**Selenian Boondocks**

*Random Musings from the Warped Minds of Jonathan Goff, Ken Murphy, John Hare, and Kirk Sorensen*

# Lunar Orbital Facility Location Options

Posted on April 16, 2016 by Jonathan Goff

For travel throughout cislunar space, I've long been an advocate of having depots on both ends of the journey. The LEO depot provides a refueling stop at the first practical point after leaving the ground, and also a spot for bringing vehicles back from lunar space for refueling for their next trip out. The lunar orbit depot plays a similar role for flights to/from the lunar surface, as well potentially, as being a staging location for departures into interplanetary space. By launching from a lunar facility near the top of earth's gravity well, it's both possible to use low-thrust trajectories in and out of cislunar space, as well as to do an earth swingby with a departure burn at apogee for high-thrust departures taking maximum advantage of the Oberth effect.

One important question however has been where to place the lunar orbital facility.

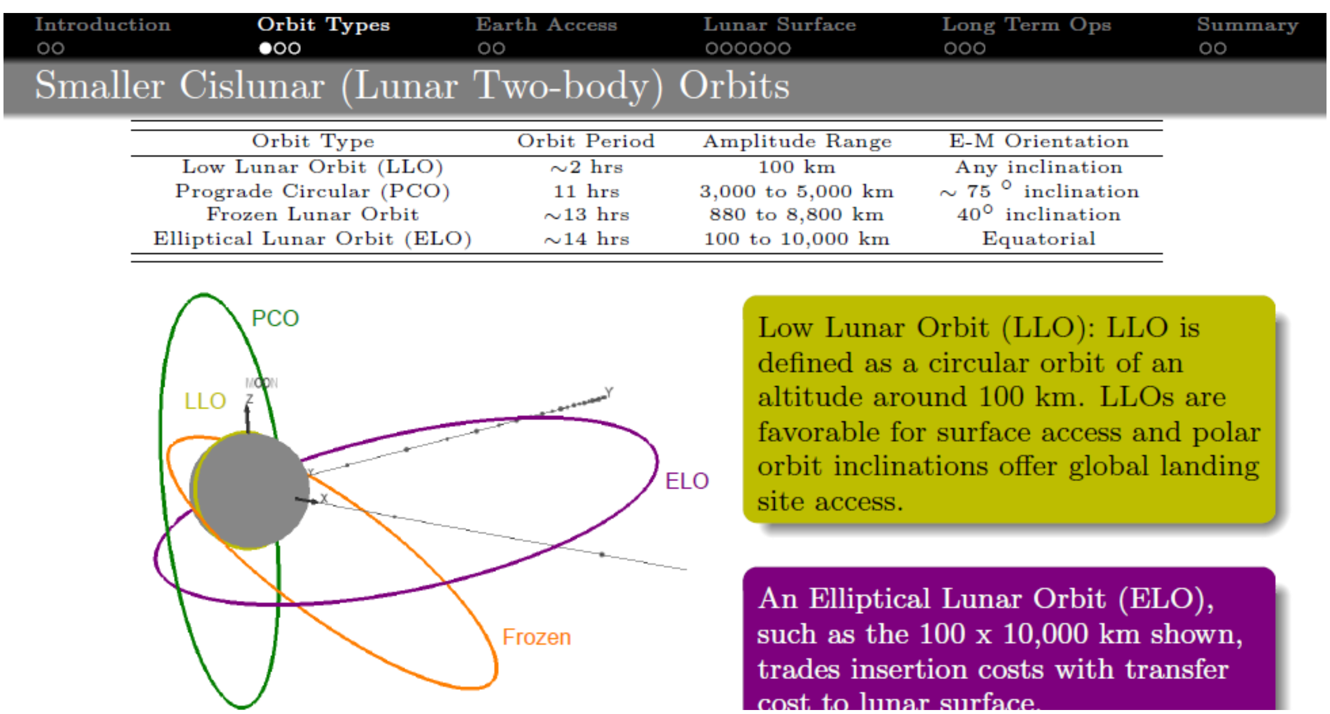
## Lunar Orbital Facility Orbit Options

A recent FISO telecon presentation by Ryan Whitley and Roland Martinez of NASA JSC describes and discusses several of these staging orbit options. I'll be reposting snapshots of a few of their slides to introduce the orbits, but here you can find their full presentation:

