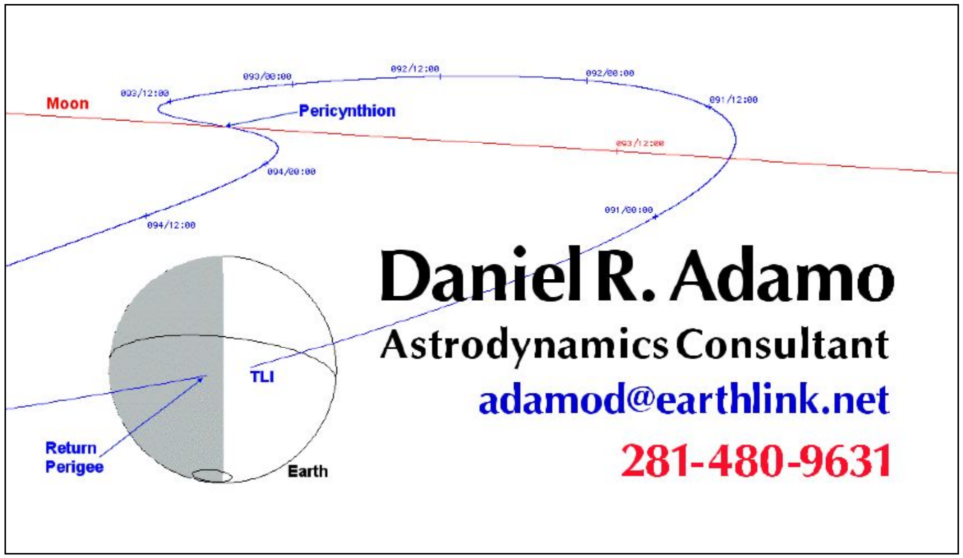
Potential Propellant Depot Locations Supporting Beyond-LEO Human Exploration



Future In-Space Operations (FISO)

13 October 2010 Telecon Colloquium Revised 9 April 2011

Potential Propellant Depot Locations

Agenda

- Provide some historic perspective
- Provide some operational and trajectory-driven insight
- Compare two propellant depot options supporting transit to cis-lunar space from LEO
  - Departure via LEO depot supported by medium lift launches (10.5 mT IMLEO[1] each)
  - Immediate LEO departure supported by heavy lift launches (150.0 mT IMLEO each)
- Take a quick look at depots supporting NEO exploration

Format

- Colloquium: an academic conference or seminar

  ORIGIN: late 16th cent. (denoting a conversation or dialogue): from Latin ***colloqui 'to converse,'*** from ***col- 'together'*** + ***loqui 'to talk'***
- Ensuing charts intended to <u>provoke</u> dialogue, so by all means engage
  - We may not make it through all the charts in an hour
  - If not, we can run past 4 PM EDT or schedule another prop depot "mind-meld"

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[1] IMLEO = initial mass in low Earth orbit at 200 km height. This parameter is arguably the most objective measure of effort required to initiate a mission under any architecture of interest. Those architectures requiring multiple launches must sum the associated IMLEOs.

