Jet Propulsion Laboratory
California Institute of Technology

In-Space Assembled Telescope (iSAT) Study

Study Members Telecon 11

Oct 31 and Nov 1, 2018

Nick Siegler
Chief Technologist, NASA Exoplanet Exploration Program
Jet Propulsion Laboratory, California Institute of Technology

Bo Naasz
NASA Rendezvous and Capture System Capability Leadership Team
NASA (GSFC)

CL#18-6882

K-T Matrix To Date

Problem Statement (Activity 1b): Prioritize assembly and infrastructure concepts for a 20 m modularized in-space assembled telescope.			
ID		**Concept A**	**Concept B**
	OPTION DESCRIPTORS	**Assembly at cis-Lunar**	**Assembly at SE-L2**
D1	**Describe the Concept architecture.**	**Assembled at cis-lunar**, modules are launched to cis-lunar via upper-stage cargo vehicle and either (1) transferred to a space tug for delivery to the assembly location; (2) the cargo vessel has 6 DOF RPO sensor capabilities and delivers the modules directly to the (3) assembly location or (4) depot. Any depot would require a tender to transfer modules to the assembly location. Assembly of the modules occurs with multiple walking and stationary long-reach robotic arms along with dextrous robotic arms directly on the telescope S/C bus or on some building way, entirely detached from the telescope other than docking points. **Other trades:** (a) First light at cis-lunar with 1-2 instruments, then propels to SE-L2, subsequent instruments installed and serviced at SE-L2 versus full telescope assembly at cis-lunar then transfer to SE-L2. (b) Can take advantage of Gateway infrastructure, including astronauts, for contingency if available. (c) Modules are delivered to LEO via cargo vessel and transferred to space tug for delivery to the assembly location.	**Same as Concept A but assembly occurs at SE-L2**

Observations from the LaRC Meeting

Narrowing of Parameter Space

- **Assembly orbit preferences for cis-lunar and SE-L2**
  - Partial or complete assembly at cis-lunar for 3 of the 6 concepts
  - No one selected the Gateway (would consider as contingency if existed)
  - No LEO, GEO, HEO
- **Servicing/upgrading orbit preferences at SE-L2**
  - Servicing: repair, refuel, orbit adjustment
  - No one scared off by 10 sec round-trip latency
  - Trade to assess bringing telescope to cis-lunar for servicing/upgrading
- **Assembly agents preference for robotic arms**
  - No free fliers, no multi-limbed robots, no astronauts
- **Emergence of the Space Tug**
  - Why a tug (and not direct to assembly platform?)
  - One set of concepts had a tender, a depot, and/or a building way
  - One concept tugs modules from LEO

Today’s Agenda

1. **Intrinsic benefits of telescope assembly in the cis-Lunar environment**
   – preliminary findings by Bo Naasz/NASA GSFC

2. **KT Matrix**
   – preliminary assessment by Nick Siegler

iSAT Assembly Location Trade

Bo Naasz
NASA Rendezvous and Capture System Capability Leadership Team
NASA (GSFC)
10/26/18

iSAT Question

What, if any, are the intrinsic benefits of doing the telescope assembly (and subsequent servicing) in the Cis-Lunar environment? Please assume there is no Gateway and no related or unrelated commercial activities to the Moon.

iSAT Assembly Location Trade

Bo Naasz

10/31/18

Cislunar vs SE-L2 Assembly Location Trade (excluding Gateway assumptions)

Red text - updates

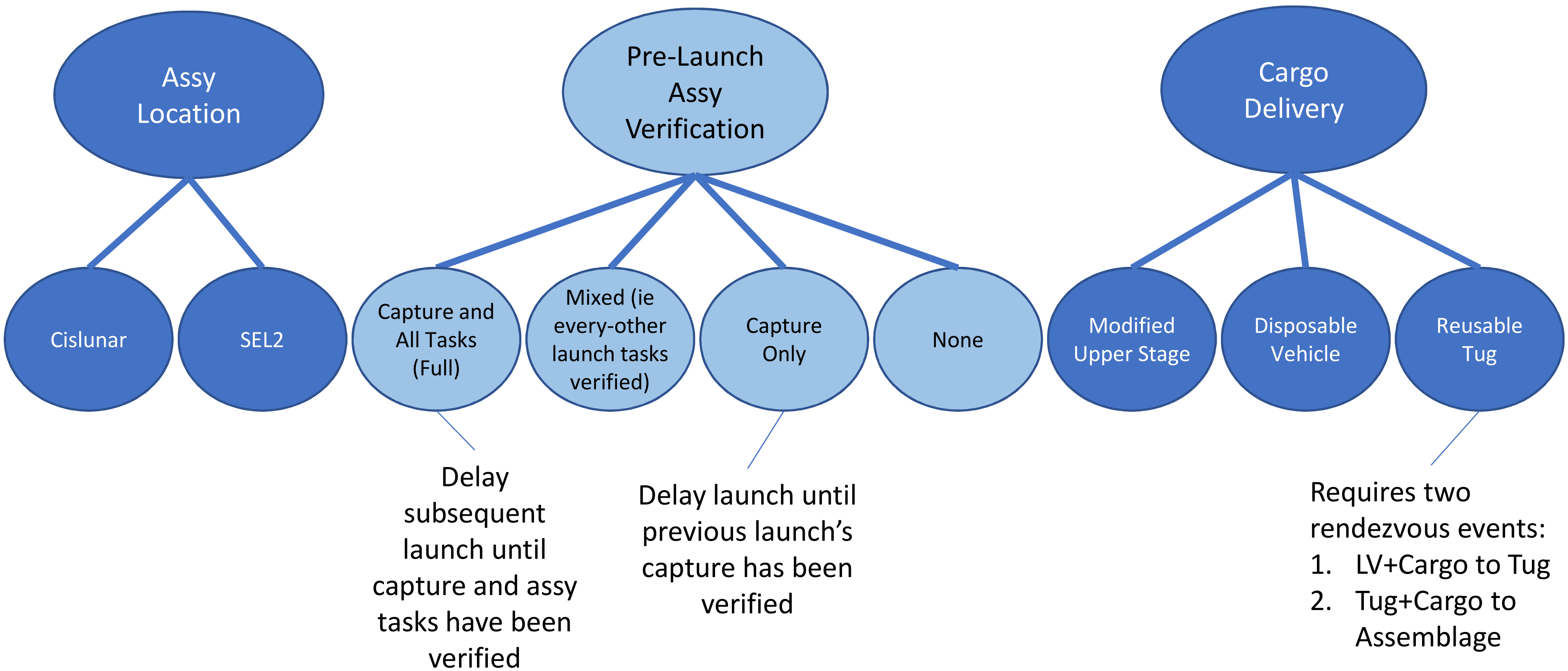
	Earth Orbit	Cislunar	Sun-Earth L2	Preferred location w/ rataionale
Launch Window Frequency (days)	1	**2-6**	180??	**Cislunar Significant Strength** – SEL2 launch windows are 180 (TBR) – probably can trade fuel to improve the situation, need some help here. See this slide
Transfer Time from launch to assy orbit per module (days)	<1	**6**	100	**Cislunar Significant Strength –** For 9 launches, Cislunar is total of 9*94=850 days less cargo transfer operations, could be a significant reduction in cargo delivery cost
Total assy time (years) (see charts 4-8 for details)	<1	**0.4-0.6**	0.7-2.9	**Cislunar Significant Strength** - Especially if capture and/or assembly verification prior to subsequent launch is desired – could cut assembly time in a quarter. Cislunar has less risk for the same amount of time, or less time for the same amount of risk. Note SEL2 numbers do not consider launch window frequency.
Launch C_3	1.3-3.22	-2.0	-0.7	**Cislunar Minor Strength** – LV performance - 250kg more per launch to cislunar (assuming not volume limited), for a total of 9*255 = 2295kg more performance in 9 launches.
Teleoperation time delay (sec)	6-Jan	<2 sec	5 sec	**Cislunar Minor Strength** – Assume much of the work is automated, but even if it isn't, increased latency from 2 to 5 seconds will not have a a major impact on telerobotic task timing
Comm	TDRS	DSN + LC	DSN + LC	**Cislunar Minor Strength -** Cislunar is closer, improved link margins

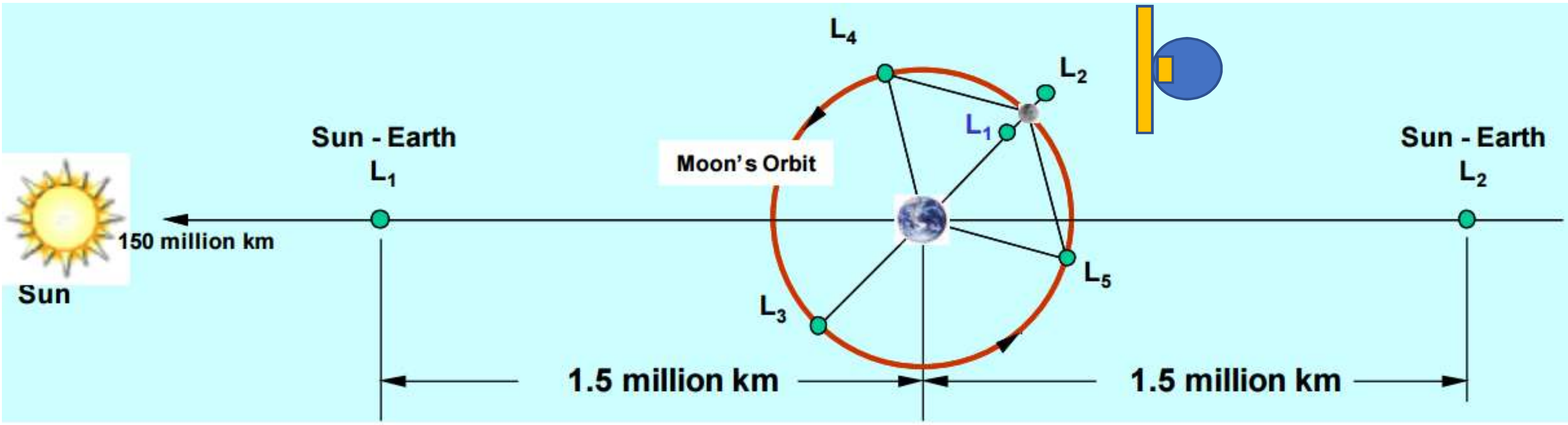
Cislunar vs SE-L2 Assembly Location Trade (excluding Gateway assumptions)