http://spirit.as.utexas.edu/%7Efiso/telecon/Whitley_4-13-16/Whitley_4-13-16.pdf

They discuss most of the commonly cited options including Low Lunar Orbit, Frozen Orbits, L2 Halo Orbits, Distant Retrograde Orbits, and a more recently discovered option, Near Rectilinear Orbits.

This slide shows some of the smaller lunar orbit options and descriptions:



Prograde Circular Orbits (PCOs) are defined as circular orbits of various sizes that rotate in the prograde direction and are highly stable, requiring few to zero corrections to be maintained.

Frozen orbits are similar but need not be circular and have orbital parameters that oscillate around fixed values.

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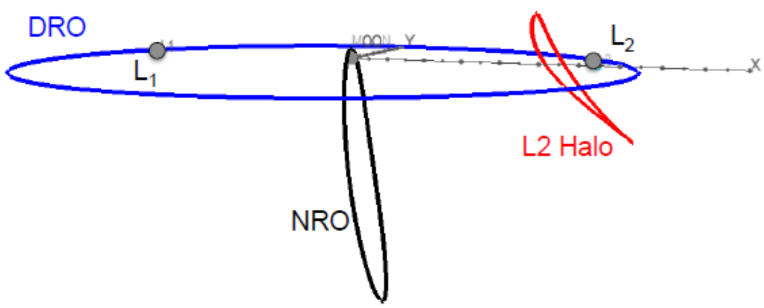
And this slide shows some of the larger lunar orbit options, with descriptions:

Introduction | Orbit Types | Earth Access | Lunar Surface | Long Term Ops | Summary

## Larger Cislunar (Three-body) Orbits

| Orbit Type | Orbit Period | Amplitude Range | E-M Orientation |
|---|---|---|---|
| Near Rectilinear Orbit (NRO) | 6-8 days | 2,000 to 75,000 km | Roughly polar |
| Earth-Moon L2 Halo | 8-14 days | 0 to 60,000 km (L2) | Dependent on size |
| Distant Retrograde Orbit (DRO) | ~14 days | 70,000 km | Equatorial |




Near-rectilinear halo orbits (NROs) were discovered as a bridge between L1 and L2 halos. NROs are halo orbits with large amplitudes over either the North or South poles that are fixed in the Earth-moon plane.

Halo orbits are a subset of orbits around the collinear libration points that are purely periodic but slightly unstable in the full ephemeris model.

Distant Retrograde Orbits (DROs) are relatively periodic three-body orbits that can be extremely stable, requiring zero corrective maneuvers.