Potential Propellant Depot Locations

Historic Examples From Earthly Transport

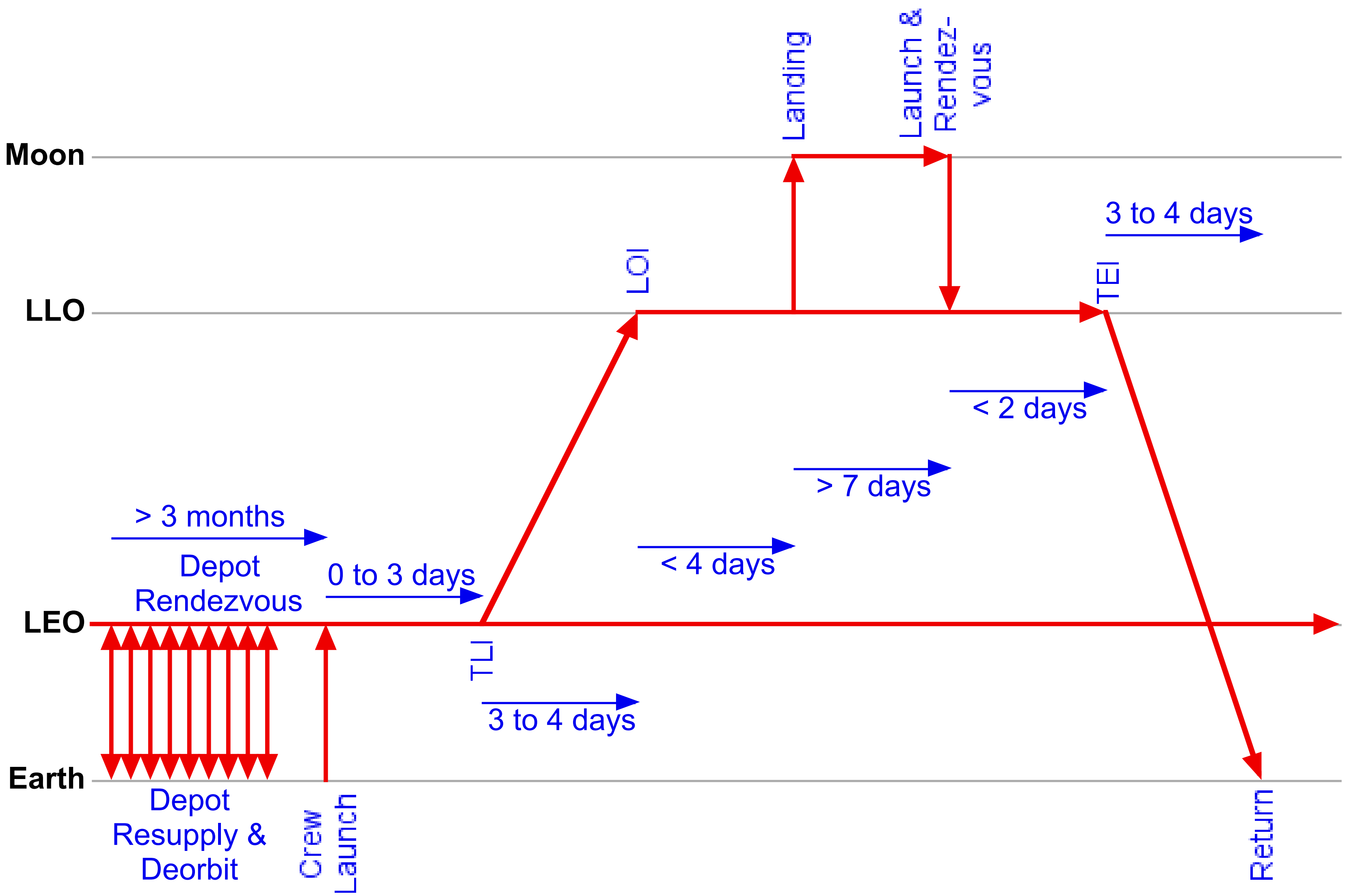
- Trucking, railroads, shipping, and airlines rarely carry all fuel needed for a round trip
- Even "milk runs" utilize refueling opportunities in a contingency or rerouting scenario

ISS: Our Current LEO Propellant Depot

- Progress and ATV 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 considers ISS to be a possible node for cis-lunar transport
  - Upside: ISS already exists, and propellant-optimal departure from it to cis-lunar 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.

