# ORBIT CONCEPTS FOR LUNAR NAVIGATION AND COMMUNICATION

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In the last years space agencies have shown their interest in exploring the Moon. The possible discover of water next to the lunar South Pole, the possibility of establish a robotic-astronomic observatory in the far side, away from the terrestrial noise, and progress in technologies for transportation and in-situ resource utilization have encouraged the space agencies to establish long-term programs for the Moon exploration. Any lunar mission will require communication and navigation elements. But spacecraft based communication and navigation architectures have to take into account the peculiarity of the lunar environment. In this paper the effects of the lunar gravity field and the proximity of the Earth on the design of stable orbits around the Moon as well as the feasibility of using halo orbits for a lunar navigation infrastructure are described.

Several studies developed in recent years set up the same qualitative conclusions. Starting from the planetary equations and gravity field data measured by Lunar Prospector these studies show the existence of frozen orbits, as those orbit whose argument of periapsis and eccentricity remains in the frame of two fixed limits, termed the frozen points. These orbits have a minimum inclination. Below of it, the orbits are no longer “frozen” and turn into spirals. The drift of the orbit parameter depends on the eccentricity. High elliptical orbits in high inclination $e$= 0.6, $i$= 56.2 º are quite stable, however, circular stable orbits has also been found e=0.05 i= 40º.

Halo orbits are special orbits near the Lagrange points L1, L2 or L3. Halo orbits near the Moon L2 point present several advantages like a constant line of sight with the Earth, a low cost insertion and the feasibility of being easily modified. The instability is the most important disadvantage. These orbits have been proposed for lunar communication and navigation with two purposes. The first purpose is to achieve the so called “Liaison Navigation”, a new kind of navigation which carries out positioning by satellite to satellite tracking using the asymmetry of the force field of the third body problem. The second purpose is to provide a continuous communication link between the Earth and the Moon.

Comparison between the two types of orbits depends on the navigation system and the accuracy required. GNSS and Doppler techniques can be adapted to a halo or conical configuration while “Liaison Navigation” requires at least one satellite in a halo orbit. A hybrid constellation where the navigation service would be carried out by satellites in conical orbits, and the communication by a satellite around L2 seem to be the most promissory option.

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# 1. ORBITS

The Moon's gravity field is mainly affected by three irregular forces, the Earth, masscons and Jupiter. Current knowledge of the lunar gravity field has come principally from radio-tracking data providing by orbiting lunar spacecrafts. As the trajectory of the spacecraft is perturbed by mass excesses or deficiencies, the orbit is changing along its path; these changes can help us to understand the real shape of the gravity field. The field is modelled as a series of spherical harmonics. These harmonics depends on the longitude, latitude and altitude of the point over the Moon's surface. Considering just the influence of the altitude we can simplify the lunar gravity field in three different levels. Next to the surface, below 100km, masscons are the main influence, and it is possible to neglect the force of the Earth, within 100km and 750km of altitude, both origins, the masscons and the Earth should be considered, above 750km, masscons could be completely ignored. Consequently the suitable type of the orbits around the Moon, elliptical, circular, etc changes with the altitude. In this section we focus our attention on orbits located in the third frame,

Halo orbits are free of these considerations and their study can be achieved using the current expression of gravity field with a significant level of accuracy.

## 1.1 Frozen Orbits

Recently, there has been a huge increase of papers focused on frozen orbits around the Moon. Folta and Quinn [1] offer a general analytical model for orbits located above an altitude of 750km which confirms most of the results of previous papers. Throughout this discussion we will use a Moon-centred universe as shows in Figure1. In this model the system of reference is the *Earth Orbit Frame*, z-axis is parallel to the normal of the apparent motion of the Earth around the Moon.

| | |
|---|---|
| $i$ Inclination | $\Omega$ Right Ascension |
| M Mean anomaly | $\omega$ Argument of periapsis |
| $\upsilon$ True anomaly | $\theta$ Argument of latitude |