Red text - updates

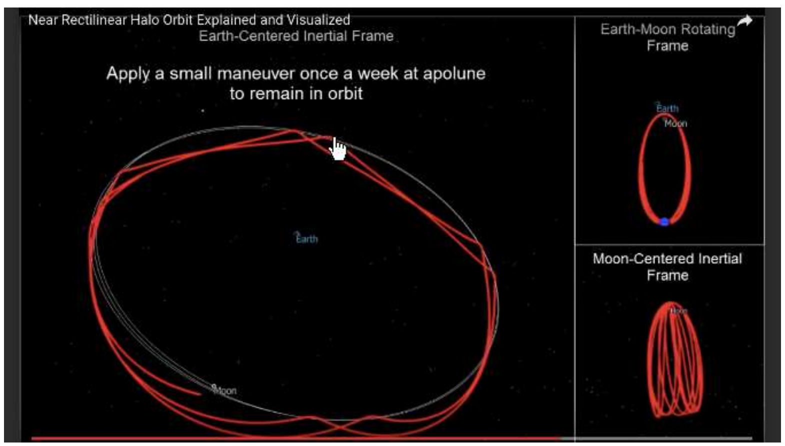
	Earth Orbit	Cislunar	Sun-Earth L2	Preferred location w/ rataionale
Inertial Nav performance				Question: Nav performance in Cislunar is likely better, this could simplify rendezvous
Cargo Delivery stage Delta V	N/A	Low	Low	See Folta – not sure if there's a discriminator here – insertion delta V's are typically minimized (almost zero) by trajectory design
Maneuver loads on assemblage	High	Very Low	Very Low	Question: Does the maneuver from Cislunar to SEL2 present a vibration/load challenge? For a 10 m/s maneuver using biprob (Isp=300) • 50,000kg assemblage, 1000N thrust, accel = 0.02m/s^2 (2 mili gees), 500sec burn • 100,000kg assemblage, 100N thrust, accel = 0.001m/s^2 (0.1 mili gees), 2.8 hour burn
Environment	High TID	1 AU	1 AU	No preference
Sun/Earth/Moon thermal and lighting geometry	Very Complex	Mild	**Constant**	**SEL2 Minor Strength** – need to find assy attitude in Cislunar that keeps dark side shaded from sun, all light out of optical path. Would pointing out of ecliptic at EML2 do this? If so, preference is slight. If Earth/Moon light on dark side during assembly is not acceptable, this could become a major strength for SEL2. Solved by adding a barrel? Question: What is the requirement for thermal stability during assembly? Commissioning? Ops? Is there a combination of EML2 orbit and attitude that meets these requirements? If not, Question: How long after the transfer burn from Cislunar to SEL2 is the system thermally stable enough for commissioning? Ops?
Transfer time from Assy to Ops	90	90?	0	**SEL2 Minor Strength** – but this is very very minor, Telescope can operate during transfer Question: how long after the transfer burn is the system thermally stable enough?
Delta V Assy to Ops Orbit (m/s)	3,500	30?	**0**	**SEL2 Minor Strength** - for a 50,000 kg observatory, this would be ~500kg bi-prop

Several related trades



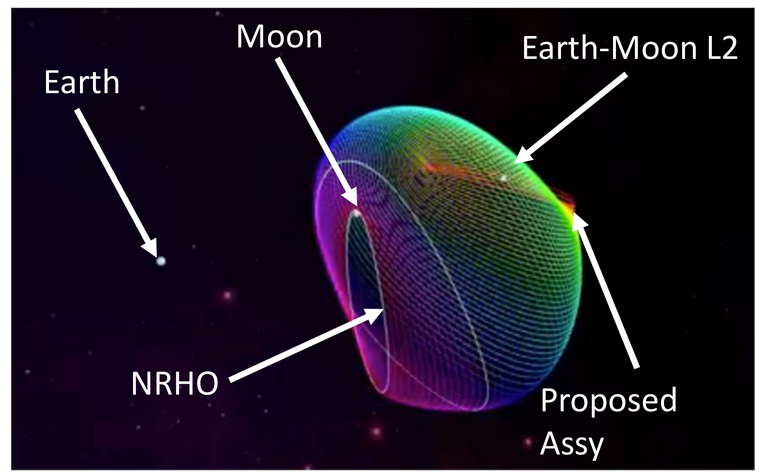


Cislunar Orbit: **NRHO is BAD** for assembly
(get's very close to moon, so greater thermal flux)



https://www.youtube.com/watch?v=X5O77OV9_ek

Cislunar Orbit: **Halo orbit around L2 is good** for assembly (never get's very close to moon)



This table lists sample values of L_1, L_2, and L_3 within the solar system. Calculations assume the two bodies orbit in a perfect circle with separation equal to the semimajor axis and no other bodies are nearby. Distances are measured from the larger body's center of mass with L_3 showing a negative location. The percentage columns show how the distances compare to the semimajor axis. E.g. for the Moon, L_1 is located 326400 km from Earth's center, which is 84.9% of the Earth-Moon distance or 15.1% in front of the Moon; **L_2 is located 448900 km from Earth's center, which is 116.8% of the Earth-Moon distance or 16.8% beyond the Moon**; and L_3 is located −381700 km from Earth's center, which is 99.3% of the Earth-Moon distance or 0.7084% in front of the Moon's 'negative' position.

Body pair	Semimajor axis (SMA)	L_1	$1 - L_1/SMA$ (%)	L_2	$L_2/SMA - 1$ (%)	L_3	$1 + L_3/SMA$ (%)
Earth-Moon	3.844×10^8 m	3.2639×10^8 m	15.09	4.489×10^8 m	16.78	-3.8168×10^8 m	0.7084

https://en.wikipedia.org/wiki/Lagrangian_point

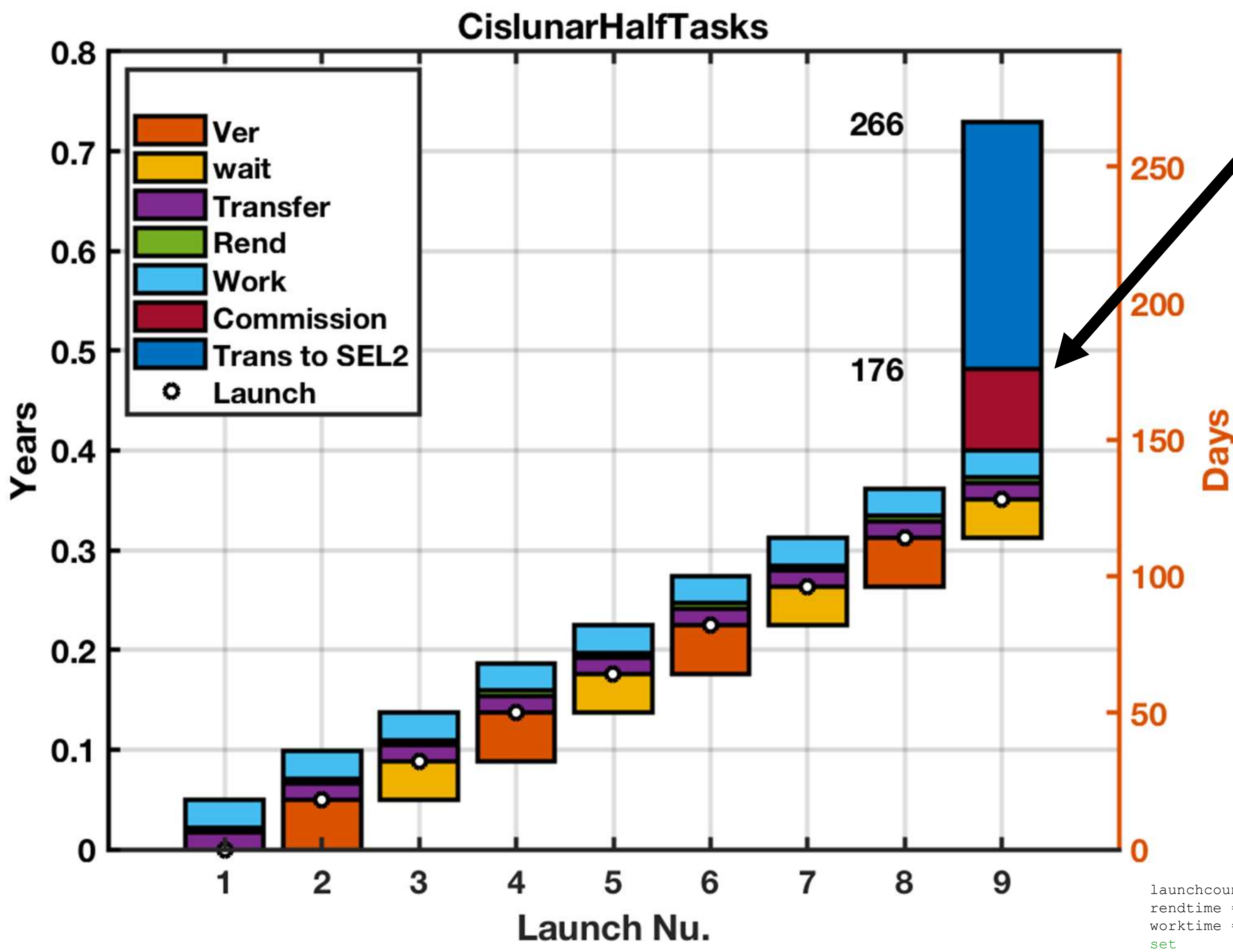
Assembly Time Calculator

Total assy time logic (extremely oversimplified):

