MOBIUS: An Evolutionary Strategy for Lunar Tourism

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The MOBIUS concept architecture presents an evolutionary methodology for lunar tourist missions. In the MOBIUS scenario, a quartet of spacecraft is suggested in a specific supersynchronous Earth orbit as a nominal trajectory for a cislunar, cycling vehicle system. Earth and lunar shuttlecraft service the cycler at Earth perigee and lunar proximal apogee of the selected supersynchronous orbit. ISS is suggested as the departure platform to lunar orbit, and eventually lunar lander shuttles will be used to service paying passengers to the lunar surface on a routine basis. A gradual and steady increment in complexity of mission vehicles and operations is proposed, allowing for evolutionary growth and a self-sustaining economic model. We believe that this strategy is optimal and has an enormous commercial potential for future space and lunar tourism. In particular, attention is paid to the viability of employing the International Space Station commercially beyond the currently proposed retirement date, extending the useful life of the $100B facility. The MOBIUS concept is modeled using state-of-the-art tools and proposes a viable profile that attempts to balance available technologies with entrepreneurial needs and capital to make commercial, self-sustaining lunar missions possible, maximizing existing assets and technologies as well as currently operating infrastructures, all in the earliest timeframe. MOBIUS architecture is promoted as an example of how government and private sector can partner to create a vibrant space activity in the 21st century that caters to the cultural needs of humanity as well as inspiring the new generation of explorers.

Nomenclature

a	=	Semimajor axis
RAAN	=	Right Ascension of the Ascending Node
ROP	=	Radius Of Perigee
ROA	=	Radius Of Apogee
AOP	=	Argument Of Perigee
ALSPE	=	Anomalously Large Solar Particle Event
CLI	=	Cis-Lunar Injection
CME	=	Coronal Mass Ejection
COV	=	Cislunar Cycling Orbital Vehicle
CPS	=	Cislunar Propulsion System
CTO	=	Cislunar Transit Orbit
ΔV	=	Spacecraft's velocity change
ECLSS	=	Environmental Control and Life Support System
EVA	=	Extra-Vehicular Activity
g_0	=	Acceleration of gravity (9.8 m/s^2 on the surface of the Earth at sea level)
G	=	Gravitational Constant
IDA	=	International Docking Adapter for ISS
I_{sp}	=	Specific impulse

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ISS = International Space Station
TDC = Tourist Docking Capsule
L1, L2 = Earth-Moon Lagrangian Points
LTL = Lunar Transit Lounge
TLI = Translunar Injection
LEO = Low Earth Orbit
LLO = Low Lunar Orbit
LSS = Life-Support System
M_s = Dry mass of spacecraft
M_P = Propellant mass
μ = Gravitational parameter of Earth (398600 km^3/s^2)
R = Distance of spacecraft from the center of Earth
SLS = Space Launch System
SOI = Sphere of Influence
SPE = Solar Particle Event
STK = System Tool Kit
TDC = Tourist Docking Capsule
MALEO = Module Assembly in Low Earth Orbit

I. Introduction

"If God wanted man to become a spacefaring species, He would have given man a moon."-Krafft Arnold Ehricke
-Lunar Bases and Space Activities of the 21st Century (1985)

Space telecommunications industry has long been the mainstay of commercial space activity. In recent years, private human space enterprises including space tourism have started to emerge as viable and self-sustaining models. A number of companies catering to human spaceflight have sprung up in recent years, and some vehicles and systems are undergoing tests, and commercial spaceports are being designed around the globe. Since the retirement of NASA's space shuttle fleet, orbital space tourism opportunities have been limited and expensive, with only the Russian Space Agency currently providing routine crew transport to the International Space Station. Now that several civilian passengers have been flown to the ISS, companies have been exploring the potential for flights beyond the LEO, especially targeting lunar tourism. Private efforts to develop lunar resources like in-situ fuel production are also underway. The current trends in world tourism, especially in the Cruise lines industry offer lessons to be noted [CLIA 2015]. The MOBIUS project is in line with such efforts and presents an evolutionary phased strategy for lunar tourism.

One of the characteristics of a viable, strong-boned evolvable mission architecture is its perpetual ability to grow and transform with frequent missions, while adapting to changes in customer needs, technologies and shifting policy and economic constraints [Rechtin 1990]. Due to the proximity of our Moon, such factors would be demonstrated more easily and verified early, and with less growing pain penalty for missions to the Moon than for those missions targeting Mars for instance, because of very limited interplanetary launch-window opportunities and much farther distance from Earth. Obviously, colonizing both our Moon and Mars and utilizing their resources would create enormous lucrative opportunities and open new venues for commerce. But due to the closeness of the Moon, easier telecommunication between Earth and the crew on the

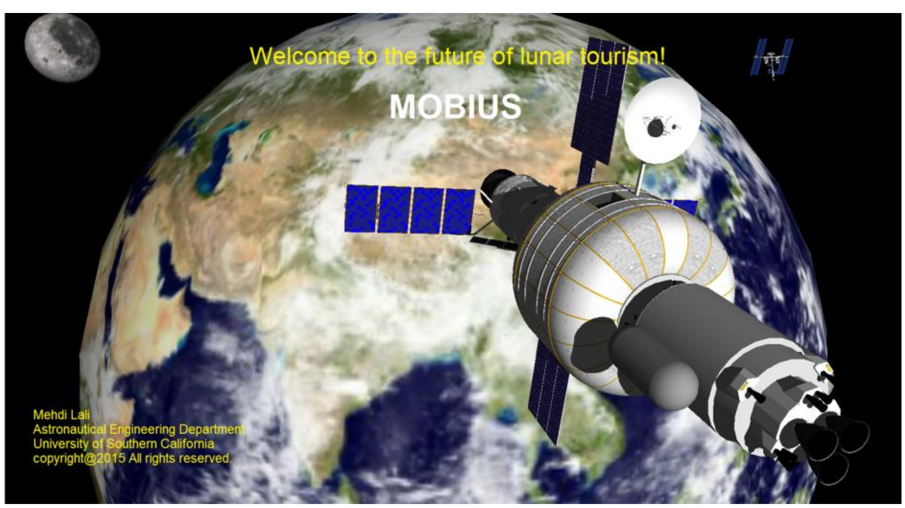

Figure 1. Cislunar Orbiting Vehicle spacecraft. *COV on its way to the Moon. Future of lunar tourism looks promising with architectures like the MOBIUS*

lunar surface, availability of frequent launch-windows, and easier transportation, future Moon programs outweigh their Mars peer architectures. The prospect of lunar missions, specifically tourism, is encouraging in this regard. It is an example of our infant steps to become a truly spacefaring species. It is one more way to bring the solar system into our economic sphere of influence.[Marburger 2006] Our Moon has a lot to offer [Schrunk etal 1999, 2007] and MOBIUS is a candidate architecture for initiating lunar tourism [figure 1].

II. MOBIUS Concept

The MOBIUS concept architecture is built around a cislunar cycler architecture. Cyclers are spacecraft that continually cycle between orbiting bodies, approaching and departing them periodically, without ever stopping at them. Shuttle craft are employed to rendezvous with cyclers as they move in precisely timed trajectories, allowing crew and cargo to be transferred, as they near each destination. The current proposed MOBIUS concept is based on a mission design architecture in which a quartet of spacecraft in nominal trajectories is used i.e., a cycling, cislunar, supersynchronous orbit: an orbit with a specific low radius of perigee at Earth and a very high radius of apogee extending up to the vicinity of the Sphere of Influence (SOI) of the Moon patched with other trajectories. In the MOBIUS mission scenario, ISS with its huge commercial potential plays an important role as the platform of choice for initiating lunar tourism. The elements of this architecture include the ISS, Cislunar Cycler Orbital Vehicle (COV), Cislunar Propulsion System (CPS), Tourist Docking Capsule (TDC), Lunar Transit Lounge (LTL) at L1, Lander, and lunar surface facilities all of which will be explained in the following sections.