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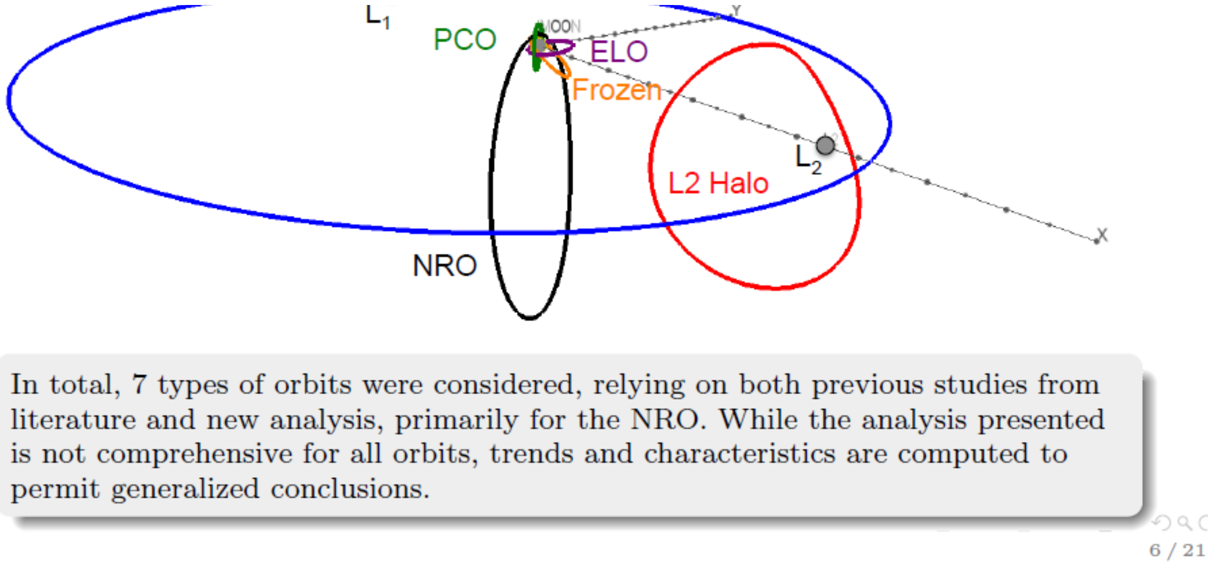
And this slide shows all of the orbits relative to each other to give you a better idea of what they look like:

Introduction | Orbit Types | Earth Access | Lunar Surface | Long Term Ops | Summary

## All Cislunar Orbits for Consideration Summarized

| Orbit Type | Orbit Period | Amplitude Range | E-M Orientation |
|---|---|---|---|
| Low Lunar Orbit (LLO) | ~2 hrs | 100 km | Any inclination |
| Prograde Circular (PCO) | 11 hrs | 3,000 to 5,000 km | ~ 75 ° inclination |
| Frozen Lunar Orbit | ~13 hrs | 880 to 8,800 km | 40° inclination |
| Elliptical Lunar Orbit (ELO) | ~14 hrs | 100 to 10,000 km | Equatorial |
| Near Rectilinear Orbit (NRO) | 6-8 days | 2,000 to 75,000 km | Roughly polar |
| Earth-Moon L2 Halo | 8-14 days | 0 to 60,000 km (L2) | Dependent on size |
| Distant Retrograde Orbit (DRO) | ~14 days | 70,000 km | Equatorial |




### Comparison of Options

While Whitley and Martinez in their FISO telecon focus on evaluating the various staging orbits from the standpoint of NASA missions using the Orion capsule, they still provide a lot of useful information for evaluating options for the location of a lunar orbital facility/depot. To me, some of the considerations for locating a lunar orbital facility are:

- How frequently do you have opportunities to travel from a LEO facility to the lunar facility, and how frequently you can travel the other direction?[1]
- How much delta-V does it take to go between the facility and LEO and the facility and the lunar surface?
- How long is the transit between the location and the lunar surface?
- How useful is the orbit for supporting deep space missions?
- How hard is it to reach various lunar surface destinations from the lunar orbital facility location?
- What is the thermal environment like in the orbit?
- And how much of the lunar surface to destination delta-V can be provided by some sort of propellantless lunar launch scheme[2]?

Based on these considerations, I'd like to focus the rest of this post on the pros and cons of the two options I consider most interesting–L2 Halo Orbits and Near Rectilinear Orbits.

### Pros and Cons of EML-2 Halo Orbits

EML-2 orbits have been my favorite option ever since learning about the low delta-V cost of reaching them via powered lunar swingbys. They have a lot going for them, including:

- One of the lowest delta-V stopping points in the lunar vicinity, requiring only ~3.43km/s of delta-V from LEO.
- Easy access to/from a LEO facility on every LEO-lunar or lunar-LEO window.
- Any-time access to/from anywhere on the lunar surface.
- Low stationkeeping delta-V[3]
- Benign and cold thermal environment[4]
- Continuous communications with Earth, and most of the farside of the Moon.
- Good staging point for both deep-space and lunar missions.
- Could become a starting location for a lunar space elevator.