- **Assumes 9 launches**
- **Minimum 14 days between launch**
- **Transfer times** (launch to assy vicinity)**:**
  - 6 days launch to cislunar
  - 100 days launch to SEL2
  - 90 days cislunar to SEL2
- **Rendezvous times:**
  - 2 days for rendezvous (after arrival in vicinity)
  - 2 rendezvous for Tug (Tug-to-LV+Payload and Tug+Payload-to-Assemblage)
  - 1 rendezvous for all other options
- **Work time: 10 days per launch**
- **Verification Options**
  - **Capture** - Launch delayed until previous launch payload capture completed
  - **All Tasks** – Capture plus 10 days work after delivery to verify readiness for next launch for all launches
  - **None** - Launches separated by 14 days (minimum reasonable launch cadence)
  - **All Capture, Half Tasks** – All captures and half of tasks verified
  - **Half Tasks** – Half of launches delayed for verification of capture and assy tasks
- **Time for Verification of each launch's assembly tasks** – how long? This analysis assumes 10 days work post capture
- Assume Any additional work post verification does not delay subsequent launch or commissioning

Notional Cislunar Assy Time w/ partial verification (from LaRC Grunsfeld Team)

Task - Assemblies and Launches	# days	
Primary spacecraft w/ two (2) assembly arms on metering truss structure	14	
Launch tug + PM truss	4	
Proximity Ops	2	
Assemble PM truss (Each Truss Element: remove, inspect, expand, inspect, soft dock, hard dock, inspect, metrology)	14	
Launch sun shade (4 days) – assume concurrent with previous step.	0	
Sun shade assembly and deploy	7	
Launch metering truss	4	
Transport and dock	6	
Complete the metering truss	2	
Launch Secondary mirror	6	
Install secondary mirror w/ laser metrology system and secondary mirror truss (extensions required)	3	
Launch 1st series of raft assemblies	6	
Install 1st series of raft PM assemblies – concurrently launch 2nd series of raft assemblies	12	
Install 2nd series of raft PM assemblies – concurrently launch 3rd series of raft assemblies	12	
Install 3rd series of raft PM assemblies	12	
Launch next assemblies (miscellaneous, light shields))	6	
Install miscellaneous assemblies	5	
Launch 1st SI (imager and coronagraph)	6	
Install 1st SI (imager and coronagraph – allows PM phasing	1	
Initial Commissioning	30	
Transfer to L2	90	
Total Timeline Estimation -->	242	days
Assembly Only -->	122	days



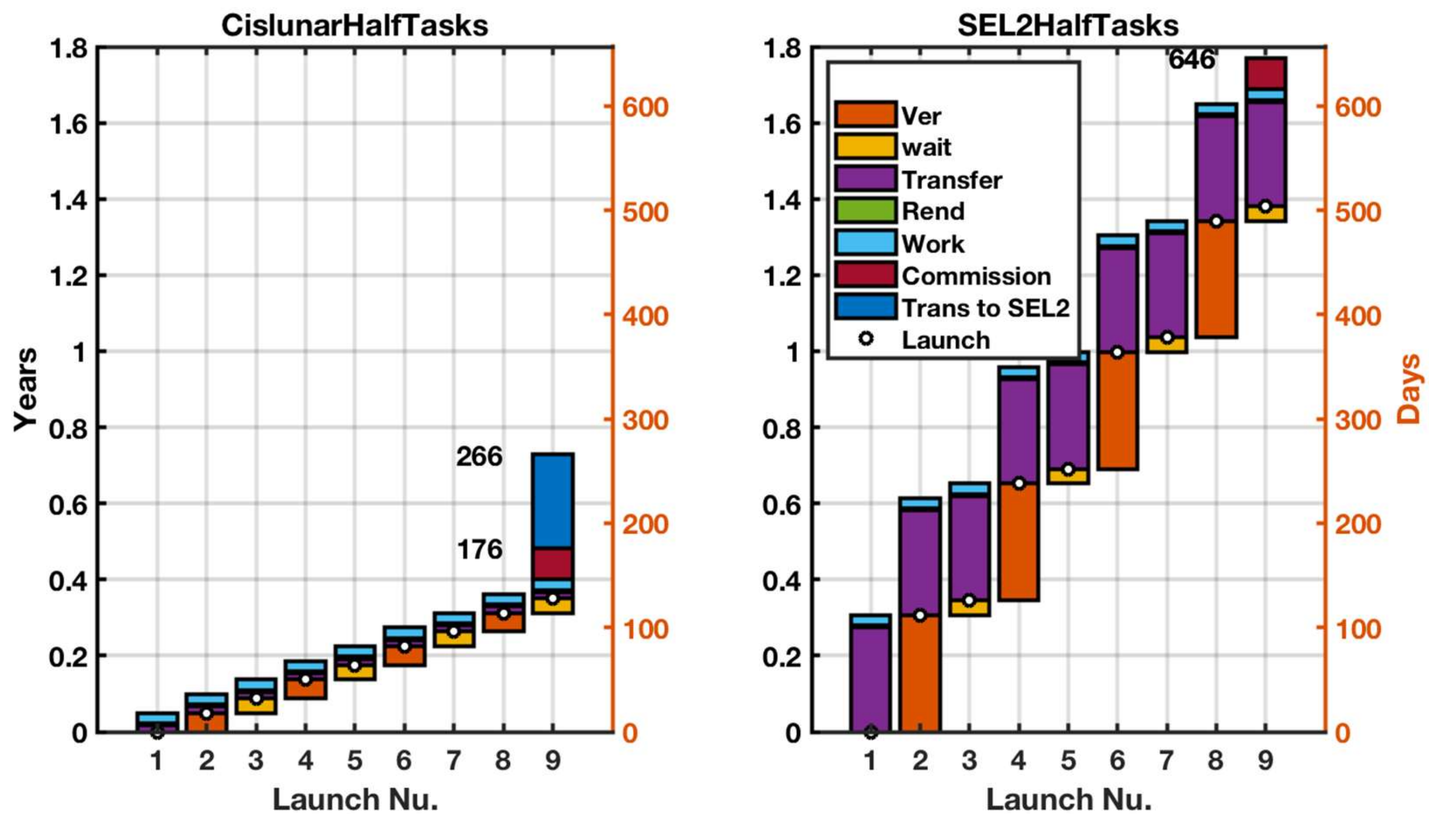
Assembly & commissioning complete in 176 days

John will be mad at me, his schedule got it done in 152 days.

This is an oversimplified model of assembly time for use in comparing the different options, is sufficiently close for this analysis

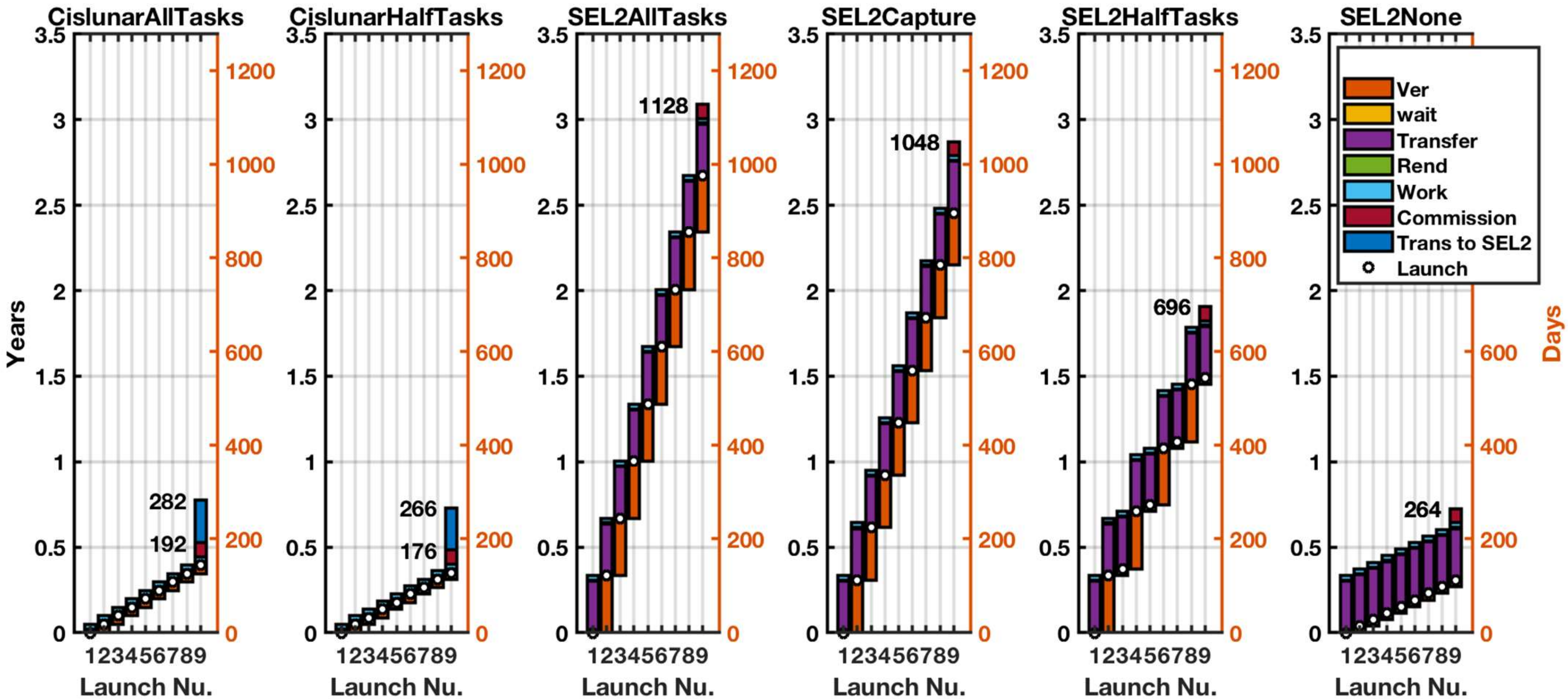
```
launchcount = 9;
rendtime = 2;  % days to add for each rendezvous event
worktime = 10; % Days of work to assemble each launch cargo
set
mintimebetweenlaunches = 14; % days
cislunartransfer = 6; %days from launch site to cislunar
SEL2transfer = 100; %days from launch site to SEL2
```

