LOW-COST LUNAR COMMUNICATION AND NAVIGATION

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Spacecraft in halo orbits near the Moon could relay communications for lunar missions on the far side or poles of the Moon. Autonomous orbit determination and low-energy orbit transfers would significantly lower the cost of establishing and maintaining small lunar communication relay constellations in halo orbits. Autonomous orbit determination would allow the constellation to navigate without expensive Earth-based tracking assets. For libration point orbits, both relative and absolute autonomous orbit determination is possible using only satellite-to-satellite tracking such as crosslink range or Doppler. The spacecraft could be used as mobile tracking stations to provide navigation as well as communications. Low-energy lunar transfers could be used to place more mass into lunar halo orbits than conventional trajectories, and using these low-energy transfers, it should be possible to launch the entire constellation on a single vehicle.

Introduction

The lunar south pole and the Aitken Basin are high-priority targets for lunar surface operations. Ground stations at Earth almost never have direct line-of-sight to either the south pole or the Aitken Basin, which rules out direct communication with the Earth. Without communication, manned missions to those locations on the Moon would be impractical and operation of robotic rovers would be impossible.

During the Apollo program, Farquhar proposed placing a satellite in a halo orbit at Earth-Moon L_2 to provide communications for the far side of the Moon.[1] Carpenter, et al. described how a constellation of four spacecraft in Earth-Moon L_2 halo orbits could provide continuous coverage of the lunar far side and the poles.[2] Grebow, et al. showed how just two spacecraft in Earth-Moon L_2 halo orbits can provide constant coverage of the lunar South Pole region.[3] However, these useful libration point orbits come with several challenges.

One challenge is that a constellation usually requires multiple launches to place spacecraft in the proper orbits. Each launch adds expense and could lead to delays for other lunar missions that would be dependent on the constellation.

Another challenge is that the use of these unstable halo orbits requires frequent stationkeeping maneuvers. For lunar halo orbits, these maneuvers would need to be performed at least every three to five days. A significant amount of tracking data must be obtained between every maneuver for proper orbit determination. The ground operations costs for a whole constellation of communication relay spacecraft could be significant.

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This paper presents methods for meeting the challenges of lunar libration point missions and also using the flexibility of libration orbits to great advantage to make the the entire exploration of the Moon safer and more efficient.

Autonomous Navigation in Libration Point Orbits

In response to the high cost of Earth-based tracking and maneuver design, it would be advantageous to reduce ground operations costs by making deep space missions more autonomous and by providing more in situ tracking resources. A new method of autonomous orbit determination could be used for just such purposes. Spacecraft in libration orbits can use scalar satellite-to-satellite tracking (SST) data, such as crosslink range or Doppler, to perform autonomous orbit determination. This technique has been called "Liaison Navigation." Due to the characteristics of libration orbits, relative tracking between two spacecraft can be used to estimate the relative and absolute positions and velocities of both spacecraft simultaneously.[4]

SST between two spacecraft only provides information on the size, shape, and relative orientation of two orbits. A pair of Keplerian orbits of a certain size, shape, and relative orientation can have any absolute orientation about the center of mass of the primary body. This means that SST alone is not sufficient to autonomously determine the absolute orientation of the conic orbits of spacecraft in near Earth orbits. However, in the three-body problem the gravitational influence of the third body can indirectly provide information about the direction to that third body and with it, the absolute orientation of the orbits. In other words, a halo orbit near the Moon is influenced very strongly by both the Earth and the Moon and has a unique size and shape. Because of the strong asymmetry of the three-body force field, a halo orbit with that size and shape can only have a single orientation with respect to the Earth and Moon. This means that a spacecraft in a halo orbit can track a second spacecraft using crosslink range measurements and determine the absolute positions and velocities of both spacecraft simultaneously without any Earth-based tracking or mathematical constraints. The second spacecraft may be in any orbit either about the Moon, about a libration point, or in transit somewhere in the Earth-Moon system.