But EML-2 does have a few drawbacks:

- Long LEO-EML2 and EML2-LEO transit times[5] for the low delta-V powered-swingby option.
- Long EML2 to lunar surface (and vice versa) travel times[6]
- It wasn't clear that a propellantless lunar launch option located at either pole could launch easily to EML2. An elliptical orbit from such a launcher would have its line of apsides pass through the launch location, which would be orthogonal to the Moon-EML2 line. You could launch into a polar LLO, and then do multiple burns from there to EML2, but the propellantless launch option would only provide the first leg of the trip (surface to LLO).

The long trip times mean that the vehicles taking people between LEO and EML2 and between EML2 and the Moon will require much more extensive life support and accommodations than would be needed if the trip were shorter. That will drive up the dry mass of those systems, and by extension the propellant and overall cost of moving people to and from EML2.

### Pros, Cons, and Questions Regarding Near Rectilinear Orbits

Starting several months ago, some of my astrogator friends started telling me about NASA's interest in Near Rectilinear Orbits for exploration missions. After all the talk about Distant Retrograde Orbits, this sounded a bit like the "flavor of the week" syndrome, but the FISO presentation helps explain some of the allure of such orbits:

- Only slightly higher delta-V to/from LEO to NROs compared to LEO to EML2[7].
- Because the NRO orbit's perilune is only 2000km from the Moon's surface, once per 6-8 day orbit, the orbit lines up so that the travel time between NROs and the lunar surface drops to 0.5 days.
- Powered swingby trajectories between LEO and NROs take approximately 5 days each direction, instead of 9-11 for EML2.
- Slight lower delta-V between NROs and the lunar surface compared to EML2.
- The NRO is close enough to an elliptical polar orbit that it *might* be possible for a polar base to use propellantless launch techniques to fling payloads nearly into NRO, with possibly only minor adjustments and raising the perilune with a burn near apolune half an orbit later[8]

The benefits of shorter transit times are pretty important, but there are still a couple of relative drawbacks and open questions:

- While it's possible to get from LEO to a given NRO orbit during every lunar injection window, the NRO facility will be at different points in its orbit during each window, which may make a first-orbit rendezvous either infeasible or it might cost additional delta-V. I'd want to get this resolved, because while this isn't an issue for one-off, ground-launched missions like the NASA folks were thinking of, this would be a real issue for reusable spaceship flights between a LEO and NRO facility.
- Likewise, departures from the NRO may not be in the optimal part of the orbit for the Earth return maneuver when the timing is right to return to the plane of the LEO facility. This isn't a problem if you're doing a direct return, but once again is a big pain in the neck for reuse of space hardware. Once again this is something I'd want to analyze more before settling on an NRO orbit.
- Additionally, the NRO facility has LOS with one lunar pole about 86% of the time (while heading out and coming back from apolune), but only sees the other facility for a brief period near perilune. If you're planning on using propellantless launch methods to send stuff from a polar lunar settlement to the NRO facility, it's going to be in an NRO with apilune on the opposite side of the moon from your lunar settlement, meaning

you'll only be in contact briefly for maybe 1 day out of a week.

- Because the perilune is only 2000km, the heating environment is going to be warmer than EML2, with slightly higher boiloff, but this is probably only a minor difference–it should still be tons easier to keep cryo boiloff low in an NRO than in LEO.

