Cislunar Navigation

J. D. Burke, The Planetary Society, 65 N. Catalina Ave., Pasadena, CA, 91107 USA

e-mail: jdburke@its.caltech.edu

R. J. Cesarone, R. C. Hastrup, M. W. Lo, California Institute of Technology, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA, 91109 USA

e-mail: Robert.J.Cesarone@jpl.nasa.gov, Rolf.C.Hastrup@jpl.nasa.gov, Martin.W.Lo@jpl.nasa.gov

Abstract

In the future, navigation and communication in Earth-Moon space and on the Moon will differ from past practice due to evolving technology and new requirements. Here we describe likely requirements, discuss options for meeting them, and advocate steps that can be taken now to begin building the navcom systems needed in coming years for exploring and using the Moon.

1. Introduction

When the Apollo 12 astronauts guided their craft to a landing next to Surveyor 3 (Fig. 1), they demonstrated accurate navigation to a designated target on the Moon. That feat was achieved with radio tracking of both missions from Earth, aided by on-board inertial and celestial references plus human observation of mapped lunar features, even in the absence of a precise selenodetic net and global lunar gravity model. Later lunar missions, including the Soviet Luna sample-returners and Lunokhod rovers and then the American Clementine and Lunar Prospector orbiters, refined knowledge both of the Moon and of various outbound and on-Moon navigation techniques. With success in delivering spacecraft back to Earth from the Moon, programs in both countries demonstrated adequate navigation on the return path as well. An outstanding example was the simplified emergency method used to save Apollo 13 [Reference 1]. Thus, we can say that navigation to and from low latitudes on the Moon's near side is a solved problem. In the future, though, new missions (including lunar ventures now planned in Europe, Japan and the USA, as mentioned later) will generate new navcom needs. Let us now assess those needs and then look at options for meeting them.

2. New Technologies and New Requirements

2.1 Earth-based tracking and data acquisition.

For reasons primarily of communications performance, but also of economy, the Deep Space Network (DSN) is expected to move upward in radio frequency, from its present S-band (2 GHz) and X-band (8 GHz) links into the Ka-band region of the spectrum [Reference 2]. The Ka-band allocation for deep space, defined as being beyond 2 Mkm from Earth, is at 32 GHz. The DSN is currently implementing equipment at its complexes to support use of this allocation. The near-Earth Ka-band allocation is at 26 GHz. Additionally, there exists, primarily at the request of human exploration proponents, an allocation at 37 GHz that permits operations in the near-Earth or deep space regions. There are no funded plans as of yet to develop the 26 GHz and 37 GHz bands. However, high bandwidth requirements of future astrophysical observatories planned for the antisunward Earth-Sun libration point (L_2) are beginning to argue strongly for 26 MHz, and future bandwidth needs of both robotic and human exploration will eventually make a strong case for 37 GHz. A side benefit of the higher frequency operation is more accuracy in traditional radiometric (Doppler and Ranging) data types.

Also, with NASA's recent commitment to demonstrate an optical communications link between Mars and Earth, this technology is soon to become a reality [Reference 2]. The result will be rapid evolution in design of both ground systems and spacecraft, with new navigation methods becoming possible.

2.2 Low-thrust propulsion.

DS-1 and ESA's SMART-1 lunar mission [Reference 4] employ solar-electric ion drive, a highly-efficient form of low-thrust propulsion, but one that requires navigation on non-ballistic, spiraling trajectories with long transit times. Ion drive or solar sailing can also enable hovering, for example in unstable cislunar libration regions or possibly "sitting" above the lunar poles.

2.3 Low-energy transfers and libration orbits.

In the interacting gravity fields of Earth, Moon and Sun [Reference 5] it is possible for spacecraft to travel to and from cislunar targets with much lower propulsive delta-V (but with much longer transit times) than would be required on conventional trajectories with impulsive velocity changes. Taking advantage of this natural benefit will require refined navigation technique. As in the case of low-thrust propulsion, there will be a demand for automation both on Earth and in spacecraft to reduce long-duration operations costs.