In perigee rendezvous phase of the outbound trip, the passengers (preferably four passengers and two crew) depart from the ISS and get onboard the COV via TDC and start the three and a half day journey. During the apogee rendezvous phase, the passengers access the LTL at L1. In the next phase, tourists can get onboard a lunar lander that will let them access the lunar surface. Likewise, the inbound trip will also consist of three phases in which the passengers ride the ascent vehicle, return to LTL and eventually dock with COV via TDC which will return them back to LEO and will be followed by an atmospheric re-entry. This scenario is cost-effective, affordable, feasible with current technologies, and potentially attractive to tourists. A phased incremental approach, in keeping with self-sustainable revenue stream, is suggested to fielding and evolving the elements of this lunar tourism architecture. Employing the ISS as the nucleus for commercial space tourism has already proven demand and the return on investment for a phased MOBIUS lunar tourism project is promising.

III. Mission Architecture Elements

In this section, all the major elements of the proposed mission design architecture are introduced.

A. International Space Station (ISS)

The International Space Station (ISS) is the most complex international scientific and engineering project in history and the largest structure humans have ever put into space. This LEO orbiting satellite is a national laboratory for human spaceflight, new technologies and an observation platform for astronomical, environmental and geophysical research. As a permanently occupied outpost in outer space, it serves as a stepping-stone for further space exploration. This includes Mars, which NASA is now states is its goal for human space exploration [Sharpe 2016].

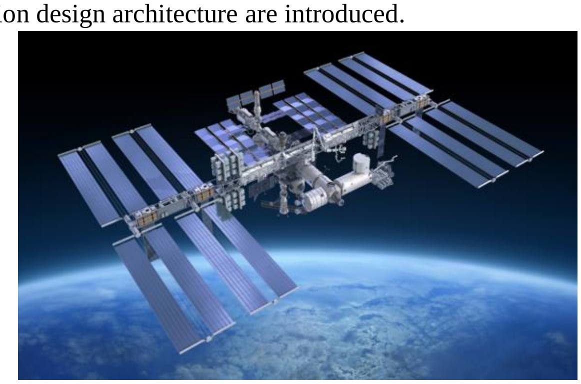

Figure 2. International Space Station (ISS). *ISS can be used as a commercial staging platform for sending the tourists to the Moon using the MOBIUS architecture.*

According to NASA administrator Charles Bolden, 2024 is the current proposed decommission year of ISS. While ISS might sound like a sweet vacation spot for future space tourists, it is unlikely that NASA will let it linger up there. The federal space agency does not have a warm spot in its heart for space junk. UN COPUOS report on Space Debris recommends deorbiting decommissioned facilities in LEO.[UN 1999]The ISS is more likely to get taken out of space the same way it was put up: deconstructed in a series of small trips [Sloat 2016]. Considering the $100 billion cost for building ISS, such a destiny awaiting ISS does not seem economically justifiable. With the recent installation of the International Docking Adapter(IDA), discussions are ongoing to turn the facility over for commercial use.[Gerstenmaier 2016, Liptak 2016] Commercializing it through MOBIUS project is one way to guarantee that such an investment will not be wasted but transformed into a self-sustaining, revenue generating facility, paving the way for a new way and a new century of space activity [Figure 2].

B. Cislunar Orbital Vehicle (COV)

Cislunar Cycling Orbital Vehicle (COV) is a cycler that will carry the tourists from LEO to the proximity of the Moon on a weekly basis. It comprises of the main capsule, Cislunar Propulsion System, and Tourist Docking Capsule (see subsequent sections). Figure 3 shows the COV with TDC and CPS attached to it.

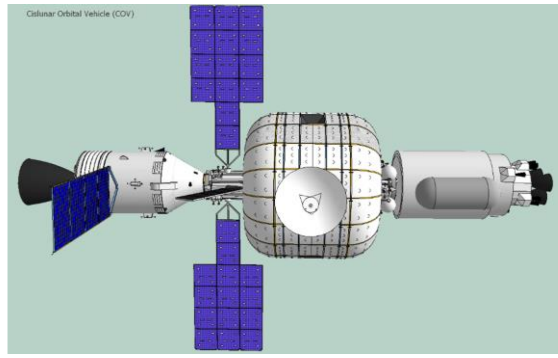

Figure 3. Cislunar Orbital Vehicle (COV). *COV and the attached propulsion system along with TDC are seen in this figure.*

Estimates show that the total minimum crew accommodation mass for ECLSS required for this mission is about 1400 kg for all passengers (6 people) per day. Minimum crew accommodation volume required for this mission is 8.2037 m^3. These estimations are based on the values presented by [NASA STD 3000, NASA HIDH 2014, Larson 1991]. These compare favorably with the Celentano curve[Cohen 2008] and the current NASA Orion capsule and the SpaceX Crew Dragon V2 being readied for service to ISS.

Addressing these ECLSS requirements including the recreational facilities, an interior design is depicted in figure 4. As seen in this 2D schematic of COV, different main segments are considered for LSS such as kitchen galley and storage, dining room, private compartment, as well as a solar storm shelter to accommodate all passengers and crew during possible hazardous anomalously large solar particle events (ALSPE) and cosmic radiation. A telescope and a unique EVA birdcage are also considered for passengers to experience outer space. Command and control room is where the flight team monitors and controls the spacecraft. The COV is offers a very spacious habitable volume.

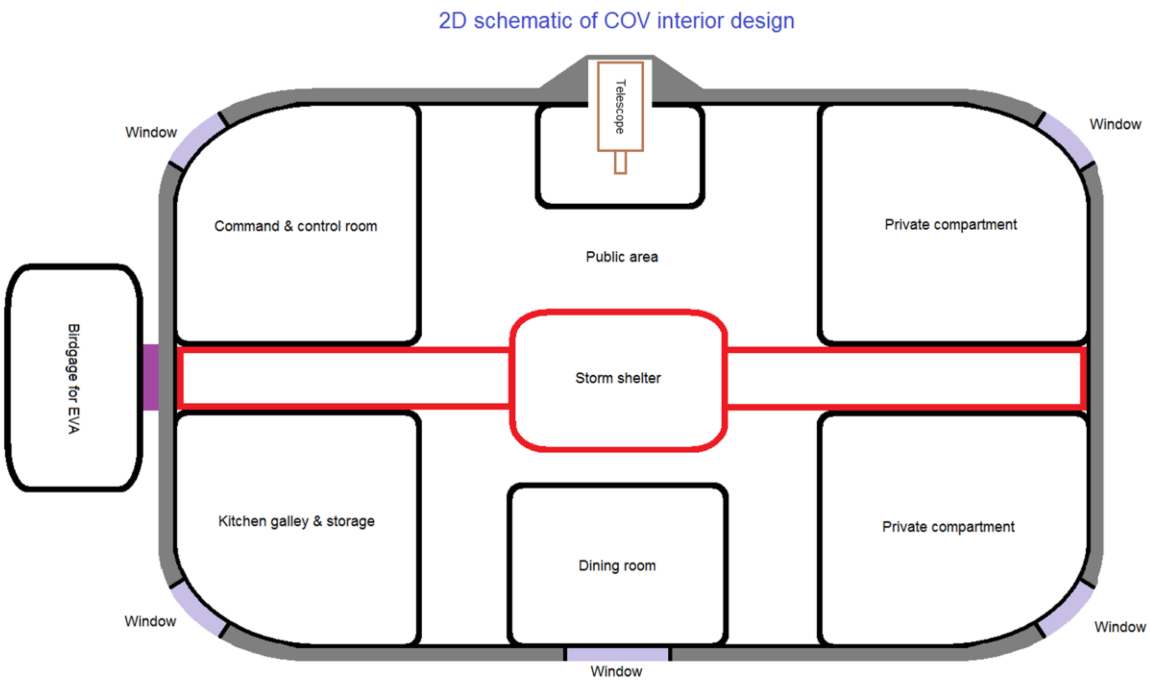

Figure 4. Interior of the Cislunar Cycler Orbiting Vehicle. *Salient features of the COV for 4 passengers and two crew. Inflatable habitat technology allows for a much more spacious and comfortable interior that is needed for longer missions with more passengers and crew support.*