Potential Propellant Depot Locations

Architecture With Refillable Propellant Depot Infrastructure In LEO



Potential Propellant Depot Locations

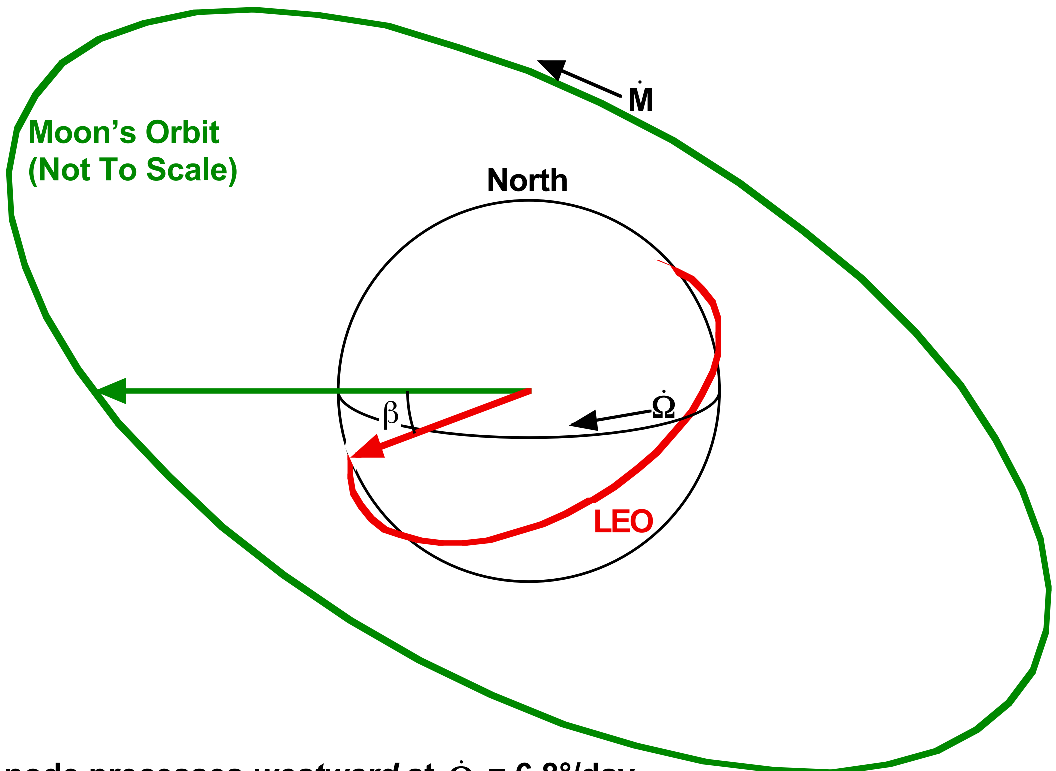
What LEO Is Best For A Depot Supporting Cis-Lunar Logistics?

- Best inclination (i) depends on launch site latitude (ϕ)
  - Maximize IMLEO by launching east such that i = | ϕ |
  - Since the Moon's inclination never exceeds 28.6°, i = ϕ = 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

Geometry Constrains When TLI Can Occur From A Reusable LEO Depot

The Moon at arrival must lie near the LEO plane when it is departed (β must be near zero)



LEO ascending node precesses *westward* at $\dot{\Omega}$ = 6.8°/day
Moon revolves *eastward* at $\dot{M}$ = 13.2°/day
Moon's LEO latitude β = 0 every 180/(6.8 + 13.2) = 9.0 days on average

