LOW COST COMMUNICATION SUPPORT OF LUNAR MISSIONS

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ABSTRACT

The National Aeronautics and Space Administration (NASA) has proposed a comprehensive program of robotic and human lunar exploration of the Moon as a step toward human exploration of Mars. The program includes characterization of the Moon by robotic orbiters and landers, development of a Crew Exploration Vehicle (CEV) to carry humans, and possible establishment of a human base on the lunar surface. The schedule is aggressive, with the first robotic mission launching in 2008 and the return of humans to the Moon around 2015[i].

We present a concept and architecture for a low-cost communications infrastructure for these missions. There are two major elements: Earth stations and a small lunar relay constellation.

The Earth stations will leverage the development of the Deep Space Network (DSN) array[ii]. A small number of antennas would be used to provide services to the initial robotic missions. Capability would be added to support the more ambitious human missions, taking advantage of the modularity and expandability of this design.

The lunar relay constellation will consist of low-cost spacecraft in elliptical orbits providing continuous coverage of the South lunar pole and some backside coverage of critical events.

This architecture can be established quickly, enabling early missions. It will then grow with the expanding mission requirements and eventually support human missions to the moon and Mars.

1. LUNAR MISSION ASSUMPTIONS

Before one can design a cost-effective system to provide communications and navigation, it is critical to understand the nature of the user missions. This presented a significant challenge here since none of the missions had been defined except in the broadest sense.

The team only knew a few facts from the announcement made by President Bush in January 2004. There would be some precursor robotic missions to the Moon, beginning in 2008. Humans would return to the Moon no sooner than 2014. There would be some sort of sustained human presence on the Moon. All this would serve as a preamble to sending humans to Mars, no sooner than 2030.

There were no published point designs for any of the missions. In fact, there was not even the highest-level roadmap for the various missions that fill the gaps between the few that were mentioned in the speech. Hence, our team began its work by hypothesizing the sequence of missions and goals for the new lunar program. In retrospect, the results we reached were extremely close to the plans that NASA eventually produced.

We assumed that human missions to the Moon would place humans either in nearside lunar equatorial regions, or at the south lunar pole.

If one assumes (as explained in the NASA vision) that the reason for returning humans to the Moon is to prepare for sending humans to Mars, then nearside lunar equatorial missions make sense. In fact, missions to the nearside of the Moon may satisfy all of these needs. In addition, nearside equatorial lunar missions would be less risky with respect to propulsion, landing, and ascent.

If, however, one assumes that we would not bother with such an expensive endeavor without doing significant research on the Moon, then the south lunar pole is a likely location for human exploration. Recent missions and radar observations have indicated that there are likely significant resources, including abundant water, in this region[iii]. One could even argue that astronauts could practice techniques for recovering drinking water and fuel from these resources, in preparation for activities on Mars. Actually, the processes are probably quite different for in-situ resource utilization (ISRU) between the Moon and Mars.

It is also possible, though unlikely, that astronauts might manufacture fuel on the Moon for use in a subsequent mission to Mars. This argument stems from the fact that it may be less expensive to move a given mass of fuel out of the lunar gravity well than off the surface of the Earth.

A third, though less likely scenario involves sending human or robotic spacecraft to the backside of the Moon to set up astronomical observatories. Although we viewed this as highly unlikely for the first 15 years of lunar re-exploration, we did consider this possibility.

In order to prepare for placing humans on the moon, NASA will need a number of robotic precursor missions. The team envisioned a set of lunar explorers that would map out landing sites and surface resources. We also need a much better gravity map of the Moon to enable more accurate and less expensive navigation of lunar orbiters and descent vehicles. Finally, robotic missions may be used to set up infrastructure for subsequent human missions. This infrastructure may include communication relays, navigation systems, habitation, human transportation systems, and resource stockpiles (food, water, and fuel) for humans.

With our new lunar mission model, we could begin developing architectures for communication and navigation.

2. OVERALL SYSTEM ARCHITECTURE

The team quickly came to the conclusion that Earth-based stations could provide most of the required communications and navigation services for these missions. More than half of the Moon, and much more than half of a lunar orbiter's trajectory, is visible from the ground. Lunar missions to the nearside equatorial regions could be easily tracked from such stations, requiring other infrastructure only for their landing and ascent phases.

Additional infrastructure would be needed to provide services for missions when they are out of view of the Earth. Although this was not required for the Apollo program, recent NASA experience, backed up by policy, has shown the need to have communications available during mission critical events. There will definitely be critical events out of view of the Earth – including lunar landing, orbit maintenance, and ascent trajectories. Also, missions to the lunar poles can place spacecraft and humans out of Earth view for long periods of time.

There is clearly a need for some sort of lunar relay platforms. The challenge was to narrow the space of possibilities to a low-cost option.

