Shuttle Flight Opportunities between Stations Orbiting the Earth and Moon

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This paper focuses on a new problem in determining flight opportunities for a shuttle vehicle consistent with the constraint of departure from and arrival at existing station orbits at both the Earth and moon. Results are obtained which demonstrate the possibility of achieving good round trip mission characteristics on either two or three month cycles which require near minimum energy trajectories, reasonable transit times, reasonable lunar stay times, and which are consistent with envisioned lunar traffic requirements. Moreover, several important conclusions are reached which are critical to the design parameters of the Earth and lunar station orbits. Finally, a typical mission plan is presented showing how the results of this paper may be used for establishing nominal shuttle mission scheduling.

Nomenclature

a = semimajor axis
e = eccentricity
h = altitude of OPSD circular orbit
i = inclination of OPSD orbit to equatorial plane
J_2 = oblateness term in Earth gravitational potential
J_3 = odd zonal harmonic in the lunar gravitational potential
n = mean motion (2π/period)
R = radius of the Earth
$\bar{S}$ = asymptote unit vector
t_0 = initial epoch
T_{TL} = translunar flight time
α = plane change angle between $\bar{S}$ and LOSS orbit plane
Δ_n = angle from lunar descending node to OPSD ascending node in lunar orbit plane
Δ_0 = initial value of Δ_n corresponds to $-\lambda_0$ [Eq. (2)]
η = inclination of the lunar orbit plane to the equatorial plane
λ_n = angle from lunar descending node to OPSD's ascending node in the equatorial plane
λ_0 = initial phase angle at time t_0
ϕ = inclination of OPSD to lunar orbit plane
ψ = lunar position angle
ω_m = angular rate of moon's motion about the Earth, 13.176°/day
$\dot{\Omega}$ = rate of change of right ascension (in equatorial plane) of the OPSD's ascending node

Introduction

THIS paper is concerned with missions involving shuttle flights between the Earth and moon which utilize two orbiting stations as intermediate terminals, one about the Earth and one about the moon. A typical round trip lunar mission will start with the ground launch of a reusable Earth Orbit Shuttle (EOS) which will bring payload and crew to low-altitude Earth orbit and return to the launch site in the so-called "airline" mode of operation. Once in orbit the EOS will rendezvous with an Orbital Propellant and Service Depot (OPSD) in a 270 naut miles circular orbit inclined at either 28.5° or 55°. This combined way-station and fuel storage facility will serve as the launch point for a variety of missions including lunar, interplanetary, satellite replacement and retrieval, geosynchronous, and certain Air Force missions. The translunar flight from the OPSD will be performed by an Orbit-to-Orbit Shuttle. The shuttle vehicle will carry the payload and crew, brought to them by the EOS, to an orbit about the moon. There, the shuttle will rendezvous with a Lunar Orbit Space Station (LOSS), which has been proposed by NASA to be in a 60 naut miles circular orbit inclined at 90° to the lunar equator. Transportation between the LOSS and a Lunar Surface Base (LSB) will be accomplished by a special shuttle dedicated to LOSS-LSB missions, or perhaps by a shuttle, coming from Earth, provided with a special lunar landing capability. The return trip to Earth, with scientific payload, instruments for repair, and crew being rotated home, will be accomplished in the reverse order of the Earth-to-moon portion of the trip.

In nominal operations of this Space Transportation System (STS), shuttle vehicles will be launched to the moon from an OPSD in regressing Earth orbit and will rendezvous with an existing LOSS facility which is in orbit about the moon. The return operation requires Earth-bound departure from the same LOSS orbit, which has undergone an orientation change relative to the Earth-moon line during the lunar stay time of the shuttle. The return must be planned in such a way that the Earth-bound shuttle may easily rendezvous with the OPSD in its inclined orbit, which has subsequently undergone an orientation change due to nodal regression during the time since the original launch to the moon. By way of contrast, the problem considered in the Apollo program was that of flight between a point on the Earth and a point on the moon and back by way of conveniently selected intermediate Earth and lunar parking orbits.

An early study of the launch problem from a regressing Earth orbit to the moon as a moving point in space was conducted by Reich and Wolpert.[1] Velocity requirements and launch opportunity timing were determined for translunar flights, but no LOSS-type target orbit was postulated at the moon and no return to earth missions were considered. The launch problem was more recently examined by Starr[2,3] as a forerunner of the study reported in this paper. Starr obtained results relating to the variation of single impulse translunar injection velocity with time as the launch orbit undergoes nodal regression. A cyclical but nonuniform time spacing of the velocity minima was found, corresponding to the results of Reich and Wolpert. In Ref. 4, a simplified model of the OPSD-Earth-Moon-LOSS system was proposed in order to quickly determine the frequency of zero plane change flight opportunities before resorting to matched-conic or other more costly analysis tools. By assuming the moon's orbit and the Earth's equator to be coplanar it is possible to demonstrate the average long-term frequency of launch and return opportunities. These results are extended in the present paper by introducing the nonlinear effects of true

Received August 30, 1971; revision received March 27, 1972.
Index categories: Manned Lunar and Interplanetary Systems; Lunar and Planetary Trajectories; Spacecraft Mission Studies and Economics.