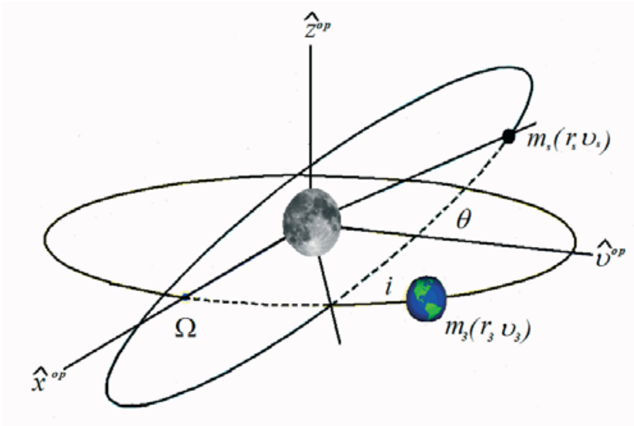


Figure 1: Orbit element expressed in the Earth Orbit Plane Frame. Lunar Frozen Orbits. David Folta and David Quinn [1]

Frozen orbit are considered as orbits with no long-term changes in eccentricity and argument of perigee. [2] Including the Earth in the planetary equations of Lagrange as a 3rd body perturbation and setting to zero the rate of eccentricity and argument of periapsis as follows [1]:

$$\frac{\partial e}{\partial t} = \frac{15}{8}\frac{n_3^{\,2}}{n} e\left(1-e^2\right)^{\frac{1}{2}} sin^2 i \, sin\, 2\omega \quad (1)$$

$$\frac{\partial \omega}{\partial t} = \frac{3}{16}\frac{n_3^{\,2}}{n}\frac{1}{\left(1-e^2\right)^{\frac{1}{2}}}\Big[\left(3+2e^2+5\,cos\,2i\right)$$

$$+5\left(1-2e^2-cos\,2i\right)cos\,2\omega\Big] \quad (2)$$

Where n3 represents the mean motion of the Earth around the Moon [3]

The conclusion shows that [1]:

The rate of eccentricity is zero for equatorial and circular orbits

For orbit whose periapsis is ω= 0º,90º,180º and 270º.

- w= 0º or 180º periapsis rate is zero just for e=1, an escape orbit.
- w= 90º or 270º periapsis rate is zero when:

$$e = \left(1 - \frac{5}{3} cos^2 i\right)^{\frac{1}{2}} \qquad (3)$$

This formula, the frozen condition, defines the critical angle of inclination, as eccentricity is constrained in the frame (0-1) the inclination has to be higher than 39.2º. Below this value there are no frozen orbits. In Figure 2 we can see the consequence of locating a satellite in an orbit with a lower inclination, 20º, according to Ely and Lieb [3] the satellite describes a circulating orbit

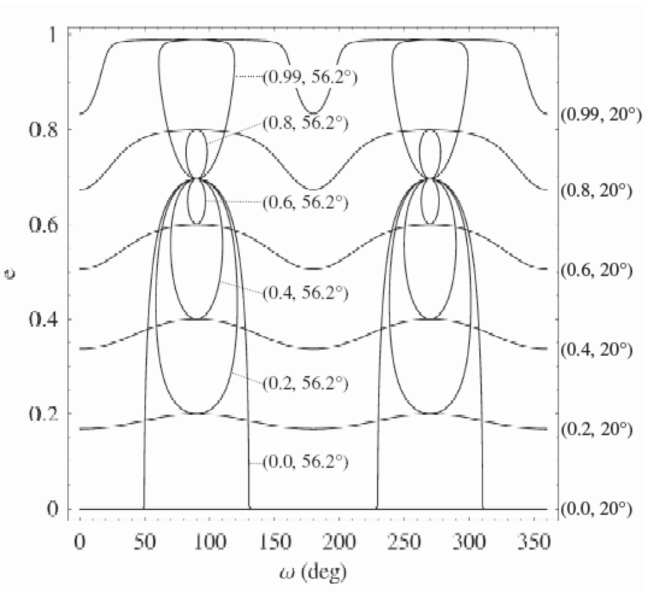


Figure 2 Trajectories in the (e−ω) phase plane for selected initial values of eccentricity and inclination (e,i). Todd A. Ely and Erica Lieb [3]

To study the evolution of frozen orbit, which accomplish the frozen condition, it is necessary to integrate the perturbation equations. The results can be plotted in a polar diagram [1] showing the evolution of eccentricity and argument of periapsis along time. Vertical axis is esinω and horizontal axis is ecosω.