The idea of placing a communications satellite in a cislunar libration orbit originated with Giuseppe Colombo [Reference 6]. This was made practical by Robert Farquhar using lunar halo orbits. ISEE3 was the first mission to use an Earth-Sun libration-point halo orbit [Reference 7]. But, to date, there has been no mission using Earth-Moon halo orbits. In 1990 ISAS [Reference 8] used a low-energy trajectory based on the ideas of Belbruno and Miller [Reference 9] to enable the HITEN mission to reach and orbit the Moon.

These low-energy paths, generated by unstable orbits which form tubes of trajectories, called invariant manifolds, connecting various regions in the Earth's neighborhood, are intimately related to low-thrust trajectories. As a spacecraft spirals out from the Earth's gravity well, it eventually reaches the dynamic regime where low-energy orbits become available. Theory guarantees that at any natural resonance of a three-body system, there exists an unstable resonant orbit with tubular invariant manifolds that provide low-energy transfers in its vicinity. Knowledge of these low-energy regimes and a deeper understanding of the fundamental dynamics are crucial for low-thrust trajectory optimization and navigation [Reference 10]. Moreover, this understanding will provide the foundation for new approaches for autonomous trajectory replanning, optimization, and navigation particularly in these highly nonlinear regimes for both impulsive and low-thrust missions. Reference 11 contains recent citations on libration orbits and low-energy transfers.

2.4 On-board references and computing.

Spacecraft autonomy, already demonstrated experimentally in, for example, JPL's New Millennium DS-1 mission [Reference 3], opens the prospect of much reduced demands for control and monitoring from Earth.

2.5 Aerobraking.

As demonstrated at Venus and Mars [Reference 12], repeated dips into a planet's atmosphere can gradually reduce orbital energy. The same technique can be used in returning payloads from the Moon to Earth orbit, given rapid and precise orbit determination and commanding (or autonomy) to keep the process under control.

2.6 Space Station departure and arrival.

If it is advantageous, lunar missions may leave from and/or return to the International Space Station. This prospect is to be investigated during the 2003 summer session of the International Space University [Reference 13]. Translunar departure from ISS orbit may not pose new navcom problems, but return via aerobraking followed by rendezvous with ISS will do so.

2.7 Operation beyond Earth line of sight.

Good reasons exist for operations in lunar regions invisible from Earth. The most exciting near-term prospect is surface roving and drilling to investigate the excess hydrogen observed near the Moon's poles [References 14 - 17]. In the farther future, Moon-based infrared and radio astronomy may benefit from the Moon's cold polar and quiet far side environments [References 18 and 19]. For any such operations there will be a need to relay information when direct Earth contact is impossible. In addition to routine science operations, communications, and perhaps navigation, coverage must be provided for mission critical events that are not visible from Earth, where the most critical event of all may be lunar landing. A main reason for far side basing is to take advantage of radio shielding from Earth. For far side astronomy, optical navcom may therefore be preferred over radio relay.

2.8 Formation flight.

To create larger-aperture telescopes from tens of meters to kilometer baselines, clusters of spacecraft may be used. For such missions, integrated trajectory design, navigation, guidance and control will be required. For example, NASA's Terrestrial Planet Finder [Reference 20] and ESA's DARWIN missions are both considering formation flight around Earth-Sun L_2. Typical scenarios require each spacecraft in the formation to make on the order of 100 small maneuvers per day in a dynamically unstable orbit. The precision control required most likely cannot be groundbased, but must have a large degree of autonomy. A similar system for the Earth-Moon libration points may support formations in the Moon's vicinity.