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inclination of the moon's orbit and variable flight time on translunar and transearth flight segments.

The problem of efficiently transferring from a lunar orbit to a hyperbolic asymptote that is not contained in the LOSS plane was examined for two impulses by Gunther[5] and for three impulses by Webb.[6] The efficiency of the three-impulse maneuver makes it desirable to incorporate it in all studies involving transfer between Earth orbit and lunar orbit. Webb and his co-workers[7,8] examined the lunar shuttle problem utilizing the three-impulse maneuver whenever dictated by lunar plane change requirements. Variable flight times were allowed and resulting velocities were calculated. One limitation, however, involved the dependence of the mission cycle behavior on arbitrarily selected initial orientation geometry of the OPSD-Earth-Moon-LOSS system. The present paper presents a systematic approach to the selection of OPSD orbital elements and initial geometrical orientation parameters in order to best achieve desired mission timing goals.

Geometrical Considerations

Figure 1 represents the Earth-to-moon portion of a mission in which the shuttle is required to depart for the moon from an OPSD orbit which is undergoing a continuous orientation change, and to rendezvous with the LOSS in a specific lunar polar orbit. On the return portion of the mission the shuttle must depart from the LOSS orbit, which has undergone some orientation change relative to the Earth-moon line during the lunar stay time, and rendezvous with the OPSD in its regressed orbit. Given no restrictions on plane change capability for the shuttle vehicle, launch and return lunar flight opportunities could occur each OPSD revolution. Unfortunately, the shuttle vehicle will probably possess only a small plane change capability in the interest of minimizing propellant costs. The determination of feasible transit paths therefore reduces to the problem of finding the best geometries which result in translunar launch and trans-Earth return opportunities which impose only small plane change requirements on the lunar shuttle.

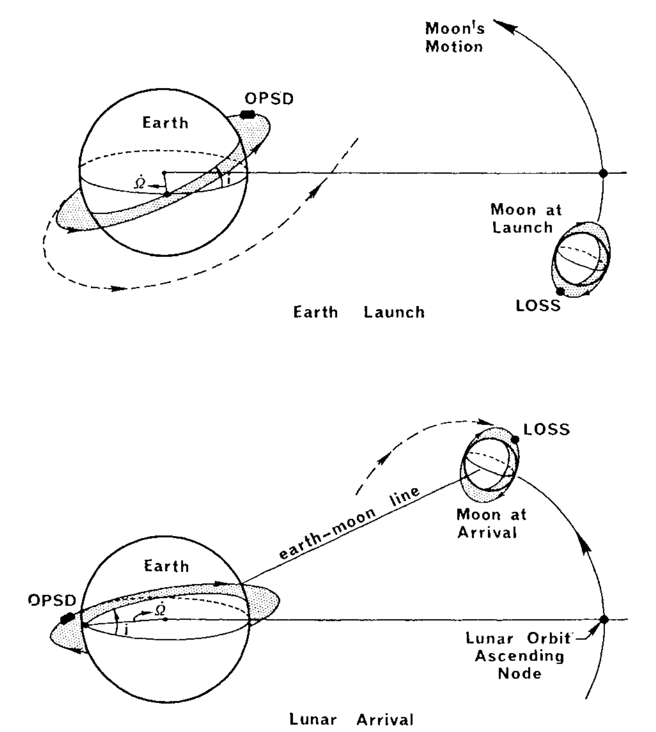

Fig. 1 Schematic representation of the lunar orbit-to-orbit shuttle problem.

In order to understand the geometry of the orbit-to-orbit shuttle problem, it is worthwhile to look at three subgeometries which combine to produce the total geometrical effect: 1) the nodal regression of the OPSD Earth orbit, 2) the orbital motion of the moon about the Earth, and 3) the changing orientation of the LOSS orbit to the Earth-moon line.

The OPSD orbit has been tentatively established as a 270 naut miles circular orbit of either 28.5° or 55° inclination relative to the Earth's equator (more refined orbital parameters which result in certain desirable synchronization characteristics, will be proposed in this paper for the Earth space station in both inclination ranges). The OPSD orbit does not retain a fixed inertial orientation but instead experiences a nodal regression which significantly affects lunar flight opportunities. This nodal regression is due to the perturbative effect of Earth oblateness, mathematically designated as the J_2 term in the gravitational potential model. The nodal rate is well approximated by the formula

$$\dot{\Omega} = -[3J_2 nR^2/2a^2(1-e^2)^2]\cos i \qquad (1)$$

Equation (1) gives nodal rates of -6.7 and $-4.4°$/day for the 270 naut miles circular orbits of 28.5° and 55° inclinations, respectively. These rates correspond to cycle times (the time for a 360° nodal rotation) of 54 and 82 days.