Let us consider a satellite located in an orbit of ω= 90º. The initial inclination will be 45º and the eccentricity 0.6. This pair of parameters does not satisfy the frozen condition, indeed the proper pairs would be (e=0.6, i=51.707º) and (e=0.4082, i=45º). These pairs are called the frozen points. According to Figure 3 the satellite will change between their two frozen points describing a circle is shown. If the inclination decreases the variation of eccentricity and periapsis increase. Below the critical value the W is unstable. Figure 3 shows a complete evolution map for orbit of e=0.6 and ω=90º. As we can see if the inclination increases the orbit shows an oscillating pattern.

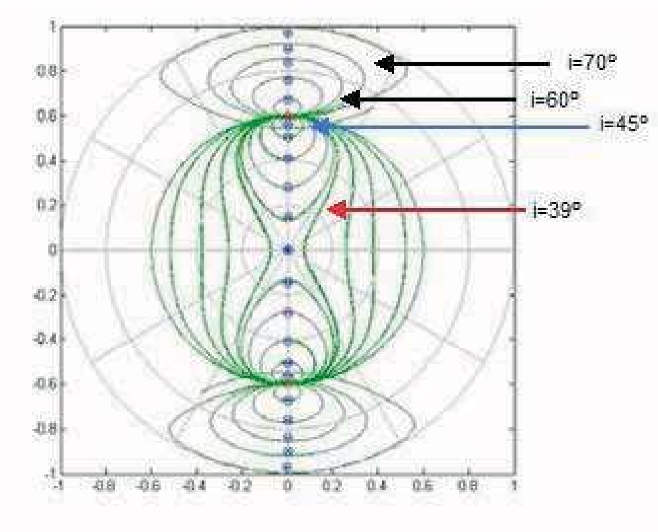


Figure 3 Long term *e* - ω evolution over 3000 days for ω =90°, *e*=0.6, *i*= from 80º to 0º Lunar Frozen Orbits. David Folta and David Quinn. [1]

Expanding the analysis to other eccentricities, it is observed that the critical inclination remains the same but the evolution circles move in order to satisfy the frozen condition while the critical inclination remains the same [1] as we can see in Figure 4.

The main goal of the evolution maps of Folta and Quinn is to show the predictive pattern of frozen orbits in a comprehensive way.

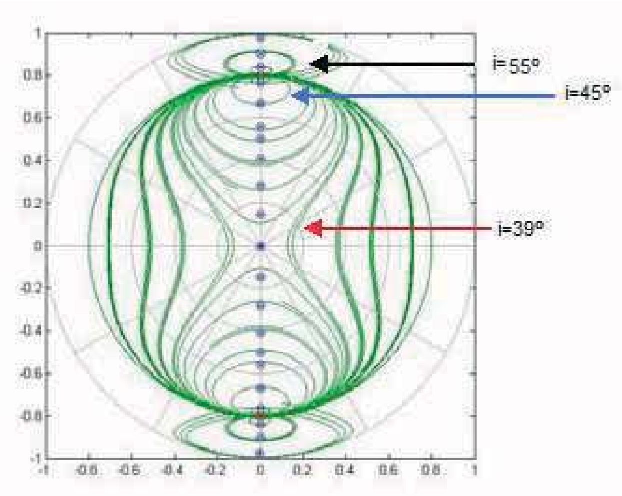


Figure 4 Long term *e* - ω evolution over 3000 days for ω =90°, *e*=0.8, *i*= from 80º to 0º Lunar Frozen Orbits. David Folta and David Quinn. [1]

### 1.2 Halo Orbits

The use of halo orbits instead of circular orbits as a relay constellation provides many advantages:

- Satellites located in halo orbits always have a line of sight with the Earth
- Satellite around L2 can cover the far-away side of the Moon
- Just a few orbiters are required to provide global coverage
- Satellites in halo orbits area always under a constant sun exposure.
- Due to invariant manifold, the satellites in halo orbits can easily move to a different halo orbit, just with a small quantity of fuel. The constellation can evolve in a very simple way.

Halo orbits are a particular solution of the third body problem, whose real solution is an invariant manifold surface. These manifolds can be assumed as smooth tubes, one of the slides would be the halo orbit. It is quite easy for a satellite to fall off from its orbit and move away on this virtual surface, but for the same reason it is quite simple to find huge variety of insertion orbits. The proper Ballistic Lunar Transfers require but 15% less energy, than conventional Hoffman and allows carrying around 30% more of payload [4]

### 1.3 Keplerian Constellations

Several constellations have been proposed to achieve communication and navigation services.