3. Navcom Options

Given the trends just described, it is worthwhile to investigate ways for exploiting new techniques and meeting new needs. First, let us discuss Earth-based tracking, the main method used to date and one sure to continue, at least as a backup to more advanced navcom schemes. The main new element needed here is information relay with lunar spacecraft beyond Earth line of sight. Imagine a robotic surface rover sent into a polar crater to investigate the putative ices indicated by the known hydrogen signature. Once the rover passes beyond the lunar limb, unless information is relayed there is no way to know anything about the mission. If the rover's signal never returns, what then? Two recent Mars missions experienced this outcome, with the result that an abandoned policy was reinstated at JPL, namely, to maintain contact with Earth whenever it is physically possible.

Continuous radio relay into and out of a dark polar lunar crater is technically feasible, for example, via a small spacecraft in a libration orbit or hovering on a non-ballistic path accompanyng the Moon as it travels around the Earth. A simpler option is to give up the requirement for uninterrupted communications and accept intermittent coverage. This can be provided by a low-altitude lunar orbiter in near-polar orbit, giving tens of minutes of relay coverage about every two hours. The Moon's gravity field is such that "frozen" high-inclination orbits exist requiring only modest delta-V for station keeping. Reasonable Earth-relay-rover communications are therefore practical by several means. The communication distances and required bandwidths are such that micro-spacecraft, launched as auxiliary payloads, can provide the relay function.

What about rover navigation? In principle, there could be a GPS-like system with a constellation of lunar orbiters. However, there are difficulties: lunar orbits, even so-called frozen ones, tend to need active station keeping. Doing that from Earth would entail large operations costs. Rover navigation using sunlight and mapped lunar surface landmarks, investigated in JPL's desert simulations on Earth [References 21 and 22], would be only partly practical in dark polar regions, as shown for example in Reference 23, a study of illumination conditions near the south pole. Because the Moon's polar axis is almost perpendicular to the ecliptic, star-sensor reference is possible, with nearly one-half of a dark sky continuously visible from each pole. Inertial reference (the simplest version being a gyrocompass) is feasible in principle but magnetic sensing is ruled out by the small magnitudes and varied directions of local remnant lunar fields. Out-and-back dead reckoning, using some heading reference and odometers, is not promising because of the path deflections that occur in traversing small craters [Reference 24]. A typical report on rover autonomy work is Reference 25. In any event, future lunar rover navigation will benefit from experience with Mars rovers [Reference 26], where long radio transit times call for some degree of on-board autonomy.

Taken together, these requirements and constraints suggest that dark-region surface reconnaissance will, at least at first, be imprecise as to locations referenced to either Earth or Moon. Radar imaging and ranging from lunar orbit can provide much better control, but will need much larger and more complex orbital spacecraft and operations. If a synthetic-aperture or ground-penetrating radar is ever placed in lunar polar orbit for scientific reasons, it will be reasonable to include a rover navcom capability.

Many of the same arguments can be applied to lunar far side surface operations, with the differences that (a) typically there will be 14 Earth days of hot sunlight and 14 of cold night, and (b) there will be a requirement to avoid radio pollution. As mentioned earlier, optical communications may be the preferred choice. In principle, an optical relay in libration orbit can meet this requirement (and can also provide a precise navigation reference), but the real problems and costs of such systems, including the required precise pointing of beams, remain to be investigated.

Fortunately for designers of lunar navcom systems, there exists a wealth of data applicable to planetary relay satellite architectures. For a number of years, NASA has been developing a relay architecture for Mars, called Mars Network [References 27 and 28]. Although Mars orbit analysis is not directly applicable to the lunar case, many parallels yet exist in the areas of rover data rate requirements to be relayed, proximity link design, and communications protocols for the proximity and end-to-end links. Much work has also been done on a software reconfigurable relay radio [References 29 and 30]. This could be applicable in the lunar relay scenario.

In addition to exploratory surface roving, emplacement of astrophysical instruments, and other surface operations for both science and evaluation of lunar resources, there is the prospect of activities in cislunar space. Libration-point orbits, attainable from Earth with low delta-V, have long been proposed as locales for a variety of purposes. For example, NASA's Exploration Team (NexT) has recently identified the Earthward Earth-Moon libration point (L_1) as a logical place in which to develop crewed infrastructure, both for its ease in getting to all latitudes on the Moon as well as for low delta-V transfer to Earth-Sun L_2 [Reference 31]. Navigating to and from these regions poses no new challenges except those previously noted in connection with low-thrust and low-energy paths.