Comparing Cislunar and SEL2 Assy (with half tasks verified)



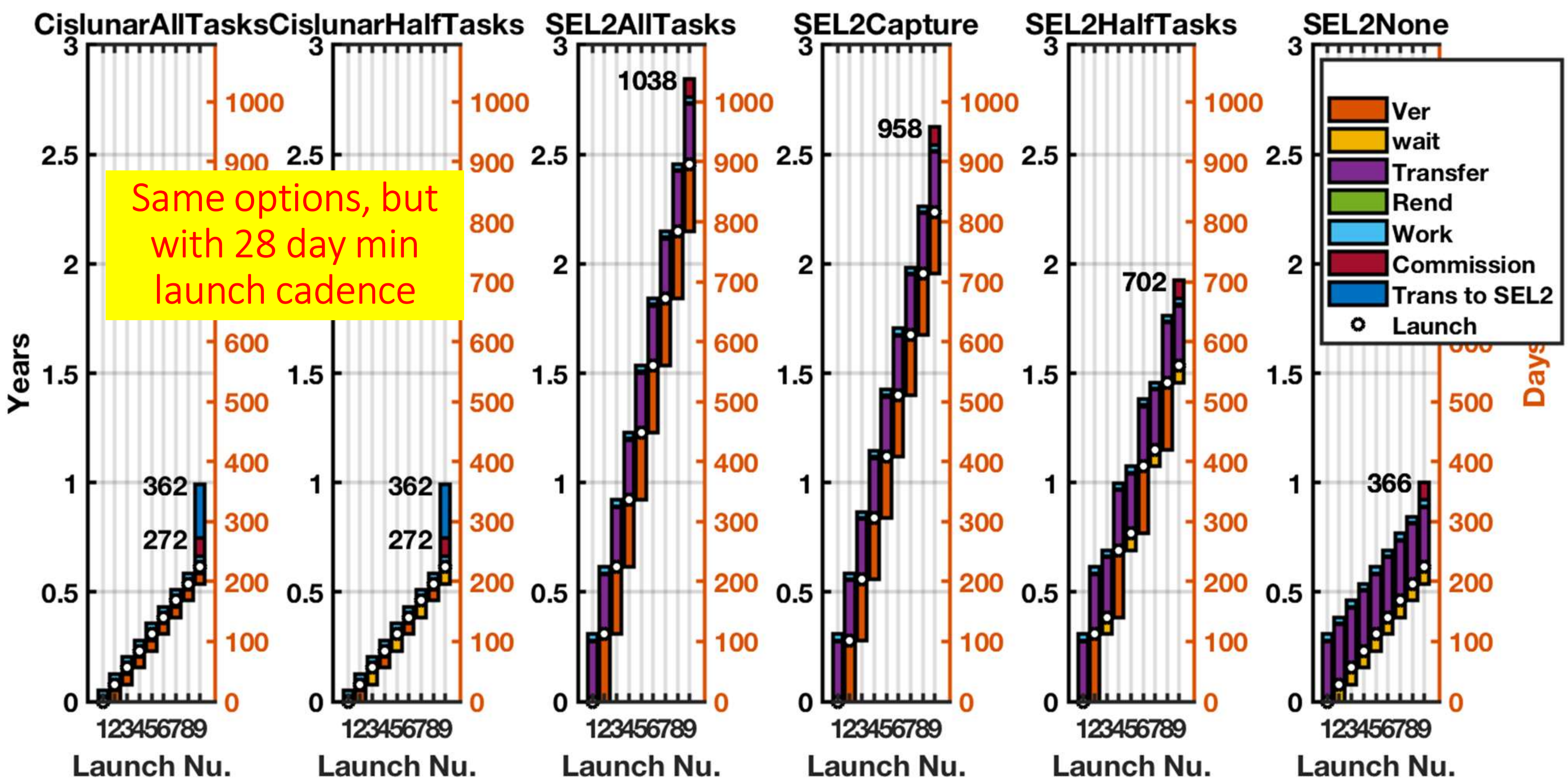

```
launchcount = 9;
rendtime = 2;  % days to add for each rendezvous event
worktime = 10; % Days of work to assemble each launch cargo set
mintimebetweenlaunches = 14; % days
cislunartransfer = 6; %days from launch site to cislunar
SEL2transfer = 100; %days from launch site to SEL2
```

Cislunar assembly complete in 25% of SEL2 assembly time




```
launchcount = 9;
rendtime = 2;  % days to add for each rendezvous event
worktime = 10; % Days of work to assemble each launch cargo s
mintimebetweenlaunches = 14; % days
cislunartransfer = 6; %days from launch site to cislunar
SEL2transfer = 100; %days from launch site to SEL2
```

Cislunar assembly complete in 20%-63% of SEL2 assembly time




```
launchcount = 9;
rendtime = 2;  % days to add for each rendezvous event
worktime = 10; % Days of work to assemble each launch cargo s
mintimebetweenlaunches = 14; % days
cislunartransfer = 6; %days from launch site to cislunar
SEL2transfer = 100; %days from launch site to SEL2
```

Cislunar assembly complete in 26%-74% of SEL2 assembly time

Assembly Time Conclusions

- If **capture and/or assembly verification** prior to subsequent launch is desired
  - Cislunar assembly time is about 25% of SE-L2 assembly time (half of tasks verified)
  - Drivers:
    - Transfer time from launch to SE-L2
    - Amount of verification – benefit is reduced to ~63% if nothing is verified
    - Launch cadence – benefit is reduced to ~40% if min time between launches is increased to 28 days
- Verification of all tasks increases the benefit of cislunar assembly
- Cislunar has less risk for the same amount of time, or less time for the same amount of risk
- How will budget constraints and actual build times affect launch cadence?

- Important note: None of these SEL2 numbers account for SEL2 launch window every 6 months – which could have a huge impact on assembly conops. Is it really 6 months?

Backup

Launch Windows for Cargo Delivery to Rendezvous with Telescope Assemblage

Cislunar

From: Ryan Whitley <ryan.j.whitley@nasa.gov>
Date: Wednesday, October 3, 2018 at 2:58 PM
Subject: RE: quick question

The frequency of the optimal transfer geometry is the same as the period of the orbit, every 6.5 days. We are still working out the final windows given Orion capability, but there will likely be a 2-3 day window around that optimal time.

-R

Sun-Earth L2

From: "Folta, David C. (GSFC-5950)" <david.c.folta@nasa.gov>
Date: Tuesday, October 30, 2018 at 11:41 AM
Subject: RE: Questions
Bo,

Yes, in a simulation, but there are some dynamical considerations too. The orbit planes must match (think inclination of the SEL2 orbit), velocities at rendezvous can be different, or there are operational constraints from prop contamination. I think we are do it, but it would take a little analysis to verify. Do you want me to look at that rendezvous too?

Dave

From: Naasz, Bo J. (GSFC-5000)
Sent: Tuesday, October 30, 2018 11:35 AM
Subject: Re: Questions

If you plan to launch every month, couldn't you just target the SEL2 orbit clocking correspondingly? IE, insert at noon, then 2, then 4, etc, wherever you anticipate the Assemblage to be ~100 days after each launch?

From: "Folta, David C. (GSFC-5950)" <david.c.folta@nasa.gov>
Date: Tuesday, October 30, 2018 at 11:26 AM
Subject: RE: Questions

Bo,

Yep, timing can be a big problem. Launch (LEO injection) to SEL2 can happen every day, except if the moon is in the way which takes out 2-3 days per month. The rendezvous at SEL2 is challenging since the orbit period for all the SEL2 orbits is 180 days (+/-2 days). So as Don mentioned, we need to time the arrival so that we are at the proper location to rendezvous. One can attain the SEL2 orbit at several locations about the orbit (front or back, etc.), but that places a constraint on launch or departures or more DV on the transfer s/c. Once at the SEL2 orbit the DV to catch up is large, hundreds of m/s usually. Remember that the orbit dynamics are not like LEO where one can simply change the sma to change the orbit period to phase the orbits.

Dave

From: Naasz, Bo J. (GSFC-5000)
Sent: Tuesday, October 30, 2018 11:17 AM
Subject: Re: Questions

Another important aspect I forgot about is the launch window – here's what Don Dichman told me months ago:

The transfer out to L2 is straightforward since we have done it several times. To rendezvous it would be desirable to time the launch of the servicing vehicle so that, when it reach the L2 vicinity, the telescope to be serviced is nearby.
A quasi-halo libration point orbit like WFIRST has a period near 6 months.
We tend to insert into the libration point orbit near the top, and it takes a few months to get out there.
That would give you a launch window once every 6 months for several weeks.