According to their maps Folta and Quinn have built, two constellations of 45º of inclination, its corresponding eccentricity 0.4082 and a semi-axis of 8049 km [1]. These two orbits, of 8 and 12 satellites respectively could provide a global coverage. [Table 1 and 2] Ely and Lieb also propose several constellations, two of them quite stable. A circular orbit with six satellites located in two orbital planes of 40º of inclination a semi-mayor axis around 7500 km providing a 2 fold of coverage for the 95.5% of the lunar surface and a 45.5% with a 3 fold of coverage. [Table 3] And an elliptical constellation of 0.6 eccentricity with three satellites to cover the South Pole, this configuration, according to the conclusion of Ely and Lieb, will remain stable without any deterministic control to correct the effects of the gravity or the solar pressure [3]. [Table 4]

## 2. NAVIGATION TECHNIQUES

From the signal emitted by a satellite it is possible to achieve the measurement of two magnitudes, the distance from the satellite to the observer, and the relative velocity of them. The first is obtained from the time that it takes the signal in arriving to the observer, GPS, GLONAS etc, and the second from the drift of the frequency of this signal due to Doppler Effect, TRANSIT, DORIS, TSIKADA, etc. Finally there is third kind of navigation, LiAISON (Linked, Autonomous, Interplanetary Satellite Orbit Navigation) that allows to two satellites, one of them in a halo orbit, to carry navigation by satellite-to-satellite techniques. So, the type of constellations, halo or Keplerian and the kind of navigation are not independent decisions

### 2.1 Doppler Navigation

Satellites emitted a continuous signal that can be tracked by a user on the Moon. Due to the Doppler shift the relative velocity of the user and the source is calculated. As the satellite position is known, users can locate themselves with respect to the satellite. Carrying out several measurements along a satellite pass, users can achieve a positioning accurately. Doppler navigation can be successfully achieved with six satellites, (TRANSIT) cheaper than GPS. This technique will require slight adjustment for the Moon.

### 2.1.1 Effects of the non-circularity

Most important differences in Doppler navigation is the effect of the non-circularity of the orbits. The Doppler formula is [5]:

$$f_r = f_s\left(1 - \frac{\dot{r}}{c}\right)\left(1 + \frac{v^2}{2c^2} + \frac{3v^4}{8c^4} + \cdots\right)$$

(4)

| | |
|---|---|
| *fr* | Frequency received by user |
| *fs* | Frequency emitted by satellite |
| $\upsilon$ | Velocity of the satellite |
| c | Velocity of the speed |
| $\dot{r}$ | Velocity of the user |

Usually this formula is truncated like;

$$f_r = f_s\left(1 - \frac{\dot{r}}{c}\right) \qquad (5)$$

This result is the same when using radial velocity and ignoring the angular one, in other words, if the angle formed by the trajectory of the satellite and the line joining the satellite and the receiver is around 90°, the truncation would be valuable. In the Earth, where our navigation satellites are located in circular orbits, the truncation of the formula is acceptable, but for halo and high elliptical orbit this truncation might not be so simple.

Second consideration concerns the integration of the Doppler count. In previous systems, TRANSIT, DORIS ,etc each Doppler count had the same length; this is based on the fact that orbits are circular, so that the frequency shift for one count is similar for the next one. This is not necessary true for halo and high elliptic orbits, a Doppler count on a high point of the orbit where the acceleration is at a maximum would be bigger than the count in the moment when the satellite is next to the equatorial plane. A priori there is no point in using the same count's length if the orbit is not equal. The time clock of the oscillator might be adjusted to the satellite position in order to optimize the Doppler count.

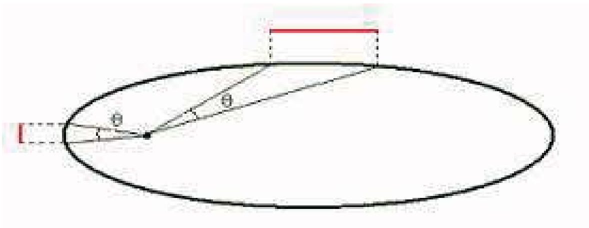


Figure 5 Different lengths for the same Doppler count

### 2.1.2 Frequency Dispersion

Assuming that the electric system is well protected, the signal will be emitted in the correct frequency. Along its way towards the receiver, the signal is going to suffer frequency dispersion; as a result, the incoming signal, is now a collection of signal whose frequencies are around a main value, the initial frequency. The receiver has to identify the shift due to the Doppler Effect from the dispersion.