The main capsule of COV is suggested to be made of inflatable technologies such as those used in the Bigelow Expandable Activity Module (BEAM) of the Bigelow Aerospace Corp [Bigelow 2016]. The evolved BA330 offers a habitable volume of 330cum at 20MT and the ISS Destiny module offers 160 cum at 15MT. Both inflatables are candidates for the MOBIUS architecture, and the smaller module is replaced by the larger one as the system evolves for more capacity. The initial structural mass estimate of the spacecraft is about 20-25 metric tons. The spacious Bigelow BA330 is depicted in figure 5.

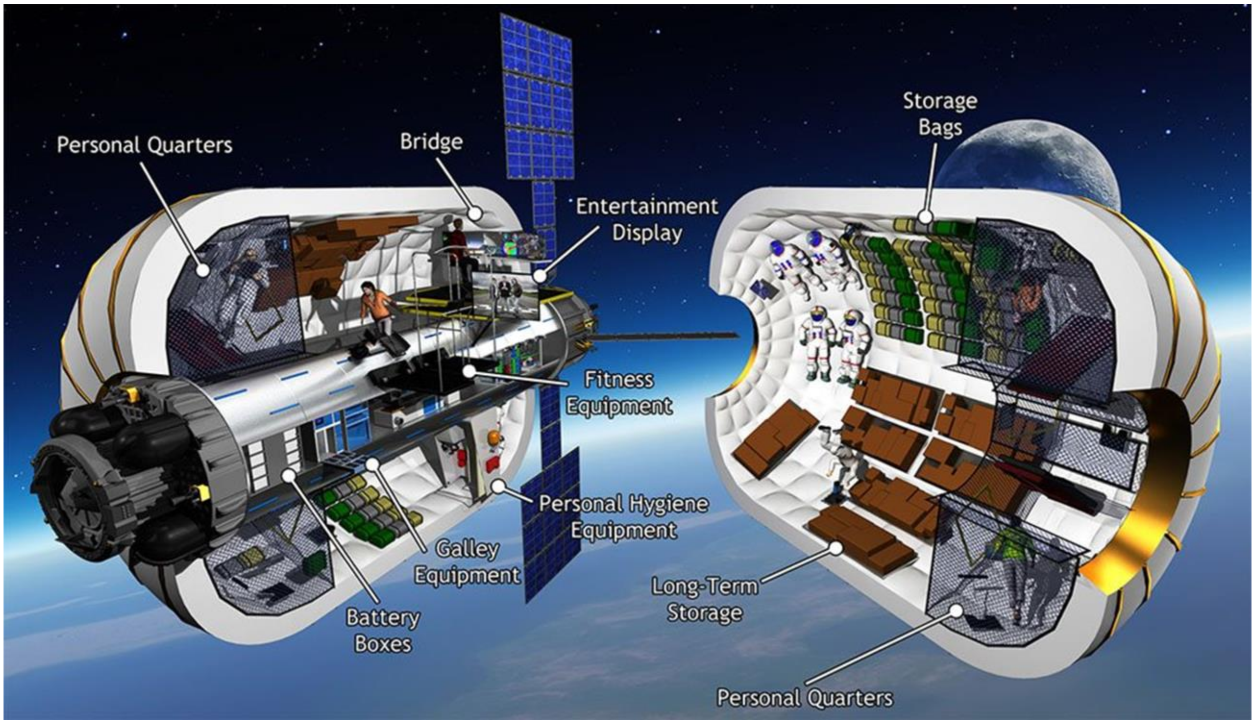

Figure 5. Bigelow BA330. *Cutaway depiction of the spacious 330 cum interior of a Bigelow BA330 inflatable module in orbit. The BA330 would make a nice candidate for the MOBIUS evolutionary architecture [credit Bigelow Aerospace].*

Let us consider the COV at LEO with an altitude of perigee of 250 km. As will be explained in section IV, radii of apogee and perigee of the CTO have to be 300,000 km and 15,000 km respectively. Therefore, we can write: $a = \frac{300000+15000}{2} = 157,500$ km where a is the semimajor axis of the cislunar transit orbit (CTO).

However, in order to inject the COV assembly to the final orbit, we need to use several Hohmann transfer trajectories:

1. Transfer from LEO to an elliptic orbit with radii of apogee and perigee of 15000 and 6628 (6378+250) km.
2. Circularize this orbit.
3. Transfer from the circular orbit with the radius of 15000 km to CTO.

Velocity of spacecraft at any position can be calculated by the following equation:

$$V = \sqrt{2(\frac{\mu}{R} - \frac{1}{a})} \quad (1)$$

Using "eq. (1)" for each of these trajectories yields the total ΔV of 4.4572 km/s. For a more in-depth evaluation of orbital maneuvers, please see [Chobotov 2002].

C. Cislunar Propulsion System (CPS)

Figure 6 shows the CAD design of CPS which will be used to insert the COV to CTO as well as for station keeping.

Equation 2 can be used for calculating the total amount of propellant that is needed to transfer the COV from LEO to CTO:

$$M_p = M_s(e^{\frac{\Delta V}{I_{sp} \cdot g_0}} - 1) \quad (2)$$

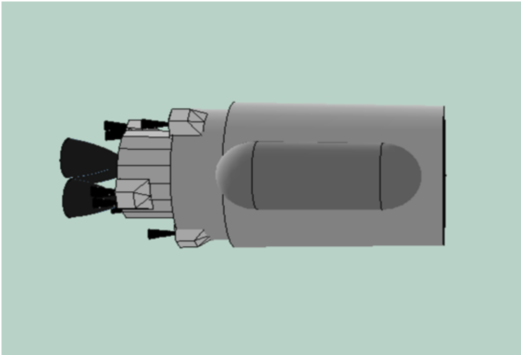

Figure 6. Cislunar Propulsion System (CPS). *The CAD design schematic of CPS that is used to insert the COV to its final orbit.*

For the total ΔV of 4.4572 km/s which was obtained previously and an I_{sp} of 470 s, the total propellant mass to inject the COV into the final orbit is 40.732 metric tons. This amount of propellant can be transferred to orbit in multiple launch deliveries. Of course, a more efficient nuclear-powered propulsion system can be evolved over time which will obviate the need for such amount of chemical fuel. Other alternative space propulsion systems can also be considered. Useful references for further studies in this regard may be found at [Chobotov 2002, Turner 2005, Cornelise 1979, Brown 1996, Sutton 1992, Wertz 1997, and Bate 1971]

D. Tourist Docking Capsule (TDC)

Figure 7 illustrates the TDC which is responsible for transferring the tourists from LEO to COV during the perigee encounter phase. The maximum number of people that it can carry is four. It will depart from ISS and perform the plane change while on its Hohmann or one-tangent burn trajectory. It uses an impulsive chemical propulsion system that puts the capsule on its way to dock with COV on a mission duration that will last several hours. TDC has to be protected by enough shielding against the energetic charged particles at van Allen radiation belt and SPEs as it passes through the inner region of magnetosphere beyond the radius of 1000 km.