I think you and I talked about this, but I can't remember the outcome. Do we have to insert near the top, or can we insert wherever we want? If we can only launch every 6 months for assembly in SEL2, that could be a showstopper.

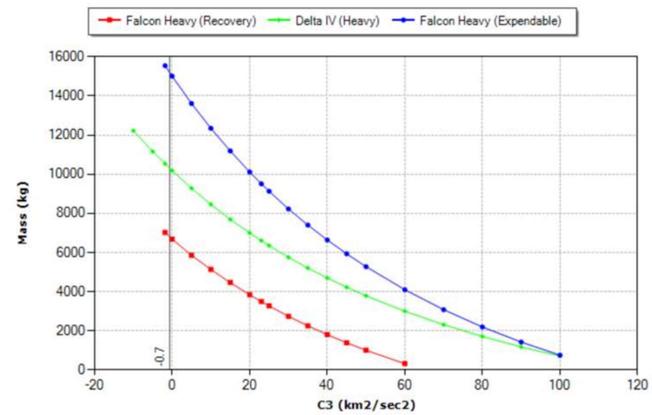
It's Complicated

LV Performance

From: "Folta, David C. (GSFC-5950)" <david.c.folta@nasa.gov>
Date: Tuesday, October 30, 2018 at 12:59 PM
Subject: RE: Questions
Bo,

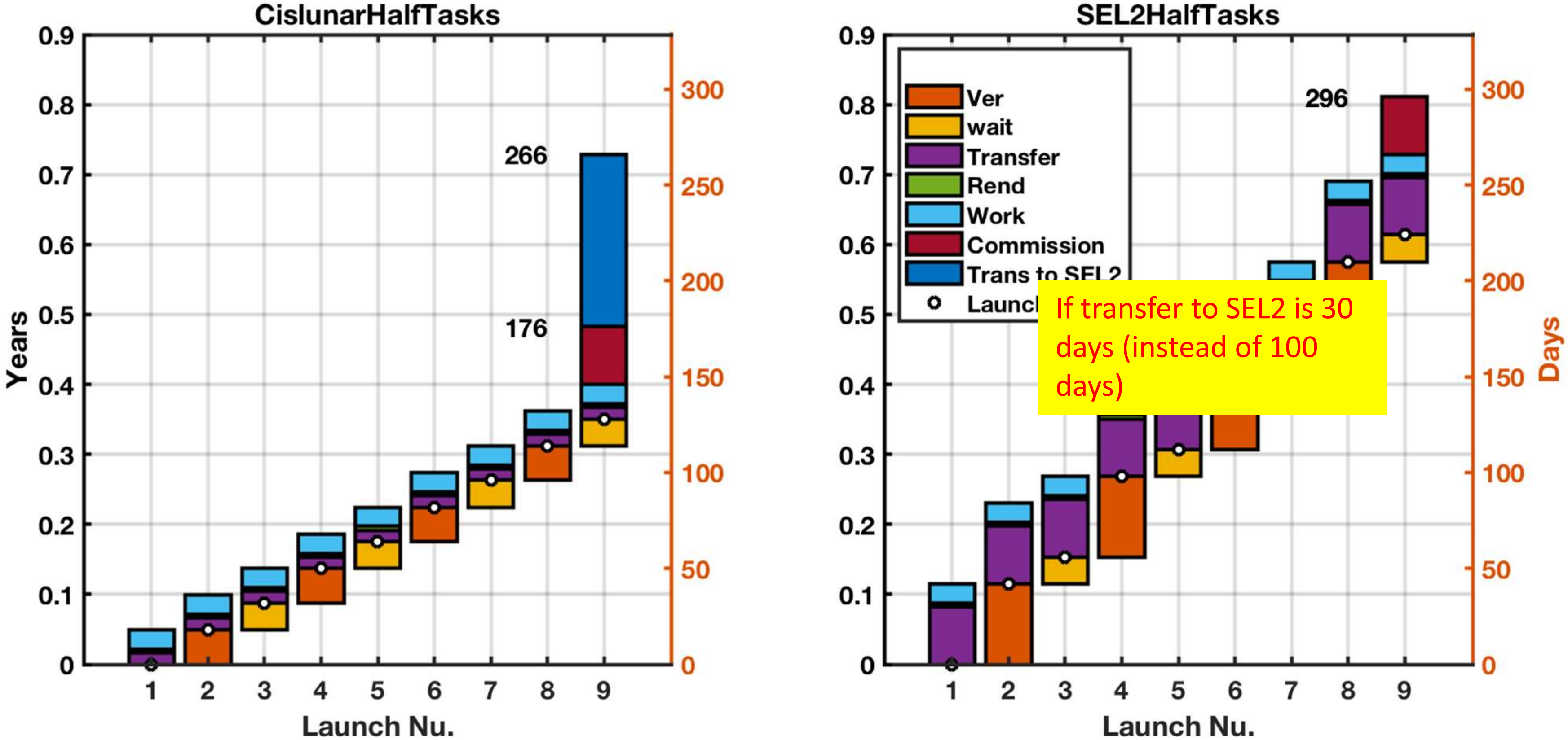
Representative C3 values are : Cis-Lunar ~ -2.0 km^2/sec^2, and SE libration ~ -0.65 km^2/sec^2. These vary some, ex, SEL2 can be between ~ -0.55 to -0.70 km^2/sec^2. Its dependent on epoch and eccentricity (both Earth's and moon's).

Dave



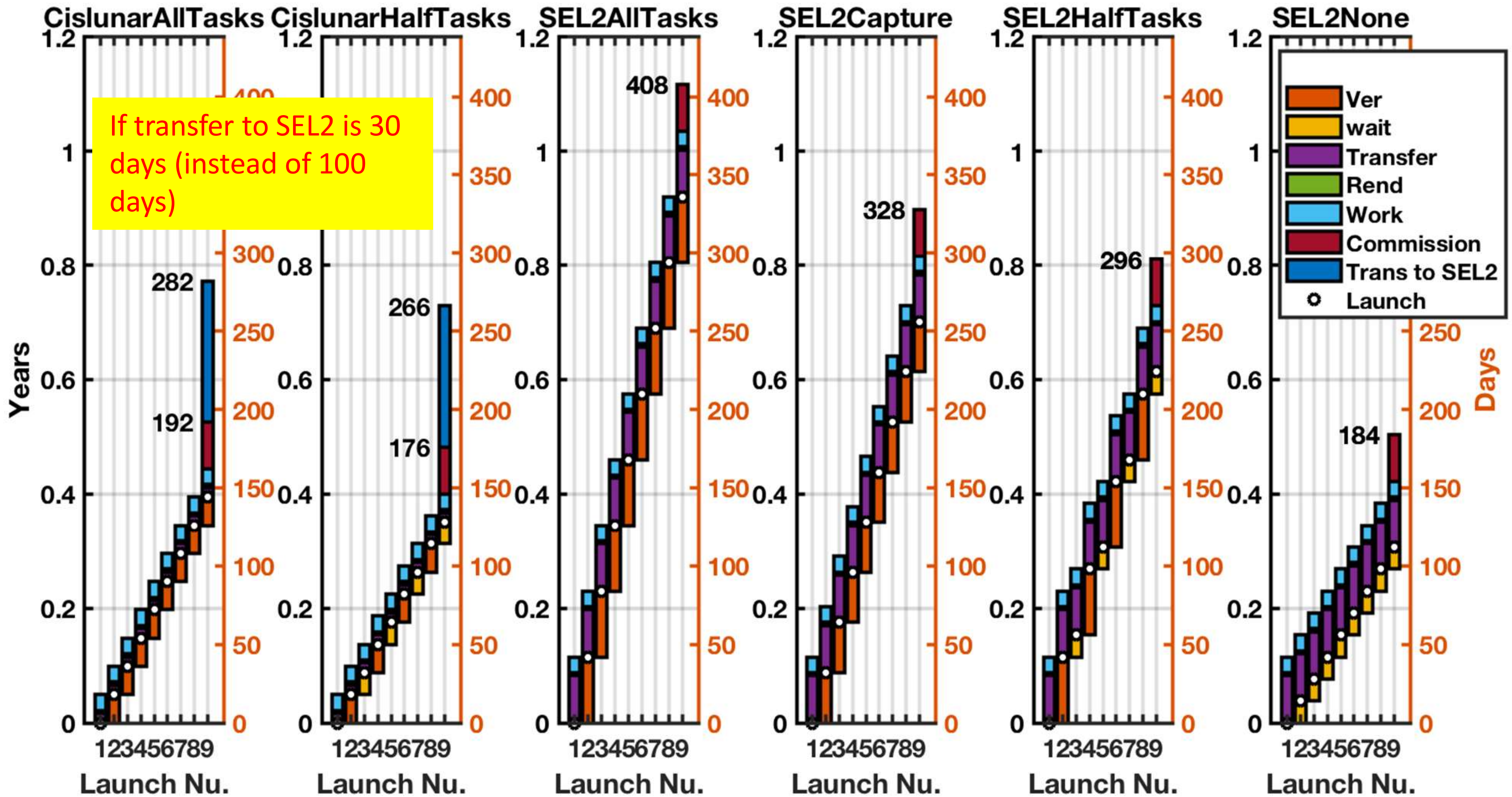
Location	C3	Vehicle	Launch Site	Capability, kg	Fairing	Adapter
Cislunar	-2	Atlas V (551)	CCAFS	6335	5m Short	47in (1194mm) payload separation ring with C22 adapter
Cislunar	-2	Delta IV (Heavy)	CCAFS	10575	19.1-meter long, 5-meter diameter payload fairing	47in (1194-mm) payload separation ring with 1575-5 payload attach fitting (PAF)
SEL2	-0.7	Falcon Heavy (Recovery)	KSC	6820	5.2m	47in (1194mm)
SEL2	-0.7	Delta IV (Heavy)	CCAFS	10320	19.1-meter long, 5-meter diameter payload fairing	47in (1194-mm) payload separation ring with 1575-5 payload attach fitting (PAF)
SEL2	-0.7	Falcon Heavy (Expendable)	KSC	15220	5.2m	47in (1194mm)