**Conclusions?**

While NRO orbits have some really interesting characteristics, I'd really want answers to those first two concerns before I'd pick it for the location of a lunar orbital facility. If you can't get to it on a regular basis from a given LEO depot without having to do complicated trajectories, or paying big penalties in flight duration or delta-V, then that would likely outweigh the benefits. If on the other hand, it's not a big deal to adjust the trajectory on the way to and from the NRO facility to enable rendezvous with the facility regardless of where it is within its orbit when the LEO to lunar launch window opens, then it could be a really interesting location for a lunar transportation node. I'll have to see if I can get some of my astrogator friends to weigh in on those questions. Until then I'm probably still more of a fan of EML-2, in spite of the annoyingly long transit times.

[Update 1: After speaking with an astrogator friend who's been looking at NROs to support lunar missions, he thinks it might be possible to put an NRO facility in an orbit whose period is synchronized with the average time between launch windows from the LEO facility. If that works, that would mean the NRO facility would be in approximately the same part of its orbit during each trip to/from the Earth. There are questions of if you can make an NRO orbit with a long enough period (~9 days) to make that work, and if the NRO facility could be made to line up both for arrivals and departures from/to Earth, but hopefully he'll have more opportunity to dig into that further later this year.]

**Bio** **Latest Posts**

**Jonathan Goff**

President/CEO at Altius Space Machines

Jonathan Goff is a space technologist, inventor, and serial space entrepreneur who created the Selenian Boondocks blog. Jon was a co-founder of Masten Space Systems, and is the founder and CEO of Altius Space Machines, a space robotics startup in Broomfield, CO. His family includes his wife, Tiffany, and five boys: Jarom (deceased), Jonathan, James, Peter, and Andrew. Jon has a BS in Manufacturing Engineering (1999) and an MS in Mechanical Engineering (2007) from Brigham Young University, and served an LDS proselytizing mission in Olongapo, Philippines from 2000-2002.

1. Due to the orbital motion of the Moon and nodal regression of a LEO facility, you get optimal lunar departure and/or return options about every 7-9 days IIRC. The choice of lunar orbital facility location may constrain this further.
2. Lunar Slings, Mass Drivers, Launch Loops, etc. All the stuff I was supposed to write about in my "The Slings and Arrows of Outrageous Lunar Transportation Schemes" series that I still need to finish
3. <10m/s/yr
4. About 10x lower LOX/LH2 boiloff rate than LEO. In fact with passive insulation you can completely surpress LOX boiloff and even freeze oxygen at EML-2
5. 9-11 days
6. 3-5 days
7. 3.58km/s vs 3.43km/s

8. Which you'd also want to be the burn that brings you to rendezvous with the NRO facility ↩

This entry was posted in Lunar Exploration and Development, Propellant Depots, Space Development, Space Transportation. Bookmark the permalink.

## 17 Responses to *Lunar Orbital Facility Location Options*

**Andrew_W** *says:*
April 17, 2016 at 4:05 am

I'll be unimaginative and just go for the near polar frozen orbit, I think polar orbits will be important because the poles are going to be where all the action is, I think the lowest practical delta V from the lunar surface is more important than low delta V from LEO, and I think the stability of the orbit will be a factor.

**gbaikie** *says:*
April 17, 2016 at 10:16 am

What is Lunar Orbital Facility?
I mean it could be everything, say hub between LEO, Moon, Mars and elsewhere.
And it could be NASA type space station.
As NASA space station it could related to Lunar exploration and research of deep space environment, plus used as staging area for Mars exploration. Such as Manned mission to Mars begin there and return from Mars to it.
And as NASA station it could be connected to ISS.
I believe that NASA should not de-orbit ISS, and ISS could be "rescued" from LEO.
But I suppose ISS could also be extended in terms of it's operation in LEO and have some operational relationship with the Lunar Orbital Facility. Or one does de-orbit ISS. Or ISS could become the Lunar Orbital Facility.

Would Lunar Orbital Facility be about getting a small space rock- Obama's evolved into asteroid mission. And/or about radiation shielding- space rocks and getting dead GEO satellites. And providing shade for cryo storage.