In addition to traditional halo orbits, there are large families of other orbits with similar low-energy properties in cislunar space. Regions around Earth-Moon libration points are interconnected by the invariant manifolds of such orbits. Many of these have been discovered recently and their properties and potential uses have not yet been identified. A systematic mapping and study of these orbital families may suggest other options for future advanced navcom applications.

4. Near-Term Actions

Lunar science missions beyond those already approved (orbital science investigations aboard ESA's technology demonstrator SMART-1 and penetrators to be delivered by ISAS's Lunar-A) include proposals for sample return from the South Pole/Aitken Basin and for scientific investigation of the possible polar ices. Another class of near-future missions, long proposed but never implemented, is partly scientific and partly of an engineering nature. In these missions, the main goal would be to advance knowledge and uses of lunar natural resources – environments, materials and energy. A typical large investigation of these prospects was the NASA-ASEE summer study reported in Reference 32.

If and when such a progressive program begins, with a series of robotic lunar activities (both engineering and scientific) intended to gain knowledge for later, more intensive robotic missions leading ultimately to human lunar exploration and settlement, it will be logical to construct the needed navcom capacities synchronously as the program proceeds. With the aid of advances in micro-spacecraft technology and huge advances in ground system capabilities, already occurring for other reasons, this navcom system building can be done at modest incremental cost. A suggested sequence of actions is as follows:

- Investigate cislunar navcom options as outlined above. This can be done at no incremental cost by including the analysis in already-approved study programs; i.e., substituting it for other planned concept studies, implying a relative elevation of interest in lunar missions.
- Systematically map out the low-energy trajectory families and their invariant manifolds in the Earth's neighborhood. Characterize and catalog them and identify potential applications to future space missions, including their navcom needs. This catalog is similar to a star catalog. It is of interest in itself scientifically; yet, at the same time, it is of enormous value to space applications. So often, difficult missions that first appeared impossible were saved by the discovery and development of a trajectory with specific characteristics. Using modern computation mathematics, it is now possible to compute and catalog such orbits in advance. This would be like JPL's Interplanetary Mission Design Handbooks [Reference 33] which have served deep space missions for many decades. Not only will this catalog serve the mission architecture and planning community, but like the star catalogs, it can be placed on board spacecraft to support the autonomous, integrated mission planning/navigation/guidance and control function of the smart spacecraft of the future. Generating this orbit catalog, requiring significant human and computing resources, is an investment benefiting many future missions. Its costs should, therefore, be included in agencies' existing technology budgets. As shown by the references cited above, the work is already an international effort.
- With the first-phase study results and documents in hand, evaluate the pros and cons of the analyzed options and select a subset for further development. Fit that development into existing technology programs. This may accrue a small incremental cost, tens to hundreds of thousands of euros or dollars annually.

Meanwhile, carry out design and architecture studies for the later program intended to use the developing navcom techniques.

- Begin flying navcom demonstrations, using micro-spacecraft as auxiliary payloads on normally scheduled missions. These host missions need not be lunar, because it is possible to achieve lunar (and even planetary) trajectories from launches into geosynchronous transfer orbit [Reference 34]. Costs in this phase would be a few million euros or dollars annually.
- Based on the demonstration results, design and emplace a purpose-built navcom architecture on Earth, on the Moon and in cislunar space. Costs in this phase are not predictable with current knowledge, but costs could obviously be limited by combining and synchronizing the navcom development with the sequence of intended user missions.

5. Policy

In parallel with the new technology and management of these missions there could be a policy evolution: Building and maintaining a shared cislunar navcom infrastructure could become a coordinated effort of the international community concerned with exploration and settlement of the Moon.