The moon revolves about the Earth in a slightly eccentric orbit ($e = 0.05$) which is inclined 5.15° to the ecliptic. The moon's orbit plane orientation continuously changes with respect to the Earth's equator. Over an 18.6 year period, the inclination of the moon's orbit plane varies between 18.5° and 28.5° and the right ascension of the lunar orbit ascending node experiences a total excursion of 26°. The mean angular orbital rate of the moon is a principal parameter in the mission timing problem. Because lunar inclination and node affect the mission timing to a much lesser degree, the effects of their variation from initial epoch values will be neglected in this paper.

The LOSS has been proposed as a 60 naut miles polar orbiting station about the moon in order to have all surface latitudes accessible to the space station without a plane change. The moon has a definite oblateness characteristic which induces nodal regression for orbits which are not polar or equatorial. Although the polar LOSS will experience some gravitational perturbations (notably from the sun, Earth, and J_3 of the moon[9]), nodal regression from oblateness will not be significant. Thus, over any month the LOSS orbit will retain a constant inertial orientation. The Earth-moon line, however, rotates through 360° during one lunar sidereal period, and as a result, the orientation of the Earth-moon line to the LOSS orbit varies through 360° as well. The geometry is slightly complicated by the fact that the lunar equator (from which the 90° inclination is measured) does not coincide with the moon's orbit plane but rather has a mean inclination of 6.68° to it. In the analysis presented in this paper this difference may be ignored without a degradation of the results. It is apparent that because the polar LOSS orbit remains fixed in inertial space, certain times during the month present more favorable (smaller) plane change requirements for entering or leaving a fixed lunar orbit.

The three subgeometries discussed previously (OPSD nodal regression, lunar motion, and LOSS orbit plane orientation) must be coordinated in such a way as to allow a sequence of feasible shuttle trajectories between the OPSD and LOSS orbits. A feasible trajectory should have small plane changes (near minimum velocity requirements), and an acceptable flight time (no greater than, say, 5 days). Small plane changes made at the moon are much less costly than similar plane changes made at the Earth (the ratio of typical circular parking orbit velocities is roughly 5:1). As a result, it seems reasonable to eliminate the necessity for plane changes on departure or arrival at the Earth-orbiting OPSD. On the other hand, it may be possible to accept some plane changes on LOSS arrival and departure.

Once it has been established that no plane changes are to be allowed at the Earth, the flight opportunity problem is simplified. The approach adopted in this study is to decouple the problem into two parts, one dealing with the launch and return opportunities between a regressing OPSD orbit and the moon as a moving point in space, and the other as a problem of minimizing the resulting plane change requirement at the moon. Restated, the problem becomes: 1) determine all opportunities for shuttle flights between a regressing OPSD orbit and the moon which involve no plane changes at the Earth; and 2) for these trajectories, determine the resulting plane changes at the moon entering and leaving the LOSS orbit, and minimize, if possible, the velocity requirements for this portion of the mission.

Determination of Flight Opportunities

A simplified technique was developed to determine all flight opportunities between the Earth and lunar stations from some arbitrary epoch and for given initial geometries. This technique and some significant results are summarized in this section of the paper. Primary emphasis will be placed on the lower OPSD inclination ($i = 28.5°$). Since the analysis of the return flight opportunities is similar in nature to the translunar opportunities, only the translunar technique will be discussed.

A variable flight time is used to reduce or eliminate plane change requirements. This is accomplished from the following consideration. A lunar arrival trajectory may be characterized as a hyperbolic conic section whose asymptote direction (given by $\bar{S}$ measured from the Earth-moon line) is primarily a function of the flight time. Variations in the flight time result in different alignments of the incoming asymptote direction and can be accomplished with only a small variation in Earth launch velocity. Freedom to orient the asymptote direction through prudent selection of the flight time widens the possiblity for zero plane change at the moon and generally reduces all the plane change requirements. This is shown in Fig. 2 where the flight time is allowed to vary from 3 to 5 days. For these flight times the orientation of the $\bar{S}_{in}$ vector with respect to the Earth-moon line is about 45° and 90°, respectively. In this analysis, the correspondence between these flight times and orientation angles is assumed linear, and the out-of-plane variation of $\bar{S}$ is neglected.

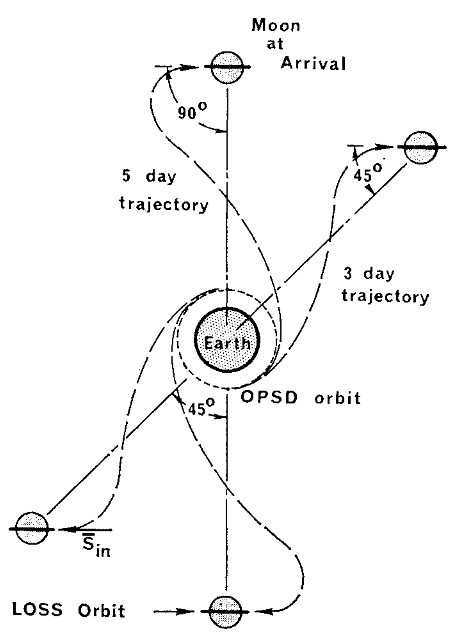

Fig. 2 Effect of variation of flight time on lunar encounter orientation.