After studying libration point relays, we quickly settled on lunar orbiters as the preferred choice. A link to a relay asset at the Earth-Moon L2 Point would be roughly 50 to 60 times longer than to a link to a typical lunar orbiter. Distance to the L4 and L5 Points are the same distance as back to the Earth. Use of such relays would place an undue burden on the user missions to carry more substantial antennas and amplifiers – or the relays themselves would have to be very large spacecraft with large antennas and amplifiers. Either way, this solution can become expensive quickly[iv].

The problem with lunar orbiters is that there is a large third body that perturbs their orbit – the Earth. Enlisting the help of JPL's navigators, we narrowed the search for such for stable (or nearly-stable) lunar orbits for such relays.

An additional element in our proposed architecture is a lunar surface relay. Assuming there will be robotic or human missions at the south lunar pole, it is likely these will spend considerable time in craters that are out of both sun and Earth view. This is because such regions are the most likely to have accumulated water ice as a result of eons of cometary collisions.

Luckily, the south polar region of the Moon is quite mountainous and there exists at least one feature, Malapert Mountain, which has views of some of these craters, yet remains in nearly constant Earth and Sun view[v]. A communications relay on the mountain could provide a link to user missions in these craters while having a continuous link back to the Earth and ample solar power. One could even imagine beaming power from this relay station to a human base in a crater. In fact, it was the existence of such mountainous regions that led us to choose the south lunar pole over the north for our mission set.

All these elements would be tied together by a set of three Earth communication sites, spaced approximately 120° degrees apart around the globe. These stations should be located near enough to the equator to track the Moon through all of its declinations (between -28° and +28°). These stations will provide direct links to lunar missions when they are in Earth view – which also includes most of the cruise between Earth and Moon. They would also provide the Earth end of lunar relay orbiters and lunar surface relays.

This small network of ground stations will provide all lunar communications and navigation services.

3. WHY USE THE DSN?

Three ground stations situated 120° apart in near-Equatorial regions would provide continuous visibility to all points on the nearside of the Moon. Any less than these three stations would not suffice. Any more would result in an unnecessary cost of operating and maintaining an additional site.

The DSN already comprises three such locations. These sites were used to track the Apollo missions. In fact, the DSN has been used to support all lunar missions since Apollo and is routinely used to track spacecraft in high Earth orbit.

For these reasons, it makes sense, from both cost and performance views, to use the DSN sites for the lunar ground stations.

The DSN currently has antennas that can be used to track lunar missions – albeit only at S-band. The DSN's beam waveguide antennas could easily be upgraded to add other communications frequencies. These solutions, however, would not be the most cost-efficient. They would result in devoted very large (26m and 34m diameter) antennas to missions that could be supported by much smaller stations (12m to 18m.) Use of these antennas for lunar missions would also reduce their availability for supporting deep space missions.

4. THE DSN ARRAY

Today's DSN consists of large (26m to 70m diameter) antennas. The sizes have been driven by the requirements of NASA's deep space missions. However, future missions will require much more performance. Recent analysis has shown that, by 2030, NASA's deep space missions will require 1,000 to 1,000,000 times the communications performance available today[vi].

While some portion of this increased performance will come from technology advances on the user spacecraft, past experience has proven the wisdom of investing in ground station improvement as a key part of the plan. Improvements in ground stations will benefit all user spacecraft – low cost or flagship missions – and for all time.

One could get a 40x improvement over a 70m antenna by building 442m antennas. This is clearly not cost effective. Instead, one can get the same equivalent performance by building a larger number of smaller antennas and arraying them together.

Arraying technology is nothing new to the DSN. Arraying was a critical part of Voyager's Uranus and Neptune encounters. Arraying was also used on a routine basis to support the Galileo mission at Jupiter after its high-gain antenna failed to deploy en-route.

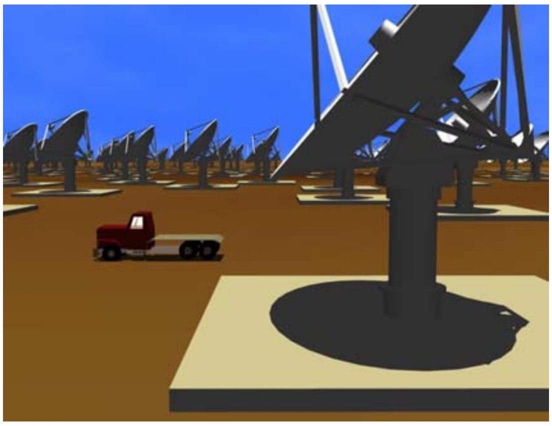

Figure 1. Artist's conception of 400-element DSN array

Analysis has shown the optimal diameter, from a cost point of view, for an individual element in a future DSN array to be approximately 12m. 400 12m antennas provide 10 times the equivalent aperture area as a single 70m antenna. In addition, it is much easier to add Ka-band (26-40 GHz) reception to a 12m antenna than to retrofit Ka-band onto a 70m antenna. When taken together, the additional aperture size and Ka-band capabilities of a 400-element array of 12m antennas represents a 40x increase in performance over a 70m antenna.