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References

1. Lovell, J. and Kluger, J.: *Lost Moon*, pp. 162-168, Houghton Mifflin, New York, 1994
2. Weber, W., et al.: *A View of the Future of NASA's Deep Space Network and Associated Systems*, Paper 02-T1-033, Space Operations, Houston, Texas, USA, Oct. 9-12, 2002
3. Rayman, M. and Williams, S.: *Design of the First Interplanetary Solar Electric Propulsion Mission*, Journal of Spacecraft and Rockets 39, 4, 589-595, 2002
4. Foing, B., et al., ESA: *SMART-1*, http://sci.esa.int/smart-1/, March 19, 2003
5. Smith, D.L.: *Next Exit 0.5 Million Kilometers*, Engineering and Science LXV, 4, 2002
6. Colombo, G.: *The Stabilization of an Aritificial Satellite at the Inferior Conjunction Point of the Earth-Moon System*, Smithsonian Astrophysical Observatory Special Report, No. 80, Nov. 1961
7. Farquhar, R.: The Flight of ISEE-3/ICE: Origins, Mission History, and a Legacy, *JAS 49, 1*, Jan.-Mar. 2001
8. Usuegi, K., et al.: Japanese First Double Lunar Swingby Mission 'HITEN', *Acta Astronautica, 25, 7*, 1991
9. Belbruno, E., and Miller, J.: Sun-Perturbed Earth-to-Moon Transfers with Ballistic Capture, *Journal of Guidance, Control, and Dynamics*, 16, 1993
10. Noca and Brophy: *Next Generation of Ion Propulsion: Setting Up New Requirements for Trajectory Otpimization*, LOTUS 2 International Symposium, IAS, Toulouse, France, June 2002
11. Gómez G., et al.: *Proceedings of the Conference Libration Point Orbits and Applications*, Aiguablava, Spain, June 10-14, 2002, World Scientific, Singapore, 2003 (in press)
12. Lyons, D.T.: *Aerobraking Automation Options*, Paper AAS 01-385, American Astronautical Society, June 2001

13. Students of ISU: *To the Moon Via ISS,* Report of team project, IAC, Bremen, 2003
14. Nozette, S., et al.: *Integration of Lunar Polar Datasets*, Return to the Moon II, pp 225-231, Space Frontier Foundation, 2001
15. Spudis, P, et al.: *The Clementine Mission*, ESA SP-1170, pp 91-102, 1996
16. Binder, A., et al.: *The Lunar Prospector Mission*, <http://lunar.arc.nasa.gov/results/neures.htm>, March 20, 2003
17. Whittaker, W., et al.: *The Icebreaker Project*, <http://www.ri.cmu/projects/project_335.html>, March 20, 2003
18. Burns, J. and Mendell, W. (editors.): *Future Astronomical Observatories on the Moon*, NASA CP - 2489, 1988
19. Students of ISU: *International Lunar Farside Observatory and Science Station (ILFOSS)*, Report of team project, summer session, 1993
20. Beichman, C., Gómez, G., Lo, M., Masdemont J, Romans, L.: *Searching For Life With The Terrestrial Planet Finder: Lagrange Point Options For A Formation Flying Interferometer*, 53rd International Astronautical Congress, October 10-19, 2002, Houston, Texas, USA (submitted to Advances in Space Research)
21. Coryell, R. and Rubin, D.: *Experiments in Piloting by Landmark on the Moon*, JPL Document 760-37, April 1, 1969
22. Brereton, R., et al.: *Experiments in Remote Geological Reconnaissance and Landmark Navigation*, JPL Document 760-41, October 15, 1969
23. Bussey, D., et al.: *Illumination Conditions at the Lunar South Pole,* Geophysical Research Letters, 26, 9, pp. 1187-1190, American Geophysical Union, May 1, 1999
24. Coryell, R. and Durr, L.: *Crater Deflection Studies*, JPL Document 760-44, March 20, 1970
25. Tompkins, P., et al.: *Automated Surface Mission Planning Considering Terrain, Shadows, Resources and Time*, Proc. 6th International Symposium on Artificial Intelligence, Robotics and Automation (I-SAIRAS '01), Montreal, June 2001
26. Jet Propulsion Laboratory; *Mars Exploration Rover Navigation* <http://mars.jpl.nasa.gov/mer/>, March 20, 2003
27. Edwards, C., et al: *Strategies for Telecommunications and Navigation in Support of Mars Exploration*, Paper IAF-00-Q.3.05, 51^{st} International Astronautical Congress, Rio de Janeiro, Brazil, October 2-6, 2000
28. Edwards, C. and Naderi, F.: *Telecommunications and Navigation Strategies for Mars Exploration*, Paper IAF-01-M.4.08, 52^{nd} International Astronautical Congress, Toulouse, France, October 1-5, 2001
29. De Paula, R., et al.: *Evolution of the Communications Systems and Technology for Mars Exploration*, Paper IAF-01-M.4.06, 52^{nd} International Astronautical Congress, Toulouse, France, October 1-5, 2001
30. Edwards, C., et al.: *NASA's Telecommunications Strategy for Mars Exploration*, Paper AIAA-254 AIAA International Communications Satellite Systems Conference, Toulouse, France, April 17-20, 2001
31. Cooke, D., et al.: *Innovations in Mission Architectures for Human and Robotic Exploration Beyond Low Earth Orbit*, Paper IAC-02-Q.6.04, World Space Congress, Houston, Texas, USA, October 10-19, 2002
32. McKay, M.F., McKay, D.S. and Duke, M.B., (Eds.): *Space Resources*, NASA SP–509 (4 vols.), NASA Johnson Space Center, 1992
33. Sergeyevsky, A.: *JPL Interplanetary Mission Design Handbooks*, 1966 - 2002
34. Penzo, P.: *Venus and Beyond Using the Ariane ASAP Launch Capability*, Paper AAS 99-357, AAS/AIAA Astrodynamics Specialist Conference, Girdwood, Alaska, August 16-19, 1999