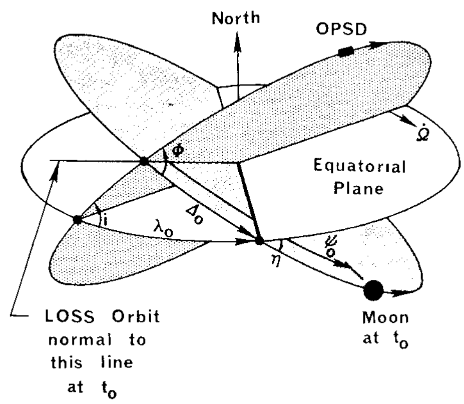

Fig. 3 The OPSD-Earth-Moon system.

The geometry which must be considered in the flight opportunity determination is shown in Fig. 3. In this OPSD-Earth-Moon system, the OPSD orbit, inclined i to the equator, regresses at a uniform nodal rate $\dot{\Omega}$ in the equatorial plane as prescribed by Eq. (1). The moon's orbit plane is also inclined to the equator plane with values of η ranging from 18.5° to 28.5°. The relative inclination ϕ of the OPSD and lunar orbit planes varies as the earth station orbit regresses and to a lesser degree as the moon's node and inclination change slowly over the years. The naught parameters given in Fig. 3 denote the geometrical conditions at time t_0.

Figure 4 geometrically illustrates the nonuniform nodal regression in the lunar orbit plane for $i = 30°$ and $\eta = 20°$. Since $\dot{\Omega}$ is a constant, the equatorial longitude of the OPSD ascending node λ_n (measured from the moon's descending node) always decreases at a uniform rate. However, the ascending node of the OPSD orbit in the lunar orbit plane given by Δ_n (also measured from the moon's descending node) does not change uniformly with time. Even if the lunar plane orientation is fixed, angle Δ_n will have identical periodicity with λ_n but will experience varying rates during the OPSD nodal regression cycle. This effect can be seen from Eq. (2)

$$\tan\Delta_n = \frac{\sin i \sin\lambda_n}{\cos i \sin\eta + \sin i \cos\eta \cos\lambda_n} \tag{2}$$

As successive OPSD orbital tracks cross the equator with uniform spacing (inertial longitude reference), the corresponding intersections with the lunar plane are nonuniform. As the cycle begins, the Δ_n steps are small implying a slow regression in the moon's orbit plane. As λ_n equal to $-180°$ is approached, the Δ_n steps become quite large implying a rapid regression. Note that the nonlinear regression for $-180° \geq \lambda_n \geq -360°$ is just the reverse of λ_n regression from

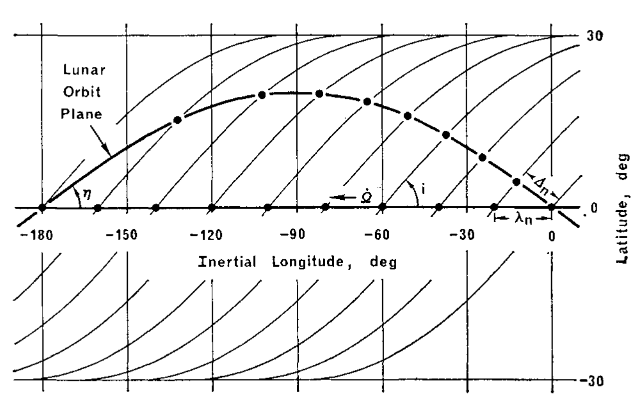

Fig. 4 Nonuniform nodal regression of the OPSD orbit in the lunar orbit plane.

0 to −180°. This nonlinear regression in the lunar orbit plane will produce a nonuniform spacing of flight opportunties.

The simplified technique used to determine the launch opportunities is graphically illustrated in Fig. 5. The non-uniformly regressing OPSD ascending node in the lunar orbit plane is presented by a point on the dashed inner circle, and the small empty circle on the inner circle represents the descending nodal point. By convention, the vertical axis in this figure is always normal to the LOSS polar orbit plane where, as in Fig. 2, the LOSS polar orbit is assumed to be normal to the lunar orbit plane. The outer circle denotes the counterclockwise (positive) motion of the moon about the Earth with a fixed angular rate ω_m equal to 13.176°/day.

In order to generalize the geometrical relationships of the problem, two initial orientation angles are specified. These are the naught parameters previously noted in conjuction with Fig. 3. As shown in Fig. 3, the orientation of the inertially fixed LOSS orbit is set by specifying a λ_0 value in the equatorial plane. This λ_0 value sets the initial OPSD orbit such that the LOSS orbit plane is normal to the nodal line determined by Δ_0 at time t_0 as shown in Fig. 5. The initial position of the moon at time t_0 is oriented with respect to this Δ_0 point by specifying ψ_0 as shown in Fig. 3.