TDC performs the rendezvous maneuver when COV is at the perigee of CTO. The details of all mission operations will be explained in section IV. The TDC design is based on the NASA Orion and the SpaceX crew Dragon capsules.

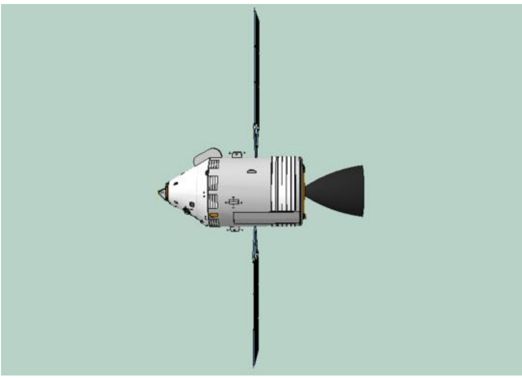

Figure 7. Tourist Docking Capsule (TDC). *CAD design of TDC which will take tourists from ISS to COV.*

E. Lunar Transit Lounge (LTL)

LTL will be located at L1 Lagrange point where it can remain stationary at a specific distance between Earth and Moon. This lunar orbital hotel will be used as the arrival port for tourists in the proximity of Moon and a platform for lunar descent as well as a departure port. As seen in the CAD design which is presented in figure 8, LTL has artificial gravity facilities to make visitors feel “at home” while providing them with an incredible lunar view from a close range. Every arriving group of passengers will stay one week in LTL a portion of which will be spent on lunar surface. The arriving TDC will dock with LTL during its apogee encounter and transfer the new crew. The previous TDC will pick up the previous crew and leave LTL to dock with COV and initiate the inbound trip.

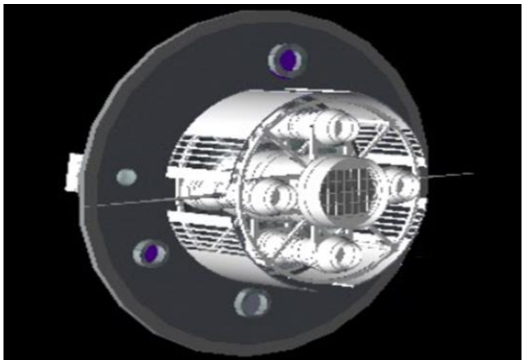

Figure 8. Lunar Transit Lounge (LTL). *LTL will be located at L1 point and used as entry and departure port to the Moon.*

F. Lander

The NASA Altair lander may be used as a reference for this mission [NASA 2010] though much smaller systems like the one proposed by Golden Spike [Tate 2012] are considered more viable for early stage MOBIUS operations. The lander is configured for descent and ascent only, with EVA and rover systems augmented as the architecture evolves. While early operations are intended to be via visual flight rules, extending to fully automated instrumental flight rules over time, the lander will also have a manual override function that would allow the pilot an abort capability in case of an anomaly. A mission may also be reconfigured to access alternative landing sites as well. Figure 9 shows a CAD design of a lander developed for MOBIUS mission.

Figure 9. MOBIUS Lander. *Lander can carry 4 people to the surface and return them back to LTL.*

G. Lunar surface facilities

The first phase of MOBIUS lunar landings are envisioned as touchdown only missions. Crew and passengers are expected to stay in the cabin and enjoy the vistas. After a brief stay, the vehicle will ascent back to lunar orbit to dock with the orbiting facility and then on to rendezvous with the cislunar cycler at the apogee of the supersynchronous MOBIUS cycler for inbound flight back to Earth. In later phases, as a permanent lunar infrastructure emerges from various cargo sorties intended to develop facilities like serviceable landing pad, habitats, roads and uninterrupted and reliable power and utilities, we expect the landing missions to include stays of several days and activities like EVA and tours on long distance rovers to sites that include the historic Apollo 11 landing site at the Sea of Tranquility and visits to other spacecraft. Since such sites are historically significant, extreme caution is desired to preserve the integrity of the site and surrounding environment [Thangavelu et al 2012] Over time we expect that the logistics of the MOBIUS architecture will allow scientists to set up facilities all over the lunar globe and service them, while increasing number of paying passengers help to sustain and maintain the evolution of MOBIUS [figure 10].

In addition, ELVIS (Elevated Lunar Viewing and Information System) is such a concept proposed in the USC School of Architecture that allows the visitor to experience the site of humanity's first lunar landing without perturbing it [Figure 11].

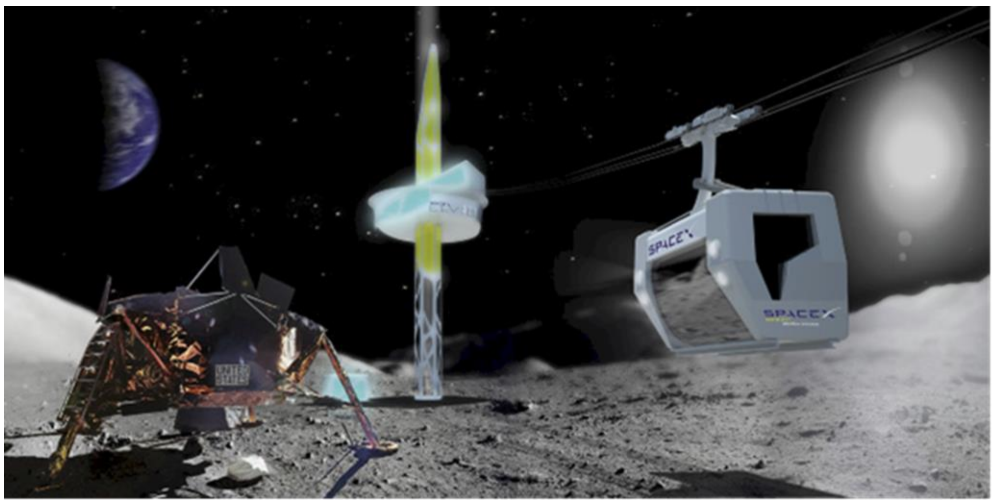

Figure 10. Cable car system. *In later phase of MOBIUS, A cable car system with holographic projection system is proposed to access "do not disturb" sites in order to "relive" the historic Apollo 11 lunar landing. [Credit: F. Sharpe USC Architecture 2012]*

