mars On 14.0 July 2020 UT At i = 29°

- LPIP = "locus of possible injection points" centered on departure asymptote's antipode **$-v_{\infty 20}$**
- TMI = trans-Mars injection point



Potential Propellant Depot Locations For Beyond-LEO Human Transport

Prograde Earth Departure For Mars On 9.0 September 2022 UT At *i* = 45°



Potential Propellant Depot Locations For Beyond-LEO Human Transport

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.