The specification of the LOSS orbit plane being normal to the intersection of the OPSD orbit with the lunar orbit plane at time t_0 does not limit the generality of the results. As the OPSD orbit regresses through 360°, the line of intersection of the OPSD and lunar orbit planes rotates through 360° in the lunar orbit plane. Since the LOSS orbit plane is assumed to be inertially fixed normal to the lunar orbit plane, then it follows that regardless of any random orientation of the LOSS orbit plane, it must be normal to the intersection line twice during the cycling of the OPSD orbit plane. As a convenience in this analysis when this condition occurs, as in Fig. 3, the time is designated t_0, the orientation of the two planes is given by λ_0, and the moon is located at this time by ψ_0. Thus the designation of λ_0 is a simple method of varying the orientation of the LOSS orbit by essentially varying the epoch. Also note that the initial parameters λ_0 and Δ_0 are opposite in direction to the more general parameters λ_n and Δ_n.

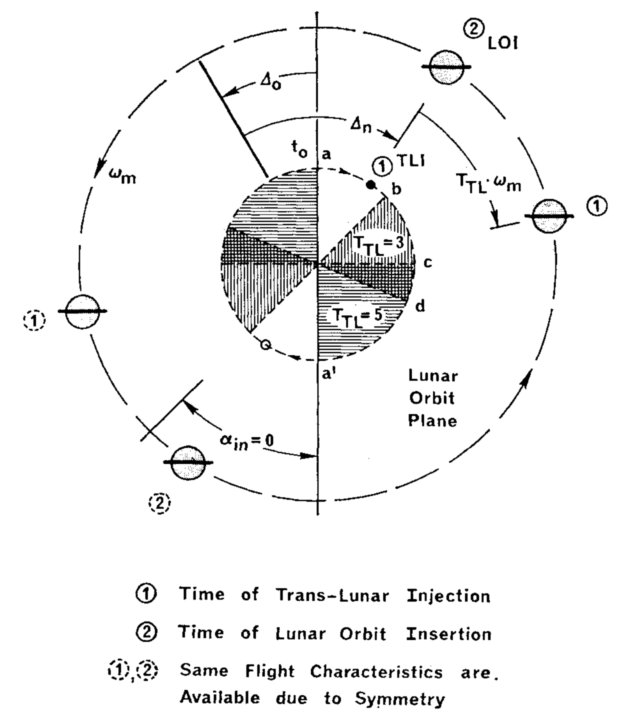

Fig. 5 Geometric relationships used in the determination of trans-lunar flight opportunities.

As a function of time from time t_0 the nodal points in Fig. 5 will move clockwise (negative) as the OPSD orbit regresses at a fixed rate in the equatorial plane. This nodal clockwise movement will be nonuniform and will be determined as a function of time from Eq. (2). If a launch opportunity occurs, as the nonlinear nodal point moves around the time of flight T_{TL} will be as noted in Fig. 5. In order to minimize the plane change requirement at lunar arrival, regions of fixed flight time and regions of variable flight time will be utilized. From "a" to "b" in Fig. 5 the flight time is assumed to vary linearly from 5 to 3 days. From "c" to "d" the flight time will vary depending on the position of the moon at launch time. A launch opportunity will occur when the moon is approaching the nodal point and is separated by an angle given by $T_{TL}\cdot\omega_m$. In this way the moon (projected on the celestial sphere) at arrival time will be coincident with the nodal point at launch time. This assures a no-plane change launch from the OPSD orbit.

For a given flight opportunity, the moon at the time of lunar orbit insertion (LOI) will be at the same angular orientation as the nodal point was at translunar injection (TLI).

Since the LOSS orbit is always normal to the vertical axis in Fig. 5, and since the orientation of the lunar incoming hyperbolic trajectory will be at an angle of 45° to 90° from the Earth-moon line depending on the flight time, the plane change requirement can be readily obtained.

This summarizes the technique which can be used to determine all the flight opportunities and the associated plane change requirements for a given set of initial conditions as a function of time. Numerical results could be obtained for all reasonable combinations of $\dot{\Omega}$, λ_0, ψ_0 and η if desired, but clearly such an approach would result in an unmanageable volume of data. A careful selection of parameter values for study is clearly in order.

The time required for the nodal point to cycle through 360° is defined as a regression period and is of course dependent on the regression rate $\dot{\Omega}$. Note that if the moon's position after one regression period were to shift an integral factor of 180° then after a finite period of time the initial geometries would repeat. The time required for this cycle to occur is defined as a recurrence period. Since the orbital rate of the moon ω_m is assumed to be constant, the time required for a recurrence period depends only on the nodal rate $\dot{\Omega}$. Table 1 shows recurrence periods for a range of selected values of nodal rates. Also shown are the circular orbit altitude-inclination combinations which will yield these selected values [Eq. (1)]. Notice the extremely long cycle durations for most of the nodal rates. However, if $\dot{\Omega}$ is adjusted to form a simple fraction ratio with the lunar rate ω_m, the recurrence period

Table 1 Selected values of the ratio $\omega_m/\dot{\Omega}$ and the resulting recurrence periods.