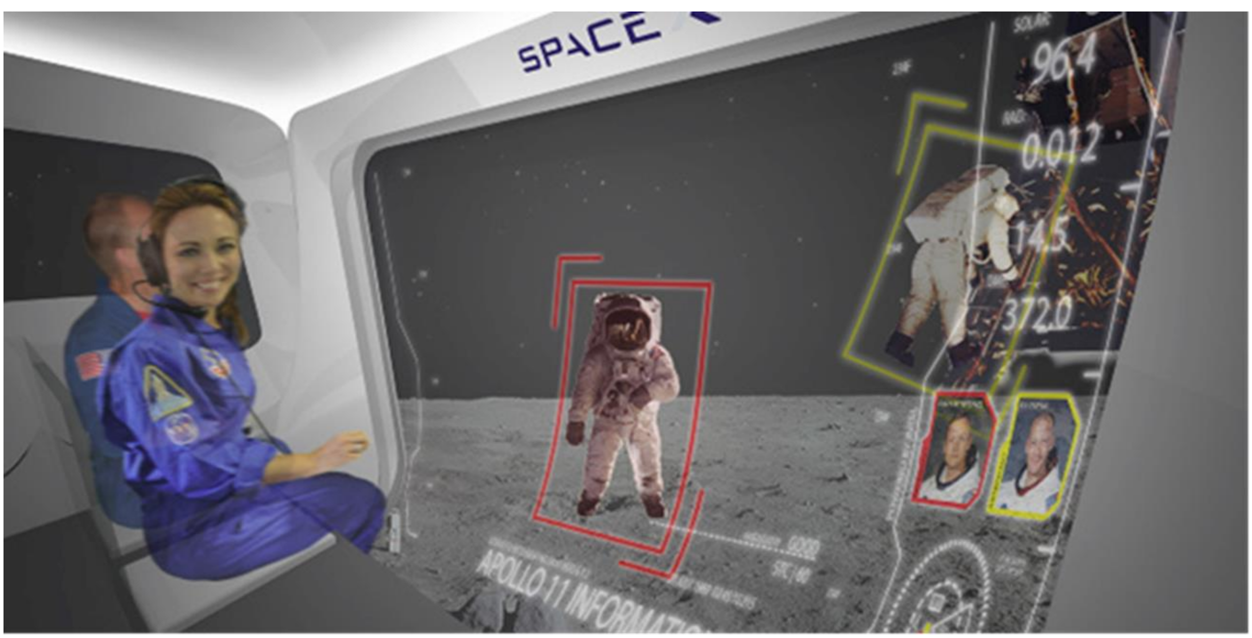

Figure 11. ELVIS. *Crew stationed at ELVIS take visitors on an in-depth information and technology tour, aided by holographic projection of historic event like Armstrong's first steps. [Credit: F. Sharpe USC Architecture]*

IV. Methodology

A. Cislunar Transit Orbit (CTO)

The most important element of MOBIUS mission structure is the CTO and how the spacecraft commutes between the Earth and the Moon. As mentioned earlier, this nominal trajectory is a specific cycling, cislunar, supersynchronous orbit with a low radius of perigee at Earth and a very high radius of apogee extending up to the vicinity of the SOI of the Moon. Figure 12 is generated in MATLAB to simulate this orbit. Considering the lunar orbital period (~28 days) and the necessity of each of the four COVs circling the Earth in the quartet of orbits (see figure 12) to pass the L1 Lagrangian point every four weeks, the choice of semimajor axis, RAAN, AOP, ROP, and ROA has to be made carefully to meet the mission requirements and accommodate the optimization constraints. The results of the math-modeling and the simulations conducted in STK and MATLAB show that the proposed configuration would generate a favorable, optimal outcome.

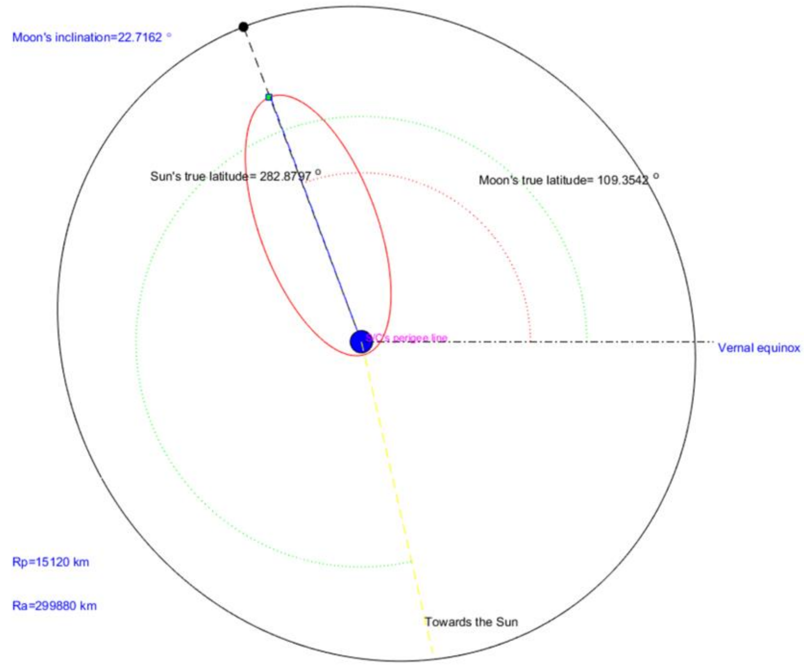

Figure 12. CTO and lunar orbit. *This figure shows CTO (red) and lunar orbit (black) and the location of COV (green) with reference to vernal equinox.*

Figure 13 shows an edge-on illustration of MOBIUS supersynchronous CTO. As seen in the configuration, there is a 28.1 degrees of difference in the inclination of the Moon and that of the ISS. Calculations indicate that a ΔV of 2.98 km/s is required for the TDC, which is launched from ISS, to perform the rendezvous maneuver (plane change)

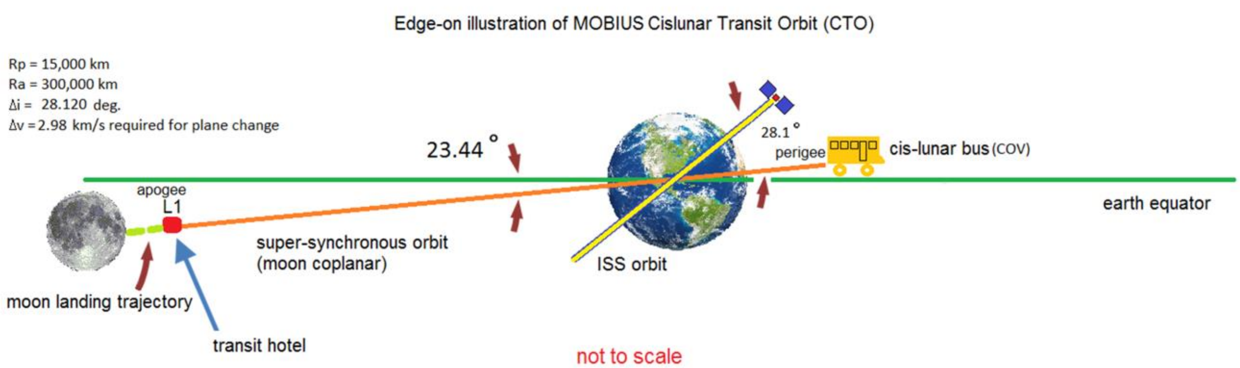

Figure 13. Edge-on illustration of MOBIUS CTO. *This figure shows Cislunar Transit Orbit (CTO) and ISS orbit and the location of COV with reference to Earth equator.*

with COV at perigee with the radius of about 15,000 km

The following issues have to be taken into consideration:

- Moon is at nearly 363,104 km at its perigee and 405,696 km at apogee.
- CTO's low radius of perigee, Rp, should be at least 15,000 km to ensure that the COV always travels outside the Van Allen radiation belt.

- The very high radius of apogee, Ra, should be about 300,000 km extending up to the vicinity of Moon and the proximity of L1.
- The Ra should not fall in the SOI of the Moon (66100 km) nor should Rp cross Van Allen belt.
- The COV should pass the L1 Lagrange point by about 6000 km distance or more depending on the CTO's semimajor axis.