Comparing Cislunar and SEL2 Assy (with half tasks verified)

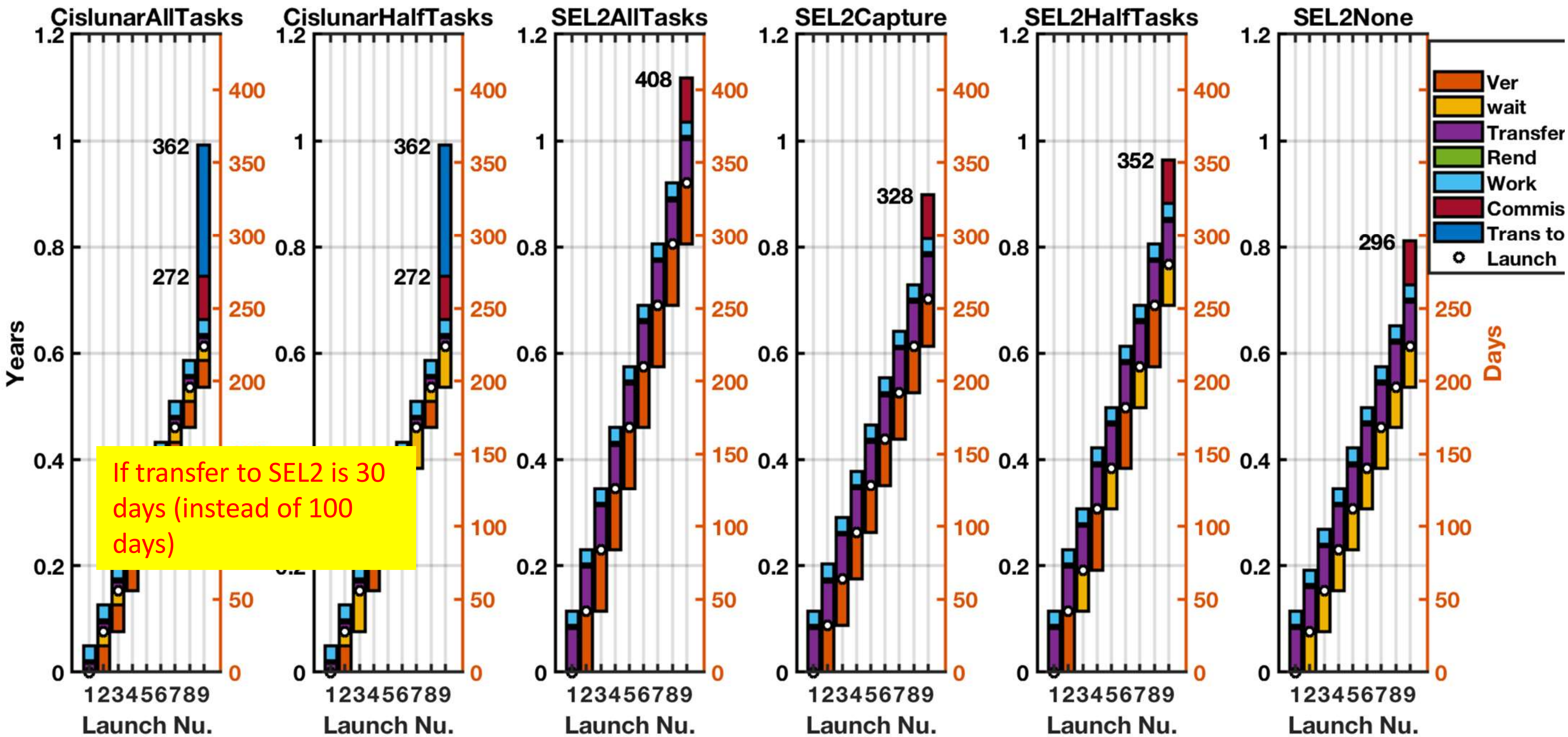



```
launchcount = 9;
rendtime = 2;  % days to add for each rendezvous event
worktime = 10; % Days of work to assemble each launch cargo set
mintimebetweenlaunches = 14; % days
cislunartransfer = 6; %days from launch site to cislunar
SEL2transfer = 30; %days from launch site to SEL2
```

Cislunar assembly complete in 60% of SEL2 assembly time




```
launchcount = 9;
rendtime = 2;  % days to add for each rendezvous event
worktime = 10; % Days of work to assemble each launch cargo set
mintimebetweenlaunches = 14; % days
cislunartransfer = 6; %days from launch site to cislunar
SEL2transfer = 30; %days from launch site to SEL2
```

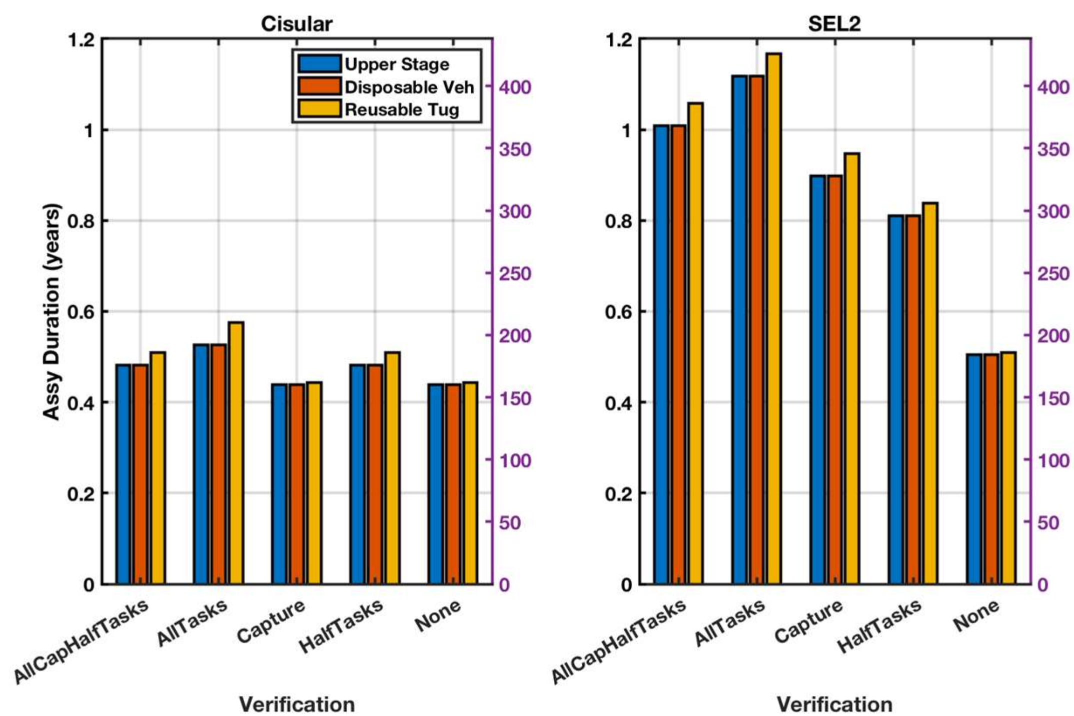


Same options, with 28 day min launch cadence

```
launchcount = 9;
rendtime = 2;  % days to add for each rendezvous event
worktime = 10; % Days of work to assemble each launch cargo set
mintimebetweenlaunches = 28; % days
cislunartransfer = 6; %days from launch site to cislunar
SEL2transfer = 30; %days from launch site to SEL2
```

Option #	Assy Location	Capture and Assembly Ver. Approach	Cargo Delivery Mode	Assy Years	Days	LV Limited
1	Cislunar	Capture	Upper Stage	0.44	160	8
2	Cislunar	Capture	Disposable Veh	0.44	160	8
3	Cislunar	Capture	Reusable Tug	0.44	162	8
4	Cislunar	AllTasks	Upper Stage	0.53	192	0
5	Cislunar	AllTasks	Disposable Veh	0.53	192	0
6	Cislunar	AllTasks	Reusable Tug	0.58	210	0
7	Cislunar	None	Upper Stage	0.44	160	8
8	Cislunar	None	Disposable Veh	0.44	160	8
9	Cislunar	None	Reusable Tug	0.44	162	8
10	Cislunar	AllCapHalfTasks	Upper Stage	0.48	176	4
11	Cislunar	AllCapHalfTasks	Disposable Veh	0.48	176	4
12	Cislunar	AllCapHalfTasks	Reusable Tug	0.51	186	4
13	Cislunar	HalfTasks	Upper Stage	0.48	176	4
14	Cislunar	HalfTasks	Disposable Veh	0.48	176	4
15	Cislunar	HalfTasks	Reusable Tug	0.51	186	4
16	SEL2	Capture	Upper Stage	0.9	328	0
17	SEL2	Capture	Disposable Veh	0.9	328	0
18	SEL2	Capture	Reusable Tug	0.95	346	0
19	SEL2	AllTasks	Upper Stage	1.12	408	0
20	SEL2	AllTasks	Disposable Veh	1.12	408	0
21	SEL2	AllTasks	Reusable Tug	1.17	426	0
22	SEL2	None	Upper Stage	0.5	184	8
23	SEL2	None	Disposable Veh	0.5	184	8
24	SEL2	None	Reusable Tug	0.51	186	8
25	SEL2	AllCapHalfTasks	Upper Stage	1.01	368	0
26	SEL2	AllCapHalfTasks	Disposable Veh	1.01	368	0
27	SEL2	AllCapHalfTasks	Reusable Tug	1.06	386	0
28	SEL2	HalfTasks	Upper Stage	0.81	296	4
29	SEL2	HalfTasks	Disposable Veh	0.81	296	4
30	SEL2	HalfTasks	Reusable Tug	0.84	306	4