$\omega_m/\dot{\Omega}$	$\dot{\Omega}$ deg/days	Recurrence Period days	Altitude, naut miles 260	270	280
			Inclination, deg		
−39/20	−6.757	533	28.93	27.94	26.90
−47/24	−6.728	642	29.37	28.39	27.37
−59/30	−6.700	806	29.80	28.84	27.84
−71/36	−6.681	970	30.22	29.13	28.29
−79/40	−6.672	1079	30.63	29.27	28.74
−119/60	−6.644	1626	31.03	29.70	29.17
−2	−6.588	55	31.43	30.53	29.60
−25/12	−6.325	342	35.00	34.31	33.41
−17/8	−6.201	232	38.03	37.83	36.62
−9/4	−5.856	123	40.67	40.03	39.38
−5/2	−5.271	68	46.95	46.44	45.92
−3	−4.392	82	55.33	54.95	54.57

reduces to the regression period. This means that after the nodal point cycles through 360° the moon will have returned to its initial position of time t_0 (or 180° away).

These special cases, as noted in Table 1 for values of $\omega_m/\dot{\Omega} = -2$ and -3, are worthy of special consideration because they correspond approximately to the proposed OPSD low and high-inclination orbits. Moreover, it is possible to restrict a numerical study to these short cycles and determine the initial phase angles λ_0 and ψ_0 which result in flight opportunities with minimum plane change requirements at the moon. Once such a cycle is established it could be assumed to repeat over many years of shuttle operations. Such a numerical study was performed for $\omega_m/\dot{\Omega} = -2$. For this ratio, the nodal point completes one revolution in 54.6 days during which time six launch and return opportunities occur. For a given initial lunar position angle ψ_0 and orientation of the moon's descending node, given by λ_0, the launch and return characteristics can be determined for any 54.6 day cycle.

In order to determine a specific geometry for the most favorable mission sequencing, data were developed in two steps. First, the lunar arrival and departure plane change requirements as a function of the initial position angles λ_0 and ψ_0 were scrutinized to determine flight opportunities with minimum plane change requirements. The cases with most favorable plane change requirements were then examined to reveal shuttle mission timing characteristics.

Using this procedure, a very favorable geometry was uncovered. Figure 6 presents curves of the lunar plane change requirements for each of the six lunar incoming and outgoing flight opportunities which would occur during a 55 day recurrence period. In this figure, the initial position angle λ_0 is 0° or 180° and the initial lunar position angle ψ_0 ranges from 0° to 180°. Note that for an initial lunar position angle of 90° during the 55 day cycle two launch and return opportunities occur which require no plane changes. In addition, there is an additional launch and return opportunity with about a 12° plane change requirement.

The next step is to consider a timing schedule of this case as presented in Fig. 7. The lower part of the figure shows launch opportunities (solid lines) and return opportunities (dashed lines) during the cycle, with the time of flight being the difference between the arrival and departure times. The upper portion of the figure shows the plane changes necessary at lunar arrival and departure corresponding to the flight opportunities. Notice that neither the launch nor return opportunities are evenly spaced with time because of the nonuniform OPSD nodal rate in the moon's orbit plane. However, six launch and six return opportunities do indeed exist in the 55 day cycle—an average of about 9 days between opportunities as predicted by the uniform nodal rate analysis of Ref. 4.

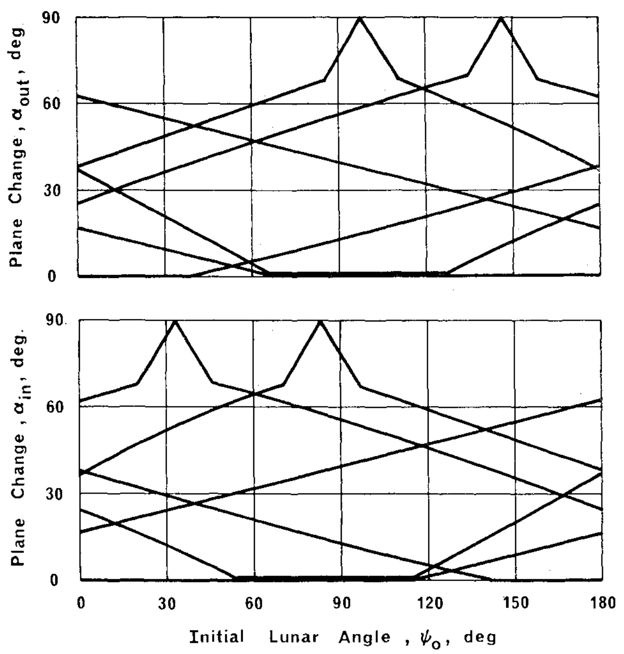

Fig. 6 Plane change requirements for the six flight opportunities for $\omega_m/\dot{\Omega} = -2$, $\lambda_0 = 0$, 180°.