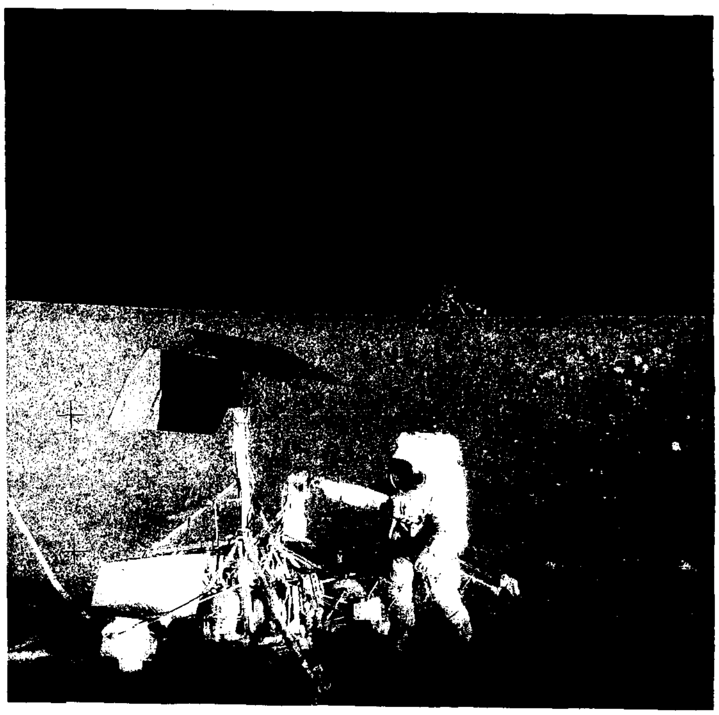

Figure 1. The Apollo 12 crew, Richard F. Gordon, Charles (Pete) Conrad and Alan Bean, navigated to a landing 163 meters from Surveyor 3, which had been sitting on the Moon for 31 months. NASA photo of Conrad by Bean, AS12-4-7133