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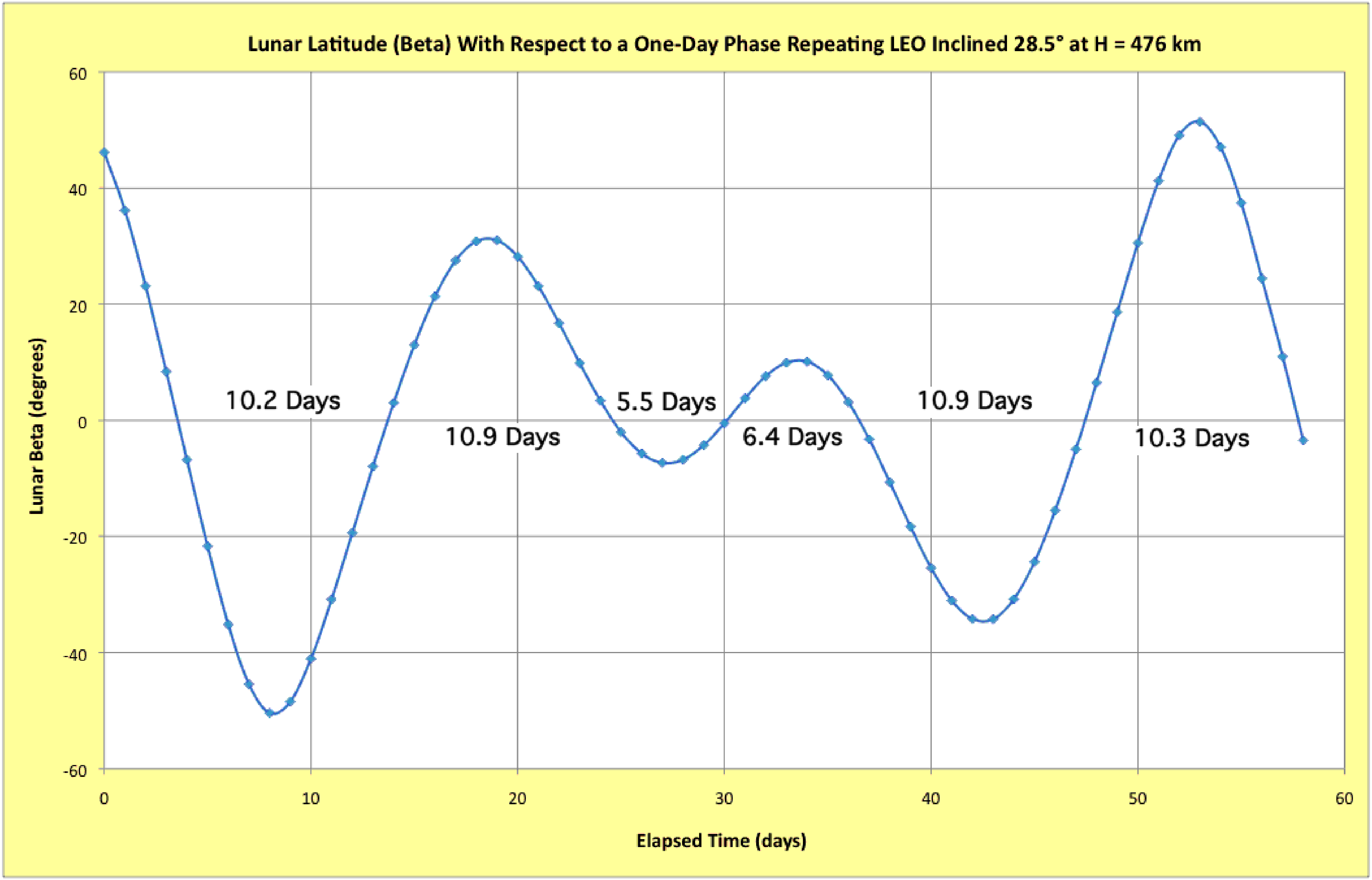

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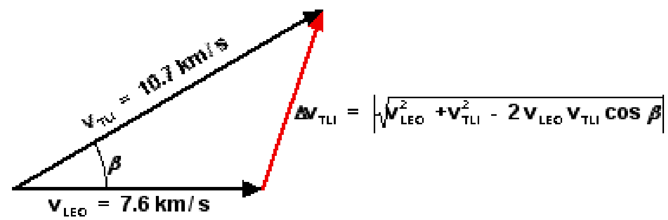