B. Mission Trajectory Design

Since the orbital period of the selected orbit is about one week, the half period, i.e., the time that it takes for the COV to travel from perigee to apogee is 3.5 days. Let us consider the mission architecture illustrated in figure 14. Ideally, from an equatorial plane, there are four supersynchronous orbits extended to the vicinity of the Moon with 90 degrees of difference in RAAN from each other during a typical lunar orbital period. Now consider the orbit on the left side where the COV is at its perigee and docks with TDC to pick up the passengers who departed Earth orbit. It will take 3.5 days for the COV to reach the apogee and that's the time the Moon also gets closest to this point and the right time to deliver passengers via TDC from COV to LTL which is located at L1. The tourists then will have the chance to land on the surface of the Moon via Lander after staying in LTL and enjoying the lunar sight from LLO. One week later when the Moon reaches the apogee of the next supersynchronous orbit, another COV cycling this orbit will transfer the new tourists to LTL and picks up the previous ones who arrived one week earlier. This cycle will be repeated with two other orbits which allow continuous transfer of tourists to the Moon on a weekly basis. Note that for departures from ISS in its current plane and inclination, the precession of the ISS plane about the Earth allows for only three such supersynchronous orbital rendezvous opportunities. The details of MOBIUS mission design and the related simulations and calculations are presented in the next sections.

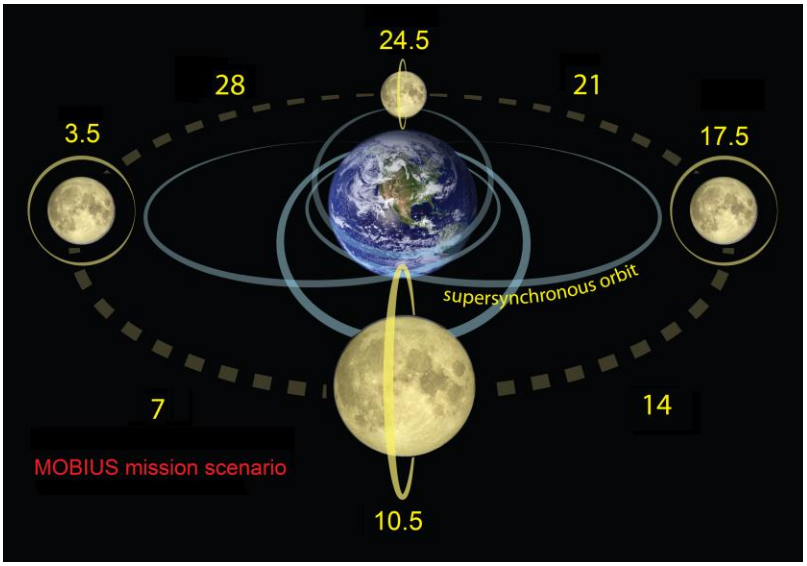

Figure 14. MOBIUS Mission supersynchronous cycling trajectory architecture. *A quartet of spacecraft in supersynchronous orbits which will transfer tourists to the LLO on a weekly basis.*

C. Deployment of Cislunar Orbital Vehicle

The COV stack is built up in LEO. The deployment of COV to the final orbit (CTO) should be un-crewed and performed through several spiraling transfer orbits as depicted in figure 15. Multiple burns at perigee during each pass would elongate the radius of apogee ultimately and extend it to the vicinity of the Moon. A total ΔV of 4.4572 km/s in incremental maneuvers to avoid structural damage and ensure a smooth transfer process.

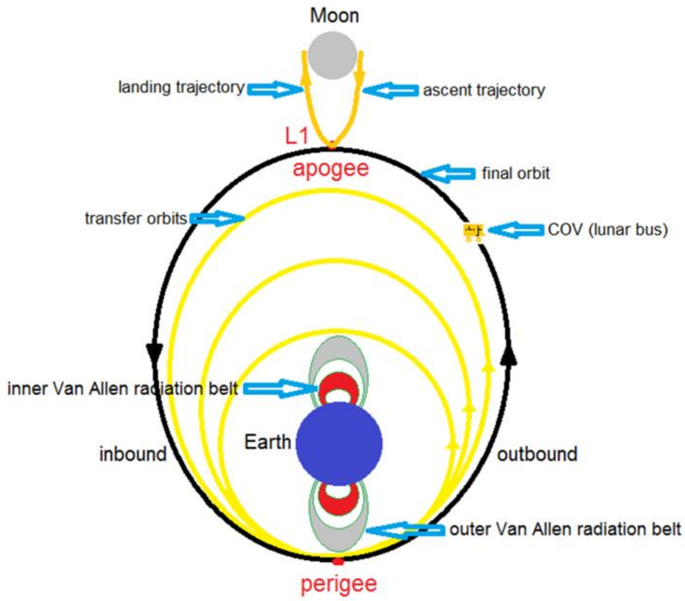

Figure 15. Deployment of COV to final orbit. *COV should be deployed to the final orbit (CTO) through a series of spiraling orbits prior to carrying the passengers. Multiple burns at perigee during each pass would elongate the radius of apogee and extend it to the vicinity of the Moon.*

D. Rendezvous at Perigee

Outbound tourist and logistics transfers to COV occur during Earth perigee rendezvous. The TDC departs from the ISS on a one-tangent burn or Hohmann transfer trajectory to rendezvous with COV while performing the plane change maneuver. The choice of the type of transfer method depends on the TDC's propulsion system's ability to generate the required velocity change, as the former needs higher retrograde ΔV during docking phase than the latter does. Figure 16 shows such a maneuver for a possible one-tangent burn trajectory transferring passengers from ISS to COV. A similar maneuver is also performed by the TDC during the inbound trip as COV approaches the Earth perigee in which the TDC undocks from COV, does the plane change to align with ISS orbit, and finally docks with ISS using any of the abovementioned available transfer methods or directly goes for atmospheric re-entry without performing the plane change depending on the passengers' decision. If technically feasible, it is suggested that, after ISS retirement and its availability for commercial use, its orbit be changed to become coplanar with that of the Moon to eliminate the necessity for plane change maneuver which will dramatically decrease fuel and tankage needed for plane change and thus drastically cut down on the mission costs.

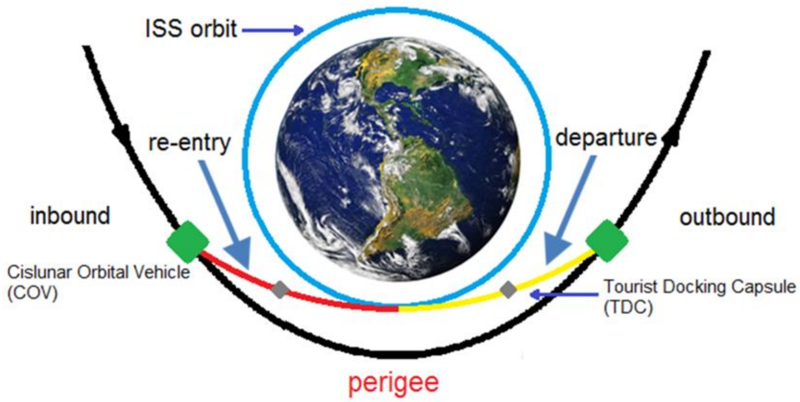

Figure 16. COV rendezvous at perigee. *Configuration of COV, LEO, and CTO and the related patched trajectories during an Earth perigee encounter is illustrated in this figure.*