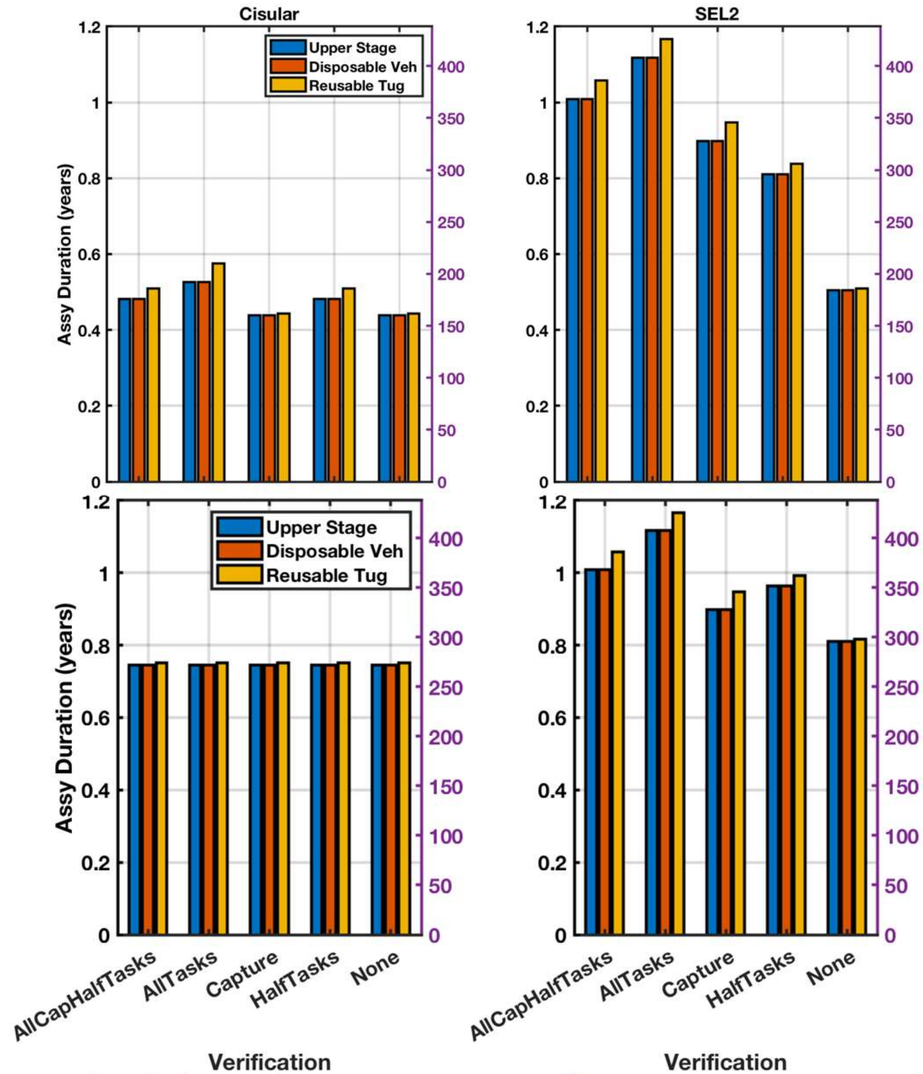
# of Launches limited by LV Cadence (min time between launches)




```
launchcount = 9;
rendtime = 2;  % days to add for each rendezvous event
worktime = 10; % Days of work to assemble each launch cargo set
mintimebetweenlaunches = 14; % days
cislunartransfer = 6; %days from launch site to cislunar
SEL2transfer = 30; %days from launch site to SEL2
```

Min 14 days between launches

Min 28 days between launches



- PSM for logistics in a month or so
  - Commercial logistics
  - Partner logistics
  - Co-manifest with orion
- PPE standpoint – use of SEP as a tug (Manzella)

- Gateway Logistics Services (Fed Biz Ops Link)
- **Solicitation Number: 80KSC0190002**

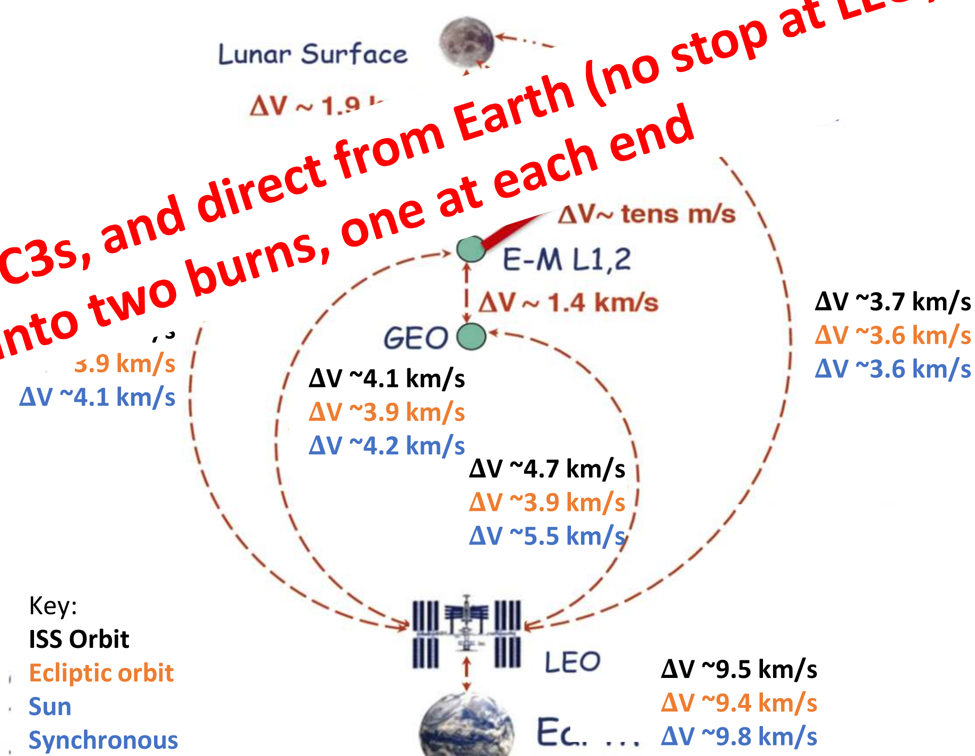
2. GATEWAY LOGISTICS MODULE CAPABILITIES
The Logistics Module must deliver pressurized and/or unpressurized cargo to the Lunar Gateway located in a Near Rectilinear Halo Orbit (NRHO) beginning no earlier than 2024 (dependent on development and/or launch of other Gateway modules). It is expected that the initial requirement will be for three missions, with a single mission expected to deliver up to **5 metric tons of pressurized cargo and 2.6 metric tons of unpressurized cargo**. The first Logistics Module may be required to transport a Robotic Arm as unpressurized cargo. The Logistics Module must **include guidance and navigation, power generation, and propulsion to enable autonomous docking** to a port on the Utilization Module or Habitat Modules via an International Docking System Standard (IDSS) compliant docking port. Once docked, the module will be used by crew primarily for stowage volume, trash stowage, and trash disposal. In addition, the module will depart the Gateway and perform self-disposal without assistance after a period of no more than three years of cislunar space operations. It is anticipated that the first two logistics missions will launch the Logistics Module using commercial launch vehicles, but after Gateway assembly, the Space Launch System (SLS) may be available for co-manifested logistics delivery.

Transfers: ΔV Roadmap from Earth

- Three LEO orbit costs represented
  :
  - ISS orbit (existing logistics)
  - Ecliptic orbit (high throw mass)
  - Sun Synchronous (Restore-L)

- Notice
  - … SEL2
  - … GEO then
    … SEL2

Folta adding transfer times, C3s, and direct from Earth (no stop at LEO)
also need to split delta V's into two burns, one at each end



NASA's Decade Planning Team (2000)