Simulations have shown that this technique works well in lunar halo orbits both in the circular restricted three-body problem[5] and in an inertial model with solar gravity and solar radiation pressure (SRP).[6] Recent simulations of a halo orbiter at Earth-Moon L_2 tracking a spacecraft in a low, polar lunar orbit have shown that this technique works very well. The simulation model used the JPL DE403 planetary and lunar ephemerides, SRP, and the LP100K lunar gravity field. The 1σ position error for the lunar spacecraft was on the order of 7 m, and it was about 80 m for the libration point spacecraft.[7] Range biases, spacecraft reflectance, and maneuver errors were all successfully estimated to high precision, even in the presence of SRP and gravity modeling errors. Stationkeeping maneuvers were performed four times every halo orbit, or about once every 3.4 days, and the combination of frequent maneuvers and precise orbit determination resulted in a stationkeeping budget of less than 1 m/s per year.

A constellation with at least one halo orbiter could use Liaison Navigation to determine the positions and velocities of all the spacecraft autonomously. This knowledge could be used to compute stationkeeping maneuvers on board the spacecraft. With automated maneuver planning, the burns could be performed more often to decrease the amount of fuel needed. Ground stations on Earth would only be needed to receive telemetry and relayed data, and uplink commands. Ground stations would not need to obtain any tracking data, except for small amounts used to verify that the autonomous navigation software is working properly. The spacecraft would be used to relay data and act as mobile tracking stations supporting other lunar missions.

Low-Energy Lunar Transfers

The cost of establishing the lunar communication constellation would be greatly reduced by using a low-energy trajectory such as a Ballistic Lunar Transfer (BLT).[8, 9] To implement a BLT, the launch vehicle propels a spacecraft on a $1 - 1.5$ million-kilometer journey towards the Sun-Earth L_1 or L_2 Lagrange points. The spacecraft remains out at that distance for a period of time while being attracted by the Earth, Moon, and the Sun. As the spacecraft falls back to the Moon, it ballistically inserts into its lunar halo orbit, requiring no deterministic insertion maneuver at all. The transfers take between 90 and 110 days, but the entire transfer requires much less ΔV than a conventional direct transfer. A BLT should allow payloads to be 25% to 33% larger in mass, depending on mission hardware. Figure 1 shows an example ballistic lunar transfer viewed in the Sun-Earth rotating frame in the ecliptic plane.

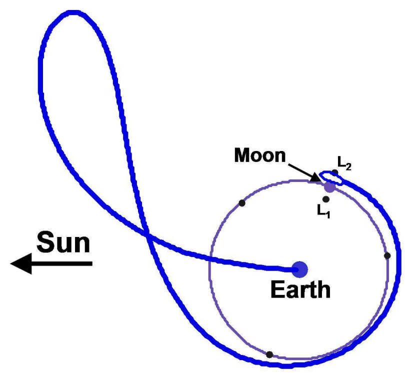

Figure 1: An example ballistic lunar transfer viewed in the Sun-Earth rotating frame from above the ecliptic.

The BLT allows larger payloads, making it possible to stack multiple spacecraft on a single launcher. The stack could remain together until reaching the halo orbit, and then the spacecraft could separate and be deployed from the halo orbit to other orbits with only minimal ΔV. From a libration orbit, spacecraft may follow free transfers to low lunar orbits such as that shown in Figure 2. The descent from the halo orbit to the Moon is free, but there is an injection maneuver required to capture into the low lunar orbit. Any lunar orbit is attainable, including polar and equatorial orbits, all with basically the same ΔV requirements. The constellation could also be reconfigured with very little ΔV by sending spacecraft from L_2 to L_1 as shown in Figure 3.[10] Spacecraft may be sent back to the Earth along a transfer that mirrors the BLT shown in Figure 1, or even follow similar low-energy transfers to Sun-Earth libration points, all with minimal ΔV.

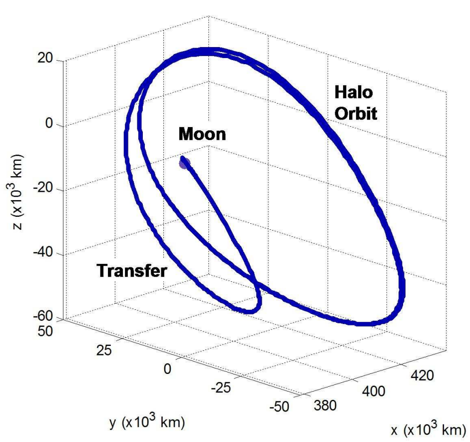

Figure 2: An example low-energy transfer from a halo orbit to a low, polar orbit about the Moon.