Or does it start as a mostly commercial thing. So related to use Lunar tourism and lunar mining. And someplace to bring space rocks and/or dead satellites and/or supplying NASA Mars program- lunar water and LOX [and/or radiation shielding].

So way look at it, NASA should explore the Moon to determine if and where there is commercially minable lunar water.
And key aspect of this NASA program, is short duration of program and thereby low costs in terms of tax payer money and time- 40 billion and less than 10 years to complete NASA lunar exploration which then followed by Mars exploration program which has purpose to determine if and where on Mars would be best locations for human settlements.
And NASA starts Lunar exploration program by establishing a depot in LEO. And this depot will refuel robotic exploration missions to the Moon, which is followed by refueling crewed exploration of the Moon. The crewed mission to Moon are to confirm and complete robotic lunar exploration and return lunar samples.
While Lunar exploration is done, ISS should be resolved in some fashion and the first option should not be to de-orbit it.
So when lunar exploration and ISS is finished, NASA explores Mars.
And before NASA begins sending crew to Mars, prospects of commercially mining water on the Moon will have results which can used to determine whether such activity is viable. But commercial lunar mining is not on critical path of Mars exploration and Lunar exploration could indicate that mining the Moon is not viable in near term. Though NASA Mars exploration program may play part in "making" commercial lunar mining viable.

Anyways, this NASA lunar exploration includes LEO depot, many robotic lunar missions and few crewed missions to the Moon. And doesn't include lunar bases, lunar mining or lunar orbiting bases.

As far as NASA mars exploration program, I think it should include staging Mars crewed missions somewhere in High Earth. Also staging in Mars high orbits.
So Mars exploration could include something like this Lunar Orbital Facility or be connected to it, or if the Lunar Orbital Facility is commercial [and having something to do with commercial lunar mining and NASA Mars exploration]

**ken anthony** *says:*
April 17, 2016 at 10:21 am

This is the problem with thinking stations vs. ships. Let ships be your depots with enough delta-V to move them where you want them and you can make adjustments to what is best. A station/depot with too little delta-V removes that option.

Analysis is great, but flexibility is better. Think lots of cheap ships incrementally improved over time.

Ironic thing is, is if a depot has enough fuel to be useful it should be able to use that fuel as delta-V. But we keep repeating the same mistakes (like different co2 canisters on the LEM and Command modules.) Analysis always comes up short.

**Chris Stelter** *says:*
April 17, 2016 at 10:45 am

Given the annual reboost delta-v needed for ISS, you could travel between any of these high orbit options.

The really great thing about being in a very high orbit is that you're VERY close (energy and delta-v-wise) to any other very high orbit in the Earth-Moon system.

A space station with only as much maneuverability as ISS would be capable of moving in between these different orbits.

**Marcel Williams** *says:*
April 17, 2016 at 11:23 am

I prefer the classic L1 Gateway.

1. Trying to take advantage of the lower delta-v requirement (3.43 km/s) from LEO to EML2 would require approximately eight days of travel and continuous cosmic ray exposure. A faster 4 day EML2 trip would require a slightly larger delta-v than a four day trip from LEO to EML1. A delta-v of 4.41 could transport astronauts to EML1 in just two days. Such a high delta-v could easily be accomplished by reusable vehicles such as the future ACES-41 with an Orion capsule.

An EML2 habitat and docking spacecraft could potentially interfere with radio astronomy on the far side of the Moon. Europe has already shown a great deal of interest in establishing an outpost there.

3. Aesthetically, tourist at EML1 would be able to view an Earth larger than could be viewed at EML2 and even larger than seen from the surface of the Moon.

4. Station keeping a habitat at EML1 or EML2 would only require a few tonnes of propellant annually— even if the habitats had a few thousands tonnes of heavy radiation shielding.

Marcel

**Jonathan Goff** *says:*
April 17, 2016 at 4:38 pm

Andrew,
The frozen orbits they analyzed in this paper required almost the same 800m/s to get to a polar LLO as coming from EML2 or NRO due to the need for a big plane change. There might be near polar frozen orbits with less delta-V required, but most likely those would be hard to access frequently from Earth. I guess I just don't see the benefit of your approach.