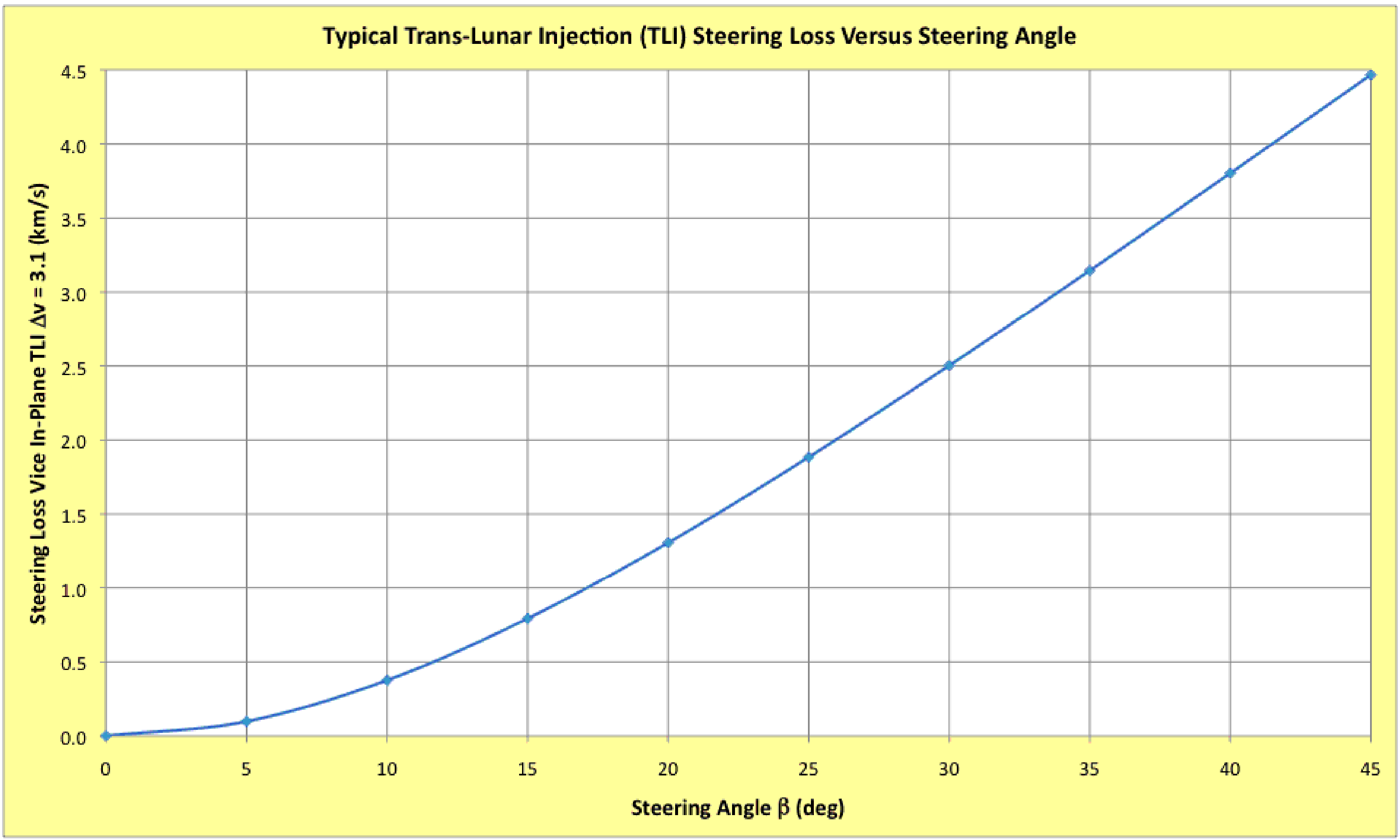

Potential Propellant Depot Locations

What Propellant Mass (M_P) Is Delivered To A 200 km LEO By A 150.0 mT IMLEO Launch?

- Assume LOX/LH2 in a propulsive system with 10% inert mass
  - $M_{BO} \equiv$ propulsive system burnout mass
  - $k \equiv M_{BO} / M_P = 0.1$
  - $I_{SP} = 450$ s $\Rightarrow$ $v_{EX} = g\, I_{SP} = 4.413$ km/s
- From the previous β discussion, assume TLI capability (Δv_{TLI}) is 3.3 km/s
- Assume $M_Y \equiv$ payload mass injected by TLI = 62.8 mT
- "Use The Rocket Equation, Luke!"
  - $f \equiv e^{\Delta v_{TLI} / v_{EX}}$
  - $M_{BO} + M_P + M_Y = (M_{BO} + M_Y)\, f$
  - Substituting $k\, M_P$ for M_{BO} above produces $M_P = \dfrac{M_Y\,(f - 1)}{1 + k\,(1 - f)} = 79.2$ mT

Potential Propellant Depot Locations

What Propellant Mass (m_D) Is Deliverable To A 476 km LEO Depot By A 10.5 mT IMLEO Launch?