Figures 17-20 depict different stages of this phase. The CAD illustrations are designed in Google Sketchup software. Figure 17 shows the TDC as it has just started the transfer of passengers to COV during Hohmann or one-tangent burn maneuvers as the COV gets close to Earth during the perigee encounter phase. Remember that this transfer trajectory involves the plane change maneuver as well. Figure 18 shows the caption of the flight simulation where TDC is in the mid-way towards the COV. ISS, TDC, and COV are seen in the background. Figure 19 shows the TDC as it has come close to COV and is performing the retrograde ΔV burn to align its velocity vector with that of the COV and dock with it. Figure 20 shows the last stage of this phase where TDC has docked with COV and the

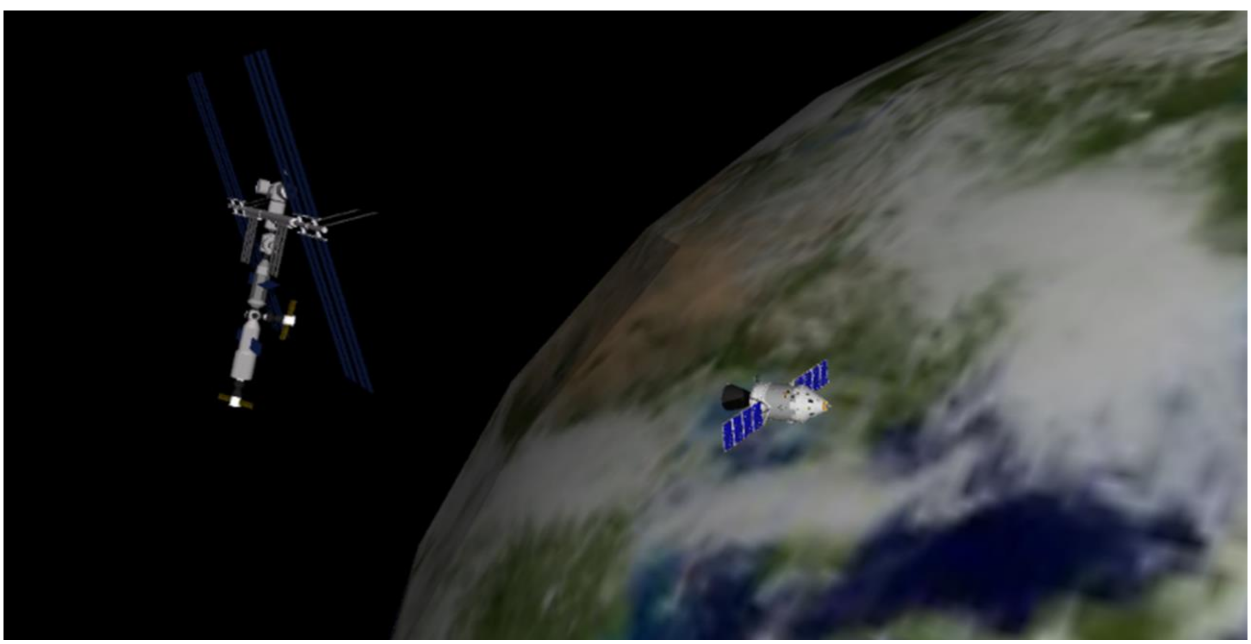

Figure 17. TDC departure from ISS. *TDC has just departed from the ISS carrying 4 passengers to COV via either one-tangent burn or Hohmann transfer methods during the COV's perigee encounter.*

whole complex is ready for CLI/TLI burn.

Figure 18. Tourist Docking Capsule(TDC) departure from ISS. *TDC is shown on its way to dock with COV at Earth perigee.*

Figure 19. Tourist Docking Capsule(TDC) rendezvous with COV. *TDC is performing the rendezvous maneuver during the COV's Earth perigee encounter.*

Figure 20. COV ready for CLI/TLI burn. *TDC has docked with COV and tourists have boarded the spacecraft. It's on its three and a half day journey towards lunar apogee close to LTL.*

E. Rendezvous at Apogee

In this of phase of operations of outbound trip, the COV approaches the vicinity of L1 Lagrange point where the LTL is located and to which passengers are transferred, allowing them to appreciate the Moon at close range. LTL will be at least 6000 km away from the designated apogee point due to the distance difference between L1 and the lunar SOI. As depicted in figure 21, after about 3.5 days journey, the TDC, which docked with COV at perigee, remains attached to it until it gets close to CTO's apogee where it undocks from COV transferring the passengers to LTL. Since the COV's velocity is rather small at CTO's apogee, a much smaller ΔV is needed for docking and undocking maneuvers according to the calculations and STK simulations. The only choice for this trajectory is one-tangent burn due to astrodynamics limitations. On the other hand, the previous tourists already at LTL will depart from the lounge via the TDC and dock with COV during the inbound phase. Both the outbound and

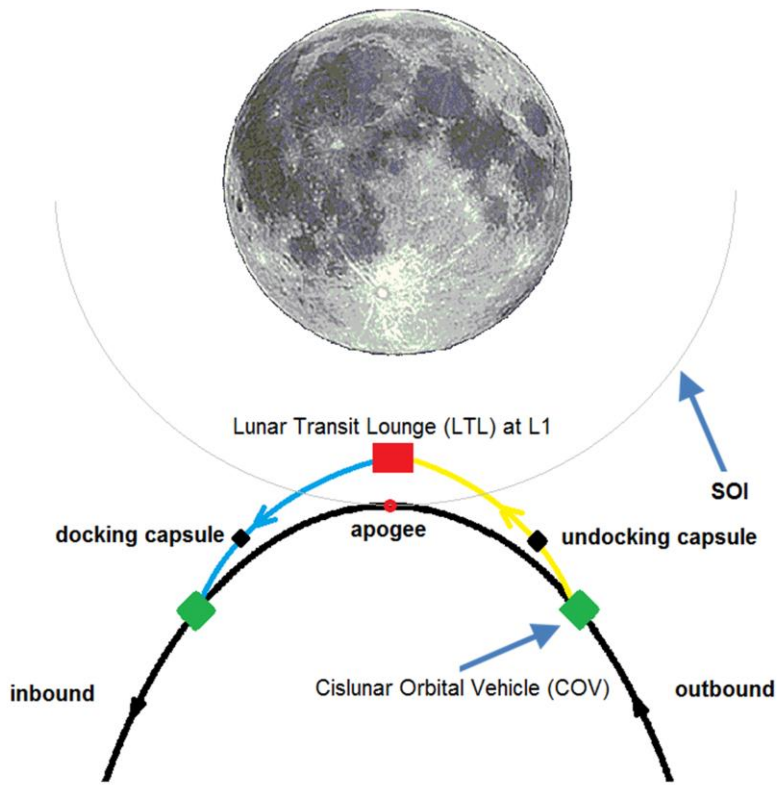

Figure 21. COV rendezvous at apogee. *COV transfers the passengers to the LTL via TDC while passing by the L1 and picks up the previous ones on its way for the inbound trip.*

inbound dockings will start almost simultaneously transferring the new passengers from COV to LTL and boarding the previous ones to the COV. The STK simulations show that, in this proposed CTO with the previously specified orbital elements, the COV will always remain in the orbit with minimal station keeping requirements and no need for any propulsion system – except for the initial deployment process – due to the fact that it does not enter the SOI of the Moon and allows the TDCs do the transferring of the tourists through the patched trajectories as explained above. Figure 22 shows the apogee encounter phase where TDC is detached from COV and is on its way to dock with LTL while another TDC is simultaneously transferring the previous tourists from LTL and is on its way to dock with COV farther ahead. Lander is also seen in the background which is on the descent trajectory to carry another group of tourists and land them on the surface of the Moon.