## 2.2 GNSS Navigation

Orbits around the Moon appear a very good option for a GNSS constellation in the same way than in the Earth. These circular orbits can be combined with high elliptical or halo orbits to create a hybrid constellation.

### 2.2.1 GNSS modifications

- Two way navigation system.

Two-way navigation system can avoid the burden of using an ultra-stable oscillator in the receiver. [6]

- Doppler effect in the carrier

The Doppler Effect causes a drift in the frequency of the carrier signal; if the resulting frequency cannot be tracked by the receiver the satellite would be useless. For satellites in circular orbits we can accept the signal coming from satellites whose elevation angle is constrained above a critical angle. If we have a satellite in a halo or elliptical orbit, we have to consider that the Doppler Effect is caused only along the line joining the satellite and the receiver so there will be necessity to study the drift in these orbits. This drift will depend on the relative position of the user and the satellite, considering the velocity of the user neglected in comparison with the satellite velocity. The receiver should carry a tracking system able to change the frequency of the searching system depending on the expected position of the satellite. [7]

- Dilution of precision

The dilution of precision is currently defined for circular orbits but the combination with of halo orbits makes the current dilution formula useless. Since the satellite needs to be located in frozen or halo orbits whose location is not easily chosen, the dilution of precision can be quite high, the individual solutions are quite poor, but dynamic smoothing with a Kalman estimator can provide better navigational fit. [6] [7]

- Synchronization

Synchronization, in the case of GNSS, is a fundamental part of the technique. Because of the effect of the solar wind on the oscillator, the protection of the clocks in the satellite and receiver is critical. It would be also possible to achieve the timing form the Earth. (See 2.2.2)

The main difficulties to achieve GNSS navigation are the loss of the signal, the frequency dispersion due to solar wind and the drift of the frequency by the Doppler Effect. All these matters have been studied by Carpenter, Folta, Quinn and Moreau [7] in their research of the use of GPS navigation in halo orbit. It points the feasibility of creating a navigation system in L2 and L1. Supposing a spacecraft in a transfer orbit between the Earth and the Moon, and also other spacecraft in the vicinity of L2,, the results suggest that the filter identifies the correct signal despite of the loss of the signal and its residuals are uncorrelated. It concludes that the accuracy for a satellite around L1 would be around 1km. Navigation in L2 should be also possible under certain constrains of code.

### 2.2.2 Terrestrial GPS signal in the Moon

The side lobes of the terrestrial GPS signals arrive to the Moon's surface. This signal could be used to achieve the timing of the satellite located there; satellites could also track themselves using the incoming signal from the Earth. As expected terrestrial signals are quite weak on the Moon, the proper amplifier and Costas filter introduce noise into the receiver. GPS carrier signal in the classical frequencies L2 and L1 can hardly overcome the constraints imposed by the Costa filter and DDL loop. The use of L5 as a carrier will allow the use of the terrestrial GPS signal in the Moon. [6]

## 2.3 LiAISON Linked, Autonomous, Interplanetary Satellite Orbit Navigation.

LiAISON is a promissory technique which establishes the feasibility of achieving an absolute position of a user from the relative position of two satellites located, or at least one of them, in a halo obit. Halo orbits, due to the consequences of the perturbation of the third body, have a single shape and size and have just one orientation in respect to the Earth or the Moon. [8] According to this, if two satellites are located in halo orbits (or at least one of them) and achieve SST (satellite to satellite tracking) the information provided by the gravitational force of the third body would allow to calculate absolute position and motion of both satellites simultaneously.