- As before, assume $k \equiv m_{BO} / m_P = 0.1$ and $v_{EX} = 4.413$ km/s. Note there is no dedicated payload mass in a 10.5 mT IMLEO launch ($m_Y \equiv 0$).
- In delivering depot propellant to 476 km height, each 10.5 mT launch undergoes a gravity loss. Since M_P must raise one end of the 150.0 mT launch's LEO from 200 km during TLI, the gravity loss only applies to the orbit's other end. Raising a 476 x 200 km LEO to a 476 x 476 km LEO requires $\Delta v_U = 0.079$ km/s.
- The rocket equation then provides $m_S' \equiv$ "wet" propulsive system mass at depot arrival
  - $m_S \equiv 10.5 \text{ mT} = m_{BO} + m_P \Rightarrow m_{BO} = \dfrac{k\, m_S}{k + 1} = 1.0 \text{ mT}$
  - $m_S' = m_S\, e^{-\Delta v_U / v_{EX}} = 10.3 \text{ mT}$
- And $m_D \equiv m_S' - m_{BO} = 9.3$ mT

Potential Propellant Depot Locations

How Many 10.5 mT IMLEO Launches = One 150.0 mT IMLEO Launch?

- First, note that deliverable propellant mass m_D is optimistic because it neglects:
  - Losses due to other rendezvous and proximity operations impulses
  - Losses due to depot orbit maintenance propellant consumption
  - Losses due to cryogenic boiloff (or m_{BO} would increase from added insulation mass)
  - Losses due to separation from depot and controlled deorbit like Progress disposal
- Bottom line: M_P / m_D = 8.5 launches
- However: more 10.5 mT IMLEO launches are required to actually *apply* depot propellant to a TLI sending M_Y = 62.8 mT toward cis-lunar space ({M_Y + k M_P} / m_S' = 6.9 launches)
- Very bottom line: one 150.0 mT IMLEO launch leading directly to TLI is equivalent to 10.5 (8.5 + 6.9) = 161.7 mT IMLEO when TLI depends on the LEO propellant depot concept developed here. This result assumes depot resupply is virtually 100% efficient, subject only to an "uphill" gravity loss.

Potential Propellant Depot Locations

So What? It Probably Depends On Your Perspective...

- If you're trying to sell rockets with IMLEO << 150.0 mT, it's great for volume, but...
  - How dependable are 8.5 + 6.9 = 15.4 launches, followed by complex automated depot events, to inject meaningful payload mass toward cis-lunar space on schedule?
  - How is $M_Y + k\ M_P$ launched and assembled prior to depot tanking and TLI?
  - How are TLI times imposed by acceptable steering losses accommodated?
  - What if a time-critical emergency develops requiring TLI be performed ASAP?
  - How are timely maintenance and repairs performed on a robotic depot?
  - Is recovery of many small first stage components from the ocean sustainable?
- If you're trying to sell heavy-lift with IMLEO >> 10.5 mT, achieving TLI is simple, 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 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 $\Rightarrow$