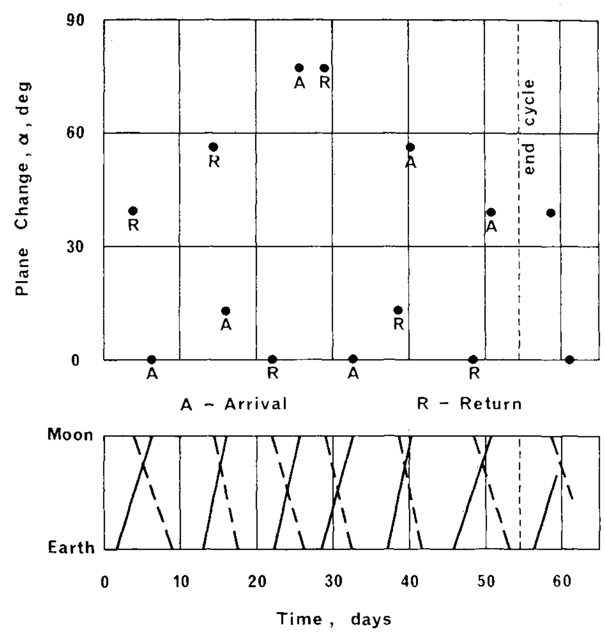

Fig. 7 Launch and return opportunities for $\omega_m/\dot{\Omega} = -2$, $\lambda_0 = 0$, 180°, $\psi_0 = 90°$.

Earth Station Orbit Selection

In the previous discussion it was pointed out that for integer ratios $\omega_m/\dot{\Omega}$, OPSD-lunar synchronization occurs. It is also possible to synchronize the OPSD orbit with the rotation of the Earth in order to achieve rendezvous compatibility with a ground launch site.

In a general, rendezvous situation when the target vehicle comes closest to the launch site, the orbit is often not coplanar with the launch site. If launch is delayed until the orbit plane contains the launch site, it is unlikely that the target vehicle will be at the appropriate point in the orbit for immediate rendezvous. Thus, a phase angle lag or lead will occur which must be reduced to zero by a series of in-plane maneuvers which, while not as costly as plane change maneuvers, may require many orbital revolutions to be economical. With rendezvous compatibility, a coplanar launch with appropriate phasing for immediate rendezvous may be made into the OPSD orbit each day.

Rendezvous compatibility can be obtained by selecting the proper combination of OPSD nodal rate and orbital period which synchronizes with the rotation rate of the Earth. Since both nodal rate and period depend upon inclination and altitude over the oblate Earth, it is possible to find many inclination-altitude combinations which satisfy the 15 revolution closure criterion.[10]

Figure 8 presents a plot of the nodal regression rate as a function of inclination for a range of altitudes. The locus of one day rendezvous compatible orbits is seen to lie in an altitude range near the proposed 270 naut miles altitude. The loci of $\omega_m/\dot{\Omega} = -2$ and -3 (moon synchronized OPSD orbits) are also shown. The intersections of the moon synchronization loci with the rendezvous compatible loci

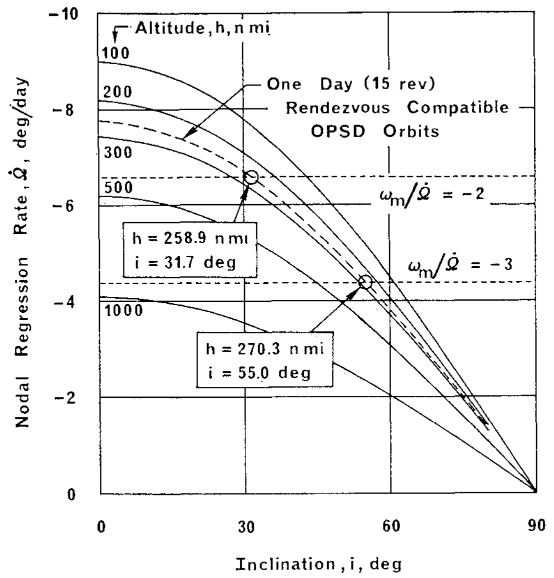

Fig. 8 Determination of most favorable OPSD orbital parameters for low and high inclinations.

designate the most favorable altitude-inclination combinations for the OPSD orbit as 1) 258.9 naut miles, 31.7° and 2) 270.3 naut miles, 55.0°, a result also obtained in Ref. 7.

Development of a Typical Mission Plan

With OPSD-moon synchronization and careful selection of the OPSD and LOSS orbit orientation, the initial favorable geometry will repeat almost indefinitely, assuming occasional minor orbit adjustments. Moreover, Earth synchronization of the recommended OPSD orbit will continue as well, and thus it is possible to establish a mission plan for an initially favorable cycle which would persist for as long as desired. Selected round trip opportunities which were obtained from Fig. 7 are presented in Fig. 9. Two round trip lunar shuttle missions are shown per 55 day period with 6 day lunar stay times and with flight times of 3 and 4.1 days. The maximum plane change required is about 12° which can be reasonably handled by single-impulse lunar capture and escape methods, hence the time-consuming three-impulse maneuver[6] may be avoided in this instance.