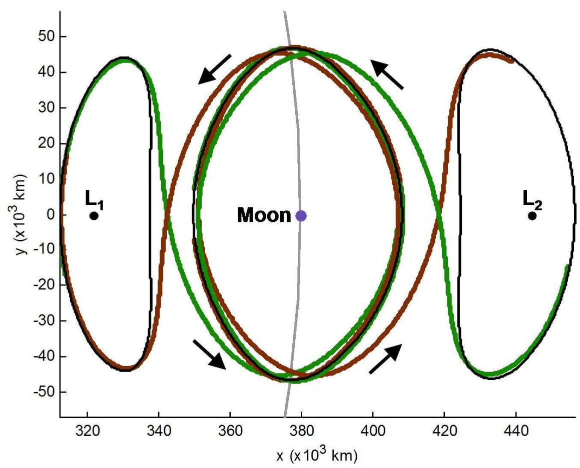

Figure 3: Example low-energy transfers between orbits about the lunar L_1 and L_2 points, including an optional distant retrograde orbit about the Moon.

Constellation Concepts

Depending on lunar exploration needs, various autonomous constellations can be designed for communications and navigation support with only 2-4 spacecraft. A few options are described below and illustrated in Figure 4.

Option 1. A useful constellation at the Moon could be built with as few as two spacecraft. With only two spacecraft, putting the second spacecraft in a low lunar orbit gives the best orbit determination results. Both would launch on a single vehicle and travel together to a halo orbit at Earth-Moon L_2. One spacecraft would detach and depart from the halo orbit and descend to the Moon and insert into a low polar orbit as shown in Figure 2. The halo orbiter would provide eight days of continuous coverage of the lunar South Pole every two weeks. It could also track manned or robotic missions orbiting the Moon in conjunction with inexpensive Earth ground stations. The halo orbiter and the ground stations could track the lunar orbiter on the far side of the Moon about 99% of the time, enabling estimation of the far side gravity field. The low lunar orbiter could also broadcast a Doppler signal to be used for surface navigation in a method similar to the Navy's TRANSIT system.

Option 2. Two spacecraft in L_2 halo orbits can provide continuous communication coverage of the South Pole and lunar orbiters could be tracked continuously using those two halo orbiters and inexpensive Earth ground stations.

Option 3. Continuous coverage of the entire Moon can be achieved using Earth-based tracking stations in conjunction with four halo orbiters at L_2 as described by Carpenter, et al.[2]

Option 4. To eliminate the need for Earth-based tracking, continuous communication coverage for almost the entire lunar surface can be obtained using two halo orbiters at L_1 and two at L_2, with only a few small mid-latitude regions unable to communicate with the constellation for brief periods.

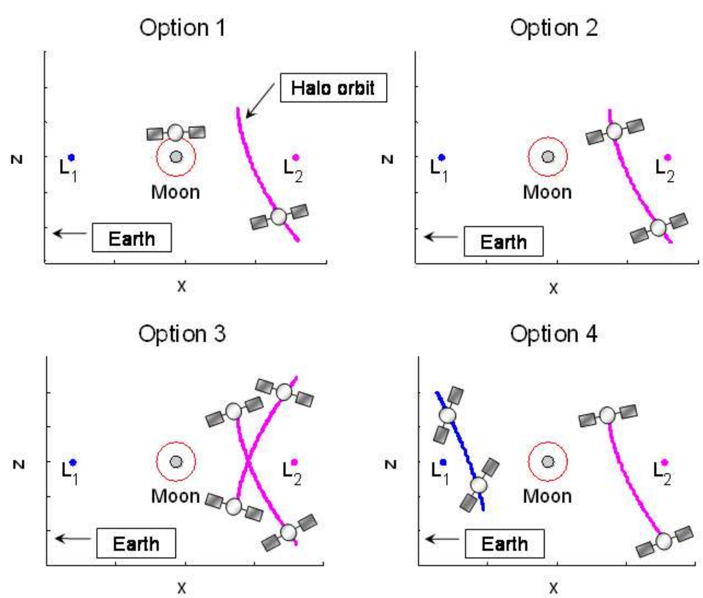

Figure 4: Illustrations of autonomous constellation options in a rotating frame where the x-axis is a line joining the Earth and Moon and the z-axis is perpendicular to the Earth-Moon orbit plane.