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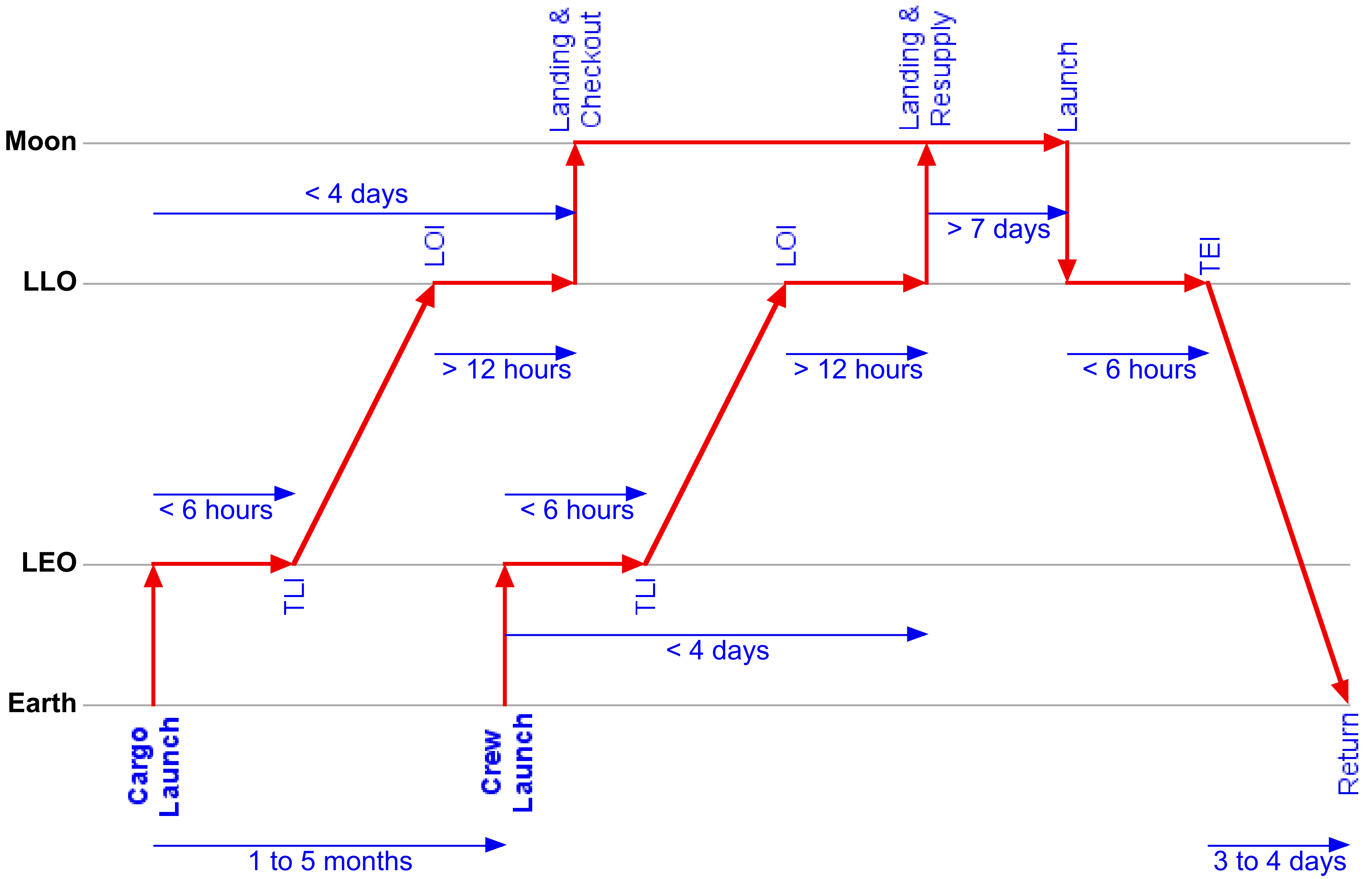
Lunar Surface Rendezvous (LSR) Architecture (ref. 17 June 2009 FISO)