Gbaikie,
I was being intentionally vague about what a Lunar Orbit Facility is. It could be a depot, or a space station, or anything else you need to rendezvous with. But most likely a small spacecraft/depot that you can switch between vehicles, transfer

propellant, and possibly stay for short durations as necessary.

Marcel,
I don't see any reason why you couldn't do an EML1 station as well as or instead of an EML2 station, but it only really saves you the LEO to lunar orbital facility and back time, it doesn't do anything to reduce the lunar orbital facility to lunar surface and back travel time, but at the cost of a non-trivially higher Earth to lunar orbital facility and back delta-V. I'm skeptical that seeing the Earth a little bit larger is going to make much of a deal either way. Getting a picture with both Earth and the Moon in the picture (with the Moon between you and the Earth) actually sounds cooler to me.

~Jon

**Chris Stelter** *says:*
April 18, 2016 at 7:51 am

Nice thing is we don't really have to choose. You can change your mind on the fly, just like how ISS sometimes operates at lower altitude for maximizing payload for construction, then later at higher altitude to minimize drag.

I used to have strong opinions about EML1 vs EML2, etc, but then I realized it doesn't really matter because you can travel between these options easily, allowing you to get the best of both worlds by utilizing one orbit for a while and then switching to another.

**Hop David** *says:*
April 18, 2016 at 1:25 pm

The NRO is an interesting orbit. It's line of apsides being nearly perpendicular to the moon's orbital plane, distance from earth doesn't vary much. Thus it's less vulnerable to tidal perturbations from earth (it seems to me).

An NRO with a 6.83 day period would have a period equal to 1/4 the moon's sidereal day. Thus geometry of the orbit would repeat each lunar orbit. This might make predictable rendezvous schedules more doable.

The geometry of a given LEO wrt moon is constantly changing. So it seems to me a fool's errand to strive for a LEO station that remains coplanar with the moon. Therefore I would advocate an equatorial LEO station — less delta V to reach and avoids the South Atlantic Anomaly. At apogee a transfer ship's speed is only .19 km/s At .19 km/s, even a healthy plane change doesn't cost much. See my blog post on lunar ice.

So I believe the benefits of a LEO station coplanar with the lunar orbit is exaggerated. This is especially true if the lunar locations of interest are at the poles.

**Jonathan Goff** *says:*
April 18, 2016 at 4:12 pm

Hop,

I wasn't trying to suggest a LEO base that was coplanar with the Moon. I agree that wouldn't be feasible. I was just stating that for any given LEO facility, the combination of the moon's orbital motion and the nodal regression of the LEO facility ends up providing Earth-to-Moon transfer opportunities, where the moon passes through the plane of the LEO facility, once every 7-9 days. I had recalled for some reason that the gap between launch windows wasn't a steady number, but am no longer sure why I thought that–nodal regression for the LEO facility is a steady number, and the moon's orbit is fairly low eccentricity. Because the Earth-Moon departure windows aren't instantaneous, it might be possible to pick a period for the NRO that is the average of the gap between the departure windows, in a way that you can minimize the delta-V penalty while still allowing you to rendezvous quickly with the NRO facility on any given Earth-Moon departure window…

I'll have to see if I can get someone like Mike Loucks to run some numbers for me.

~Jon

**Dennis Wingo** *says:*
April 18, 2016 at 5:49 pm

What Andrew said.

Before you start trading lunar related orbits you have to settle on what you are going to do (or not do), on the Moon. That dictates which orbit is the best. My preference of course is an industrial center on the Moon that manufactures interplanetary spacecraft. LLO is the best place to put them together, then you take it to EML-1 for final outfitting with terrestrially launched hardware. Then Mars is a piece of cake….or anywhere else in the solar system.