As this method is based on the asymmetry of the orbits, these ones should be as asymmetric as possible, there are some constraints that the satellite must observe:

- Spacecrafts should be separated by relatively large distances.
- Constellation orbits cannot be coplanar.
- Constellations with shorter orbit periods lead to quicker convergence.
- Constellations with more spacecraft lead to quicker convergence.
- Tracking spacecraft with circular/elliptical and halo orbits converge faster than just with a halo orbit
- Satellites in the same halo orbit should be located not in symmetric positions

Keric Hill [8] simulates the performances of a quite simple navigation system composed by two satellites, Woodstock in a low circular orbit and Snoopy in a halo orbit LL2. The general patter is that the position error for Snoopy was 78 m and for Woodstock the position error was just 6.9 m although it convergence requires about 3-6 days for Snoopy and about 2 days for Woodstock.

The promissory simulations results as well as the low cost of insertion for halo orbits have encourage several researches to build more halo orbits for LiASION navigation. All of them arrive to similar performances, LiASION constellation provides a global coverage with a low cost insertion and manoeuvring but the large time of convergence and the instability are their main difficulties. [9] [10] [11]

## 3 CONCLUSIONS

The research into Lunar Navigation seem to be divided into two groups, classical, with frozen orbits suitable to GNSS and Doppler navigation, and LiASION with halo orbits.

Frozen orbits pattern has been described in detail although orbits below 500km require deeper study, these orbits have the advantage to be suitable for classical navigation techniques .Main difficulties pointed for GNSS and Doppler are attached to the loss of the signal and drift of frequency whish actually also happen for LiASION navigation.

LiASION navigation is a low-cost flexible navigation technique with a promissory simulation results. It mains disadvantages are the instability of orbits and convergence times and specially the lack of empirical testing. The main goal of the halo configuration is the constant line of sight with the Earth.

A hybrid constellation is proposed to compensate the difficulties of both configurations. Navigation can be achieved by satellites located in frozen orbits, while communication is relayed on a L2 satellite. The Doppler technique, cheaper than GPS, provides a navigation service. When “frozen satellites” are passing over the near side of the Moon the signal can be directly broadcast to the Earth, and over the far side, the L2 satellite will receive and communicate the data to the Earth. And as this satellite is in halo orbit, LiAISON navigation can also be tested. In Figure 6 the frozen constellation corresponds to Ely and Lieb six satellites constellation.

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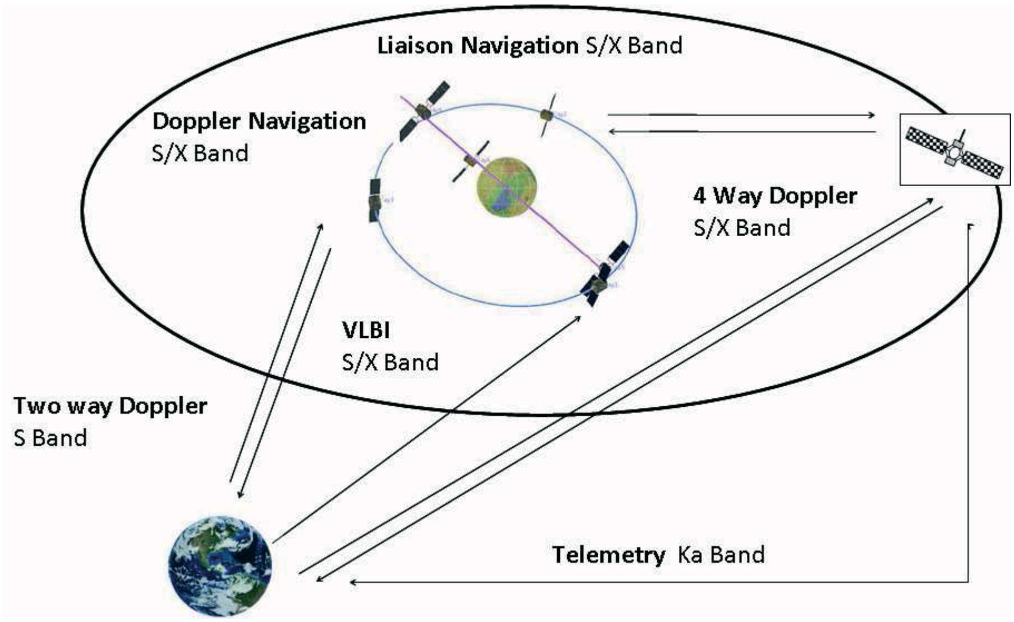


Figure 6. Constellation for Navigation (by Doppler and Liasion) and communication services. The image of the navigation constellation corresponds to Ely and Lieb [3]. Table 3.