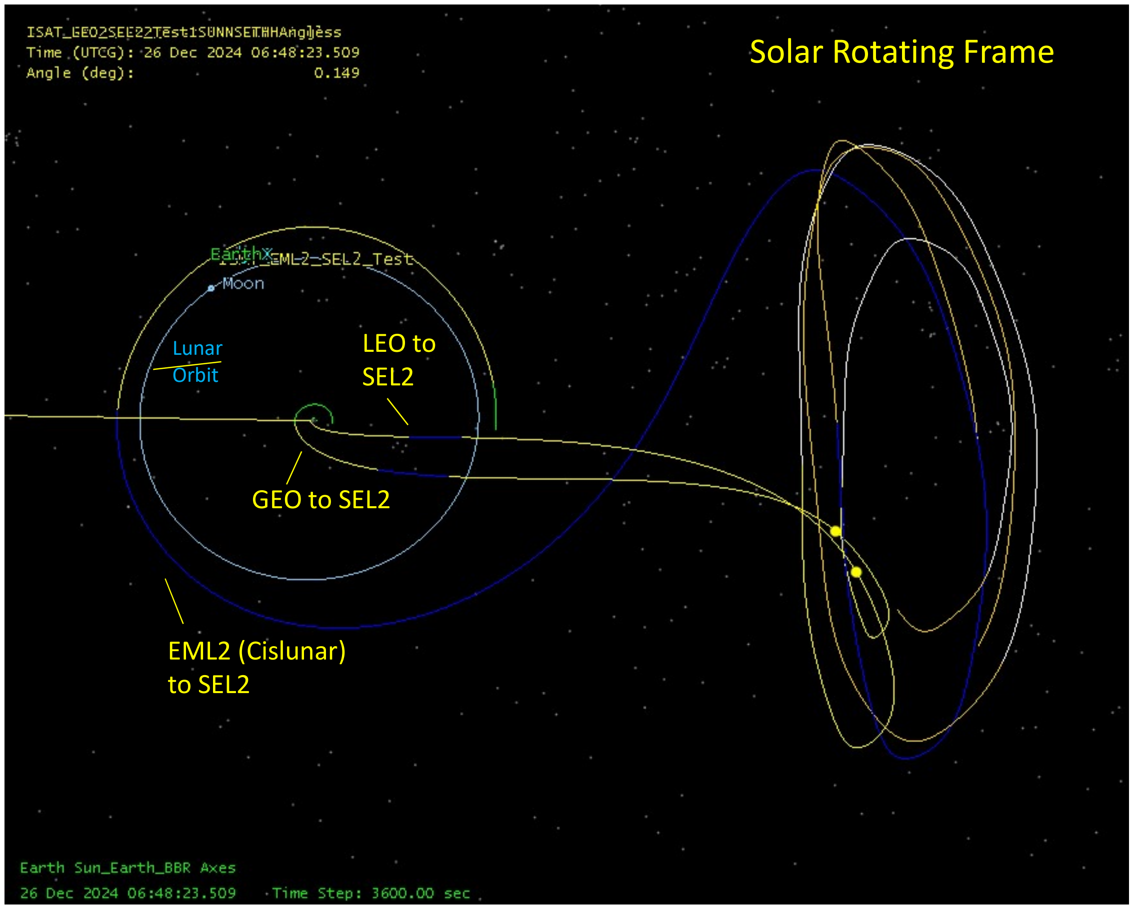
Can anyone verify these numbers?

Delta-v from / to (km/s)	LEO-Ken	LEO-Eq	GEO	EML-1	EML-2	EML-4/5	LLO	Moon	C3=0
Earth	9.3–10								
Low Earth orbit (LEO-Ken)		4.24	4.33	3.77	3.43	3.97	4.04	5.93	3.22
Low Earth orbit (LEO-Eq)	4.24		3.90	3.77	3.43	3.99	4.04	5.93	3.22
Geostationary orbit (GEO)	2.06	1.63		1.38	1.47	1.71	2.05	3.92	1.30
Lagrangian point 1 (EML-1)	0.77	0.77	1.38		0.14	0.33	0.64	2.52	0.14
Lagrangian point 2 (EML-2)	0.33	0.33	1.47	0.14		0.34	0.64	2.52	0.14
Lagrangian point 4/5 (EML-4/5)	0.84	0.98	1.71	0.33	0.34		0.98	2.58	0.43
Low lunar orbit (LLO)	1.31	1.31	2.05	0.64	0.65	0.98		1.87	1.40
Moon surface	2.74	2.74	3.92	2.52	2.53	2.58	1.87		2.80
Earth escape velocity (C3=0)	0	0	1.30	0.14	0.14	0.43	1.40	2.80	

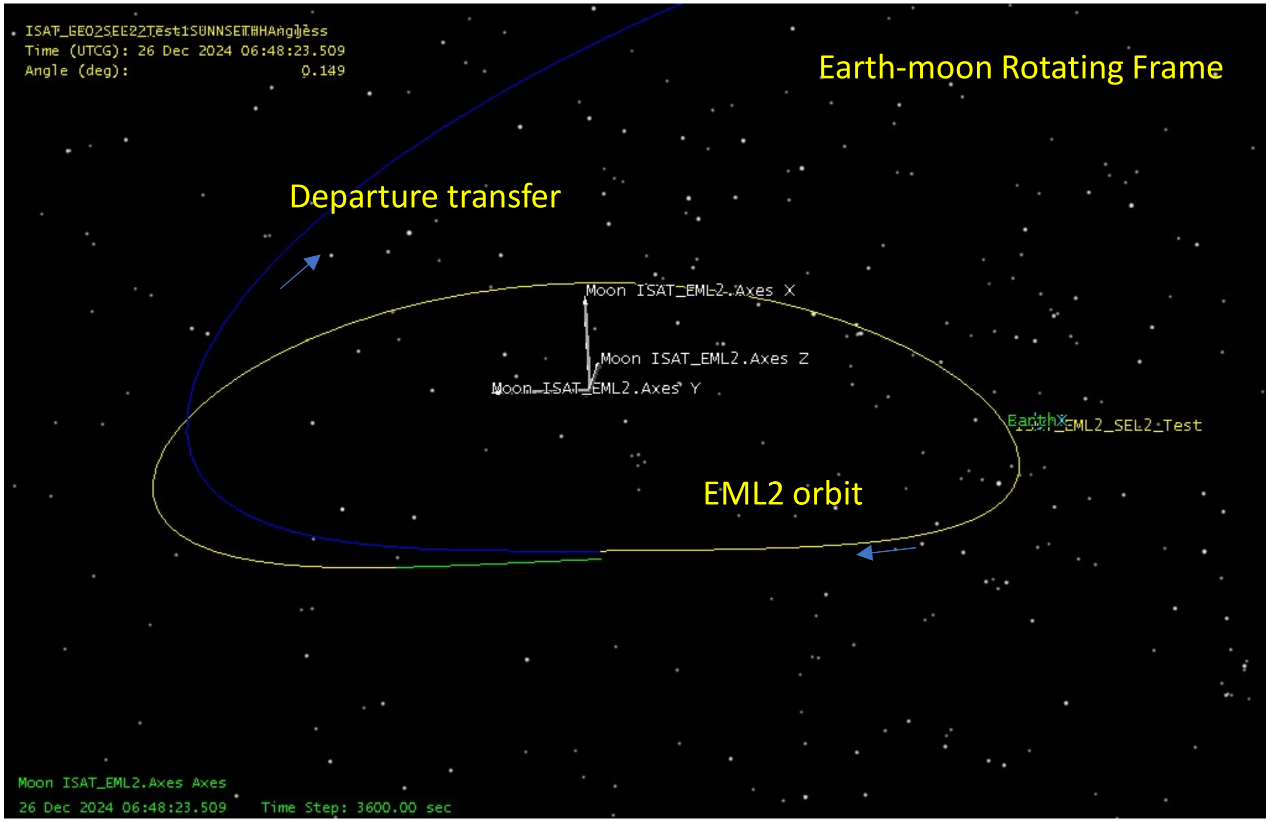
https://en.wikipedia.org/wiki/Delta-v_budget

From	To	Delta-v (km/s)
Low Earth orbit (LEO)	Earth–Moon Lagrangian 1 (EML-1)	7.0
Low Earth orbit (LEO)	Geostationary Earth orbit (GEO)	6.0
Low Earth orbit (LEO)	Low Lunar orbit (LLO)	8.0
Low Earth orbit (LEO)	Sun–Earth Lagrangian 1 (SEL-1)	7.4
Low Earth orbit (LEO)	Sun–Earth Lagrangian 2 (SEL-2)	7.4
Earth–Moon Lagrangian 1 (EML-1)	Low Lunar orbit (LLO)	0.60–0.80
Earth–Moon Lagrangian 1 (EML-1)	Geostationary Earth orbit (GEO)	1.4–1.75
Earth–Moon Lagrangian 1 (EML-1)	Sun-Earth Lagrangian 2 (SEL-2)	0.30–0.40

Sample LEO, GEO, EML2 to SEL2 transfers



Sample EML2 to SEL2 transfer



And Now Back to the KT Matrix…

(Excel)

Additional Slides

Trades & Analyses

Do now or later or just document answer?

- **Grunsfeld: the role of astronauts in iSA**
- **Mass and volume estimates to calculate number of LVs as a function of aperture size**
- Are there mass or volume limitations for a robotic arm?
- **Cost/risk trade between a tug and direct send to SE-L2**
- **Advantages of cis-Lunar vs SE-L2 in absence of Gatewa**y
  - Can we justify cislunar without Gateway?
- Why not GEO assembly and transit to SE-L2
- Cost profile across the Project Life Cycle (and how do we compare to single LV)
- **Folta orbital analysis**
- DSG as a physical location for assembly or in-vicinity?
- Staging on-board the telescope or off-board the telescope?
  - Possible off-board options such as a building way, tug, or depot
- Access to PM rafts - robotic translation capabilities along perimeter, backside of the PM trusses, long-reach arm?
  - A building way parked in cis-lunar may be a good option (a way could be an example of gov't-funded infrastructure)
- Explanation why not DSG
- Deferred Trades
  - Connections: Joint welds or latches or other
- Can robotic arms travel with the telescope and not impact WFE rqmts

General Principles from Grunsfeld Team

- Keep it simple
- Infrastructure costs must be small compared to telescope cost (no habitats for instance)
- Minimize time to construct
- Minimize cost
- Maximize dual use (if reduces cost or time)
- Minimize construction waste
- Use existing infrastructure
- Minimize or rule out free flying robots.
- Deploy if it makes sense (some sunshields?)
- Work that can be done on the ground will be done on the ground (example: shimming of segments in raft)

Jet Propulsion Laboratory
California Institute of Technology