Potential Propellant Depot Locations

Depot Support To NEO & 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 cis-lunar 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 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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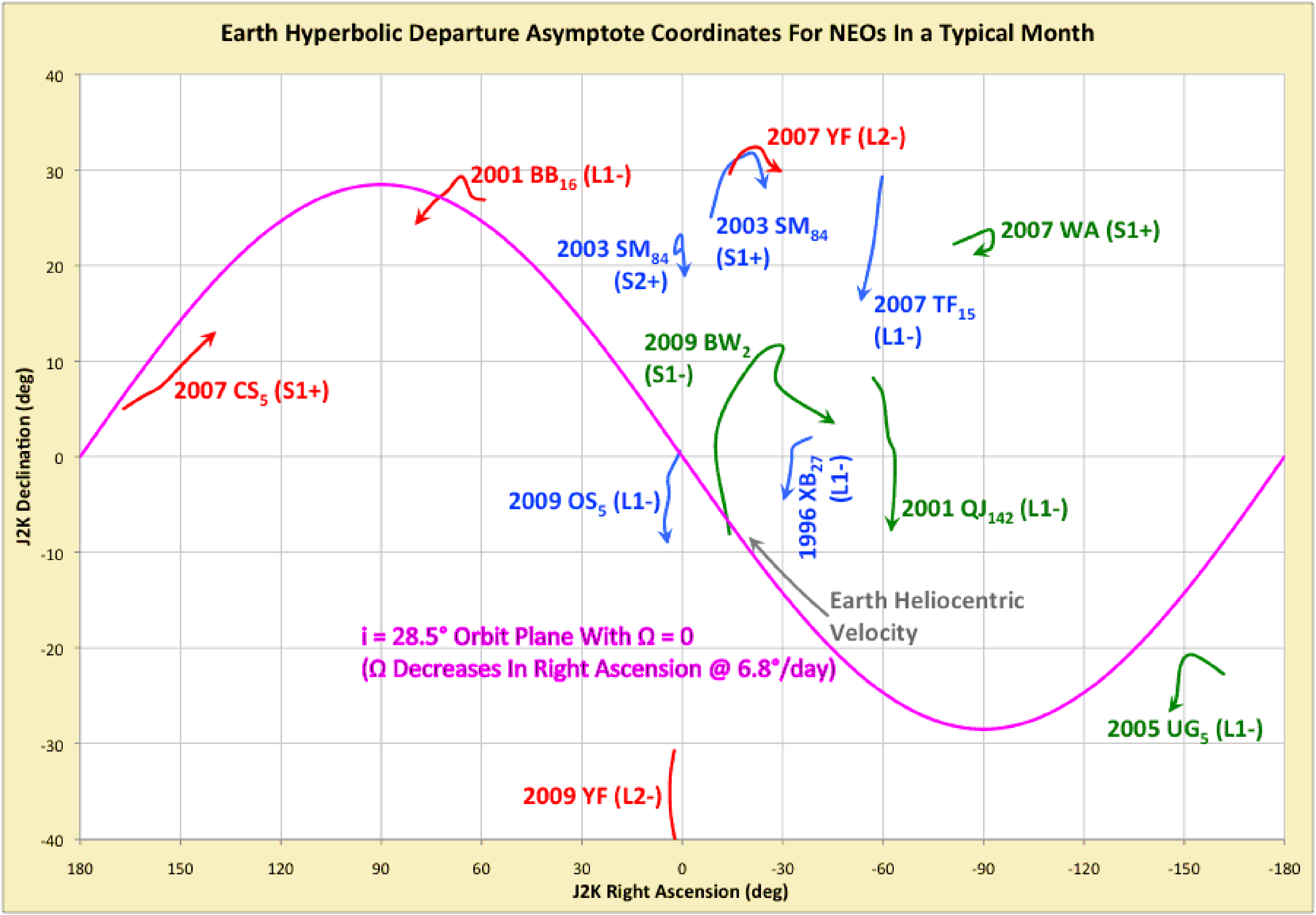

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Conclusions (Evangelism Is Undoubtedly Still In Progress)

- For cis-lunar destinations, there may be a commercial case for LEO depot infrastructure
  - Operationally, it's an unattractive alternative to heavy-lift with IMLEO ~150 mT
  - 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
- At destinations beyond the Moon, nearby depot locations make sense
  - Launch seasons at Earth are too brief and infrequent to tolerate steering losses typically imposed by reusable depot infrastructure in LEO
  - A depot at a Sun-Earth libration point starts to make sense, but these locations can impose transit delays and in-situ resource utilization potential is literally remote
  - Pre-emplace consumables or production facilities near or on the end destination