## TABLES

Table 1 Lunar Frozen orbits. AIAA2006-6749 David Folta and David Quinn

| S/C | Plane | Orbit | Period | a (km) | e | i | Ω | ω | M |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 18hr | 8049 | 0.4082 | 45º | 0° | 90° | 0° |
| 2 | 1 | 1 | 18hr | 8049 | 0.4082 | 45º | 0° | 90° | 180° |
| 3 | 1 | 2 | 18hr | 8049 | 0.4082 | 45º | 0° | 270° | 0° |
| 4 | 1 | 2 | 18hr | 8049 | 0.4082 | 45º | 0° | 270° | 180° |
| 5 | 2 | 3 | 18hr | 8049 | 0.4082 | 45º | 180° | 90° | 132° |
| 6 | 2 | 3 | 18hr | 8049 | 0.4082 | 45º | 180° | 90° | 228° |
| 7 | 2 | 4 | 18hr | 8049 | 0.4082 | 45º | 180° | 270° | 132° |
| 8 | 2 | 4 | 18hr | 8049 | 0.4082 | 45º | 180° | 270° | 228° |

Table 2 Lunar Frozen orbits. AIAA2006-6749 David Folta and David Quinn

| S/C | Plane | Orbit | Period | a (km) | e | i | Ω | ω | M |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 18hr | 8049 | 0.4082 | 45º | 0° | 90° | 0° |
| 2 | 1 | 1 | 18hr | 8049 | 0.4082 | 45º | 0° | 90° | 150° |
| 3 | 1 | 1 | 18hr | 8049 | 0.4082 | 45º | 0° | 90° | 210° |
| 4 | 1 | 2 | 18hr | 8049 | 0.4082 | 45º | 0° | 270° | 0° |
| 5 | 1 | 2 | 18hr | 8049 | 0.4082 | 45º | 0° | 270° | 150° |
| 6 | 1 | 2 | 18hr | 8049 | 0.4082 | 45º | 0° | 270° | 210° |
| 7 | 2 | 3 | 18hr | 8049 | 0.4082 | 45º | 180° | 90° | 0° |
| 8 | 2 | 3 | 18hr | 8049 | 0.4082 | 45º | 180° | 90° | 150° |
| 9 | 2 | 3 | 18hr | 8049 | 0.4082 | 45º | 180° | 90° | 210° |
| 10 | 2 | 4 | 18hr | 8049 | 0.4082 | 45º | 180° | 270° | 0° |
| 11 | 2 | 4 | 18hr | 8049 | 0.4082 | 45º | 180° | 270° | 150° |
| 12 | 2 | 4 | 18hr | 8049 | 0.4082 | 45º | 180° | 270° | 210° |

Table 3 Constellations of Elliptical Inclined Lunar Orbits Providing polar and Global Coverage. Todd A. Ely and Erica Lieb. ASS/IAAA. Paper AAS 05-343

| S/C | Plane | Orbit | Period | a (km) | e | i | Ω | ω | M |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 16hr | 7500,0 | 0,05 | 40° | 0° | 90° | 0° |
| 2 | 1 | 1 | 16hr | 7509,334 | 0,05 | 40° | 0° | 90° | 120° |
| 3 | 1 | 1 | 16hr | 7499,223 | 0,05 | 40° | 0° | 90° | 240° |
| 4 | 2 | 2 | 16hr | 7500,00 | 0,05 | 40° | 90° | 270° | 0° |
| 5 | 2 | 2 | 16hr | 7494,68 | 0,05 | 40° | 90° | 270° | 120° |
| 6 | 2 | 2 | 16hr | 7504,82 | 0,05 | 40° | 90° | 270° | 240° |

Table 4 Constellations of Elliptical Inclined Lunar Orbits Providing polar and Global Coverage. Todd A. Ely and Erica Lieb. ASS/IAAA. Paper AAS 05-343

| S/C | Period | a (km) | e | I | Ω | ω | M |
|---|---|---|---|---|---|---|---|
| 1 | 12hr | 6541.4 | 0.6 | 56.2° | 0° | 90° | 0° |
| 2 | 12hr | 6543.97 | 0.6 | 56.2° | 0° | 90° | 120° |
| 3 | 12hr | 6537.92 | 0.6 | 56.2° | 0° | 90 | 240° |