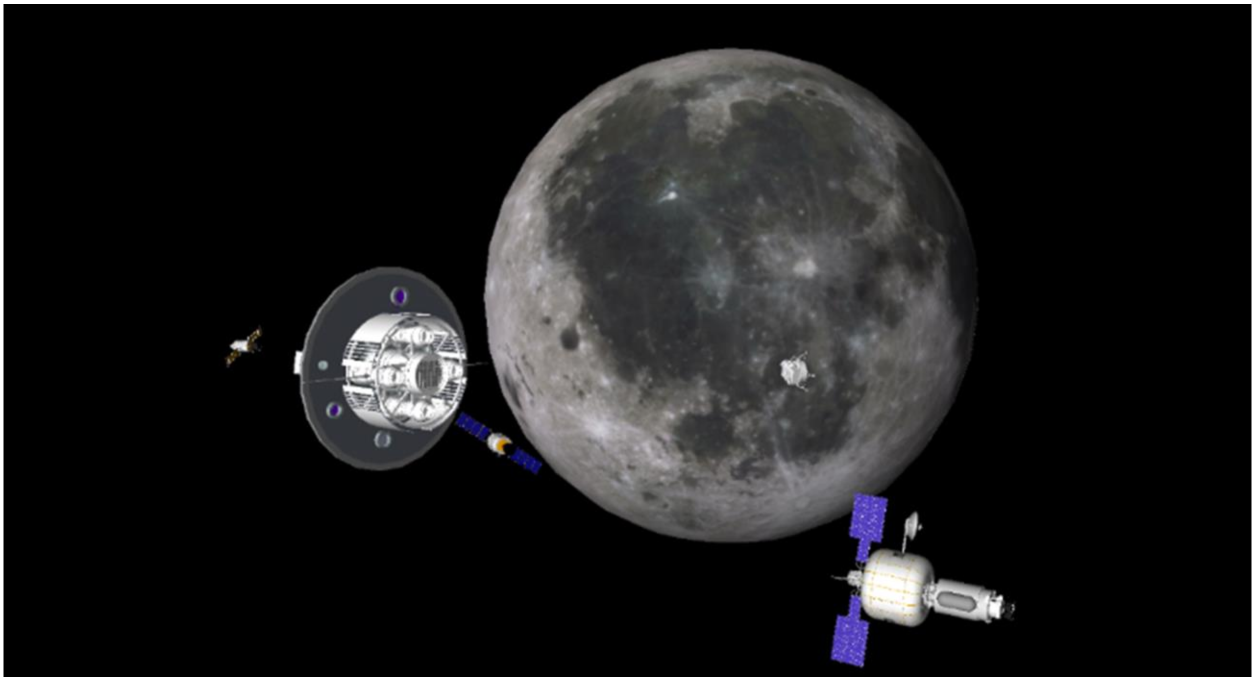

Figure 22. **COV rendezvous at apogee.** *COV has approached the apogee of CTO where TDC has undocked from the vehicle and is on its way to dock with LTL and transfer the four passengers to the lounge. The previous TDC and Lander are also visible in this image of flight simulation. The distance between COV and LTL is about 6000 km.*

V. Cislunar Orbital Dynamics

While aspects of the origin and evolution of Earth-Moon system are still being debated, the celestial mechanics of the prevailing two-body system including tidal motions, librations and associated perturbations are well known and thoroughly understood.

Certain trajectories like the Apollo free return trajectory or that employed for the Hughes AsiaSat/PAS-22 satellite rescue mission show that the Earth-Moon orbital system can be exploited in very creative ways. The backflip maneuver is a creative orbital transfer method for cislunar orbital trajectory optimization [Uphoff, C. et al 1991]. We also know that there are variations and anomalies in the lunar gravitational field caused by mascon and other features that result in non-isotropic field that is especially vulnerable to spacecraft instabilities in low lunar orbits. The recent GRAIL mission has mapped the lunar gravity field in high resolution [Zuber et al].

Certain orbits like "frozen orbits" exist that allow spacecraft to maintain their stable low lunar orbits [Leib, E. et al, 2005] like the one used by the recent LRO Cislunar Weak stability boundary solutions exist that allow slowly spiraling spacecraft to ply between the Earth and the Moon with minimal energy expenditure [Belbruno et al 2000]. This solution is useful provided the payload, like cargo, that is insensitive to prolonged exposure to space radiation.

Cycling spacecraft or cyclers that take advantage of resonant orbital periods between bodies have been studied and proposed for various missions. The Aldrin cycler [Aldrin et al 2001] and the Astrotel [Nock 2002] concepts are examples based on such optimized trajectories. Cislunar cycler orbits are useful for putting large spacecraft in perpetual motion around the Earth-Moon system with little additional energy to maintain their continuous cycling trajectories.

The MOBIUS concept addressed in this paper has looked at several Earth-Moon spacecraft transfer options and found cislunar spiraling orbits useful for injecting large manned spacecraft in unmanned mode as one method to place them in cislunar and lunar orbits. We found the Earth-Moon supersynchronous orbit and associated cycling transfer a most optimal solution for both a departure from ISS or from a more energy efficient and sustainable equatorial orbit.

VI. Heavy Lift Launch Vehicles

The MOBIUS architecture will require some of the quartet components to be launched on heavy lift launchers. The launcher stable of the world is growing, and among them, the US government Space Launch System (SLS) and the various configurations of the private Falcon Heavy stable of launchers are all considered candidates for building up the MOBIUS architecture. Clustering various upper stages, both existing and proposed, are also being investigated. Module Assembly in Low Earth orbit (MALEO) [Thangavelu 1990], the technology that was used to build the large multi-module International Space Station (ISS), will be used to integrate the MOBIUS cislunar orbital vehicle stack. The OST Rocket Pro 1.1 software [OST Inc. 2016] proves the feasibility of the process.

VII. Conclusion

The Moon is our celestial neighbor. Apollo missions have paved the way for human missions to the Moon. A new wave of lunar precursor missions are already scoping a variety of activities both scientific and commerce related. Private, for profit companies are weighing opportunities for lunar return, this time to stay, for those who can pay. Commercial lunar tourism is on the horizon and systems are being tested and certified for missions beyond low Earth orbit. The MOBIUS project presents an innovative mission profile that evolves through an economic boot strapped, pay as you go approach to viable commercial cislunar activity focused on lunar tourism. Using the ISS as a tried and tested first stage tourist attraction and departure platform, the MOBIUS project employs an Earth-Moon supersynchronous orbit to fly paying passengers on week long lunar cruises. The cislunar orbital vehicle bus or COV is built and injected into a cislunar cycling orbit. A shuttle craft is used to ferry passengers and crew at Earth perigee and lunar apogee. A phased approach allows lunar tourists to see the Moon up close during initial flights lasting a week, extends it to lunar polar orbital missions via a lunar polar orbiting facility, and finally, in a lunar surface expedition in a lander. The MOBIUS concept is modeled using state-of-the-art tools and proposes a viable profile that attempts to balance available technologies with entrepreneurial needs and capital to make commercial, self-sustaining lunar missions possible in the earliest timeframe.

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"The economic function of space industrialization is to generate jobs on Earth, not in space."

~ Krafft Arnold Ehricke (March 24, 1917 – December 11, 1984)

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