Conclusion

The unique characteristics of halo orbits near the Moon can be harnessed to provide communication relay and navigation services supporting the return to the Moon mandated by the Vision for Space Exploration. The dynamics of these halo orbits allow autonomous absolute and relative orbit determination using only scalar satellite-to-satellite tracking. This will reduce the cost for navigating lunar missions and free up ground-based tracking resources for critical human missions to the Moon and distant interplanetary missions. Using low-energy ballistic transfers, Earth-Moon halo orbiters can be very low-mass since no propulsion stage is required for insertion, constant solar power is available, and both communication and navigation are performed using the same telecommunications hardware. The cost of each spacecraft could be $20 million or less, and in all cases presented in this paper, the constellation could be launched on a single launch vehicle. Further research into these topics will most likely reveal even more options for lowering the cost of establishing a lunar communication and navigation system.

References

[1] Farquhar, R. W., "The Control and Use of Libration-Point Satellites," 1970, NASA Technical Report TR R-346.

[2] Carpenter, J., Folta, D., Moreau, M., and Quinn, D., "Libration Point Navigation Concepts Supporting the Vision for Space Exploration," AIAA 2004-4747, AIAA/AAS Astrodynamics Specialist Conference, Providence, Rhode Island, August 16-19, 2004.

[3] Grebow, D., Ozimek, M., Howell, K., and Folta, D., "Multi-Body Orbit Architectures for Lunar South Pole Coverage," AAS 06-179, AAS/AIAA Space Flight Mechanics Conference, Tampa, Florida, January 22-26, 2006.

[4] Hill, K., Lo, M. W., and Born, G. H., "Linked, Autonomous, Interplanetary Satellite Orbit Navigation (LiAISON)," AAS 05-399, AAS/AIAA Astrodynamics Specialist Conference, Lake Tahoe, CA, Aug. 7-11, 2005[1].

[5] Hill, K., Born, G. H., and Lo, M. W., "Linked, Autonomous, Interplanetary Satellite Orbit Navigation (LiAISON) in Lunar Halo Orbits," AAS 05-400, AAS/AIAA Astrodynamics Specialist Conference, Lake Tahoe, CA, Aug. 7-11, 2005[1].

[6] Hill, K., Lo, M. W., and Born, G. H., "Liaison Navigation in the Sun-Earth-Moon Four-body Problem," AAS 06-221, AAS/AIAA Space Flight Mechanics Conference, Tampa, Florida, January 22-26, 2006[1].

[7] Hill, K., Parker, J., Born, G. H., and Demandante, N., "A Lunar L_2 Navigation, Communication, and Gravity Mission," AIAA 2006-6662, AIAA/AAS Astrodynamics Specialist Conference, Keystone, Colorado, August 21-24, 2006[1].

[8] Parker, J. and Lo, M., "Shoot the Moon 3D," AAS 05-383, AAS/AIAA Astrodynamics Specialist Conference, Lake Tahoe, California, August 7-11, 2005[1].

[9] Parker, J., "Families of Low-Energy Lunar Halo Transfers," AAS 06-132, AAS/AIAA Space Flight Mechanics Conference, Tampa, Florida, January 22-26, 2006[1].

[10] Folta, D. and Vaughn, F., "A Survey of Earth-Moon Libration Orbits: Stationkeeping Strategies and Intra-Orbit Transfers," AIAA 2004-4741, AIAA/AAS Astrodynamics Specialist Conference, Providence, Rhode Island, August 16-19, 2004.

[1] see http://ccar.colorado.edu/geryon/ for electronic copies.