Figure 10 demonstrates a typical shuttle schedule involving two vehicles. The geometry of this Earth-moon-OPSD-LOSS

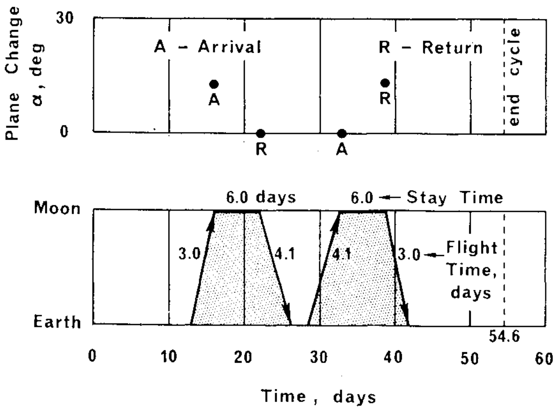

Fig. 9 Mission plan for a 55 day recurrence cycle, $\omega_m/\dot{\Omega} = -2$, $\lambda_0 = 0$, 180°, $\psi_0 = 90°$.

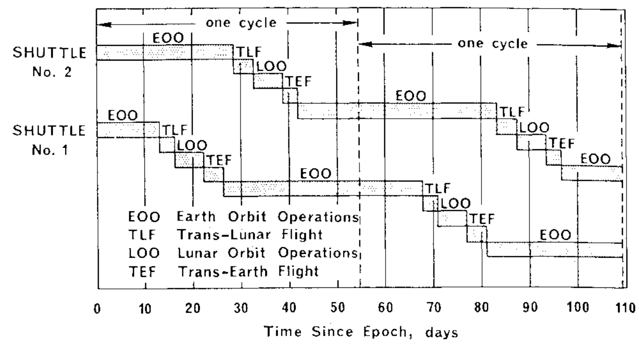

Fig. 10 Shuttle utilization for a 55 day cycle, $\omega_m/\dot{\Omega} = -2$, $\lambda_0 = 0$, 180°, $\psi_0 = 90°$.

system gives rise to a grouping of the round trips toward the center of each 55 day cycle as shown in Fig. 10. Thus, the short turnaround after the first round trip mission presumably precludes the use of a single shuttle vehicle for performing the two missions per cycle because of refueling, checkout and transfer of cargo and crew. However, two vehicles can accomplish the mission quite adequately in a leap-frog fashion. For this low-inclination OPSD orbit, 13 missions per year may be scheduled as indicated. For a 55° OPSD 10 missions per year are possible, although that mission plan is not presented here.

Conclusions

Space shuttle operations between an OPSD in an inclined, regressing Earth orbit and a LOSS in an inertially fixed lunar polar orbit pose a new set of problems beyond those considered in Apollo. Analysis of flight opportunities and mission characteristics for the lunar shuttle is not merely an extension of the trajectory studies performed for Apollo, and consequently, new analysis techniques have been required.

Despite the restrictions imposed by orbit-to-orbit shuttle operations, the lunar shuttle concept does appear to be feasible. In the analysis and the typical mission plan it was demonstrated that, by a judicious selection of initial parameters, a good cyclical translunar and trans-Earth flight opportunities can result which involve no plane changes departing from or returning to the OPSD orbit and minor or no plane changes at LOSS orbit insertion or escape. Moreover, these flight opportunities utilize reasonable transit times (from three to five days in each direction), reasonable lunar stay times (six days for the typical mission plan described), and near minimum energy trajectories (total round trip ΔV is less than 28,000 fps[11]). The missions are repeatable on either two or three month cycles, depending on OPSD inclination, and the frequency of favorable flight opportunities is consistent with envisioned lunar traffic models. However, it should be pointed out that because of the motion of the Earth-moon system about the sun, the sun angle will change from cycle to cycle. This could place a limitation on some mission opportunities and will require future consideration along with other refinements.

Finally, an important conclusion can be drawn for the design of the OPSD and LOSS orbits. It was shown in the analysis that moon synchronization is necessary in order to obtain cyclical flight characteristics. Also, Earth synchronization, or rendezvous compatibility, is desirable for efficient transportation between the Earth and the OPSD. Both synchronizations can be simultaneously realized by an appropriate selection of OPSD orbit altitude and inclination. Also by a proper selection of initial orientations (represented by the plase angles λ_0 and ψ_0), favorable mission characteristics which repeat indefinitely can be established. Since slight OPSD altitude and inclination adjustments do not significantly alter mission characteristics or velocity requirements for geosynchronous or interplanetary flights, it would seem reasonable to adopt the Earth-moon synchronized parameters recommended in this paper for the OPSD Earth station orbit.

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