**Dennis Wingo** *says:*
April 18, 2016 at 5:51 pm

Except, after reading Jon's definition of LLO, that is a non starter. 100 km is far too low for a stable orbit without lots of propellant usage. 500-1000 km is far better.

**Jonathan Goff** *says:*
April 18, 2016 at 8:48 pm

Dennis,
I didn't clearly state my goals, but for the lunar orbital facility, I was looking for something in a good point to support transportation of people and cargo/materials to and from the lunar surface. That doesn't mean it has to be the only lunar orbital facility, but it does mean that I wanted something that can both be accessed frequently and affordably from earth, that can support lunar surface deliveries with minimal penalties, and that has a good thermal environment for cryogenic propellant storage. That's why I was looking at EML-2 and NROs. For assembling a spacecraft, I could see a 500-1000km polar LLO making sense if you don't need to send people or stuff to it from Earth frequently, and if you your lunar facilities are all very close to either of the poles. But a high LLO probably wouldn't make much sense for a transfer node.

~Jon

**Jonathan Goff** *says:*
April 18, 2016 at 8:53 pm

Hop,
I spoke with an astrogator friend (Mike Loucks) about the NRO synchronization, and he thought it was worth looking into. While the moon has low eccentricity, it's not zero, so the timing between optimal departure windows to/from a LEO base isn't going to be perfectly constant, but probably close enough that the delta-V penalty will be modest. So you'd just want an NRO orbital period that matched up with the average time between launch windows from the LEO base (likely about 8-9 days). Hopefully later this year he can run the numbers on the concept. If he can, I'll report on that, but it looks potentially promising, and would remove the two biggest concerns with using NROs. The third concern (poor comms) could be resolved with either a relay satellite or a second orbital facility in the opposite set of NROs–ie if you have one facility in a south-pointing NRO, you could have a relay sat in a north-pointing NRO, then you'd have near constant comms coverage.

Anyhow, food for thought.

~Jon

**N/A** *says:*
April 18, 2016 at 8:55 pm

I'm struck by the interest for propellant launch receiver station. Wouldn't a PCO or NRO be preferred, simply by the number of opportunties to reach it from the lunar surface? A PCO+EML2 or NRO+EML2 pairing seems more appropriate, as EML2 is a proper gateway station that should be reasonably reachable from the lower "transit" station orbit. Though by that measure, a very polar LLO might be more desireable, since upmass from propellant launch exports deltaV to the transit hub.

**Nathan Wilson** *says:*
April 21, 2016 at 9:21 pm

Fascinating discussion; several good options for a stop on the way to Mars.

For getting to and from Luna, I have not seen anything I like better than a rotating space elevator (rotovator)! Using a tether and large ballast, we can store momentum from a solar electric propulsion system, and transfer it to a ship quickly. So a rotovator in low lunar orbit (say 300 km) allows the fastest transits times, plus consumes less propellant (less hauling from Earth, and more Lunar exports for other users).

A rotovator in a polar orbit can provide twice monthly service to a water plant. But in an equatorial orbit, there will be 10 transfer opportunities per (Earth) day. This is exactly what one would want for a large Lunar city.

**Colin Helms** *says:*
April 17, 2017 at 9:18 am

Could you publish a bibliography of the orbital discussion? I believe I have some of the sources, but it seems there is more of a real-time discussion that you are privy to. I've gotten into an argument about the station-keeping requirements for L2 Halo orbits with a partner, but you indicate the community is comfortable with that cost.

**Jonathan Goff** *says:*
April 17, 2017 at 11:02 am

Colin,
To be honest, I don't have much of a bibliography for this post other than the presentation I referenced. Did it have a bibliography? Also some of the other comments regarding the industry may have been based on discussions with people who do flight dynamics for a living. Sorry if this isn't as thoroughly documented as you'd like.

It's been a while since I wrote this article though, and I wanted to do a follow-up article with some further thoughts sometime soon.

~Jon