Fig. 2 shows how these increases form the foundation of the DSN's strategy to provide the future required performance.

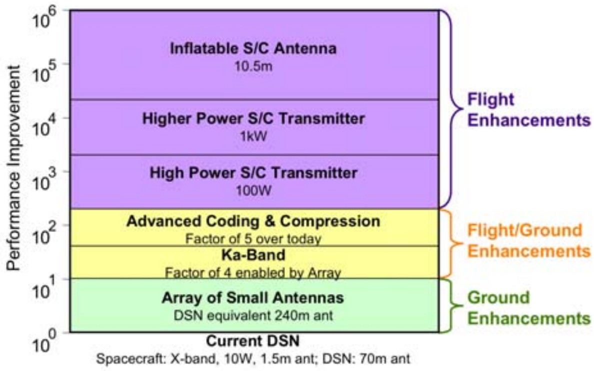

Figure 2. DSN Plan to for increased communications performance by 2030

5. EARTH STATIONS

It is not necessary to build a 400-element array of 12m antennas to provide communications support to lunar missions. In fact lunar missions require only about one-millionth the communication performance as Mars missions, due to the fact that the Moon is so much closer to the Earth. Hence, for the same performance, it would take only one half of a 12m antenna to provide the same data rate to the moon as 400 antennas could provide to Mars – all else being equal.

In the absence of any real data rate requirements, we decided to propose using single 12m antennas to serve as the Earth stations for the lunar architecture. Leveraging the DSN array activities would result in very low cost 12m antennas, front-end electronics, and transceivers. All of these components could be taken almost directly from the DSN array. We also have the option of actually using individual antennas from the DSN array as the lunar mission Earth stations.

Each of the three Earth sites would require eight 12m antennas: three to support the lunar relays (see below), one for relay to a lunar surface relay, two for spacecraft at the Moon or en-route, and two as backup to provide a reasonable degree of reliability (including scheduled maintenance.)

Since performance the initial study, NASA has begun to define a set of proposed lunar missions. The first of these, the Lunar Reconnaissance Orbiter (LRO), has a data rate requirement that just exceeds the capability of a single 12m antenna! Because of this, we have had to enhance the original recommendation by allowing several 12m antennas to be arrayed – even for lunar applications. The arraying would be done using the same systems as planned for the DSN array, but now the number of 12m antennas supporting the Moon could possibly double.

The antennas (whether used singly or in an array) would also have the ability to track multiple user spacecraft within their beams simultaneously. There are several methods for accomplishing this and they will each be studied before an implementation is chosen.

An additional benefit from the choice of 12m Earth stations is that the beam of such an antenna at S-band covers the entire Moon and reasonable orbiter altitudes as shown in Fig. 3.

At S-band, return link data rates better than 5 Mbps will be possible for a single 12m antenna. Rates up to 500 Mbps are achievable at Ka-band.

The Earth stations would also provide Doppler and range measurements of the communication signals to the user missions to serve as a principal source of navigation information.

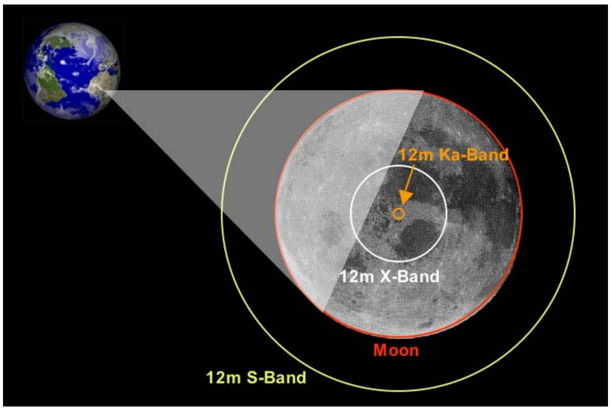

Figure 3. 12m antenna beam sizes at various frequencies.

6. LUNAR RELAYS

As the lunar program commences, we propose to build a small relay infrastructure by flying in-situ communication payloads on the precursor robotic orbiters, including LRO. This is the same strategy being used today for the Mars Network. This is a very low cost approach to enabling surface exploration out of view of the Earth – even in the early phases of the program.

Eventually, and certainly by the time humans return to the Moon, this will no longer suffice. At that time, we will need a set of relays that provide continuous communication to explorers.

These dedicated lunar relay spacecraft will be considerably more expensive that Earth stations. Hence, the goal was to minimize the number of orbiting relays required in the architecture.

It is well known that a five-satellite constellation could provide continuous visibility to all portions of the lunar surface. However, this is more than is required for the mission model we developed.

Earth stations will cover the entire nearside of the Moon. In addition, sustained exploration out of Earth view will only occur at the south lunar pole, according to our assumptions.

After a considerable amount of analysis, the team settled on a three-satellite constellation as shown in Fig 4.

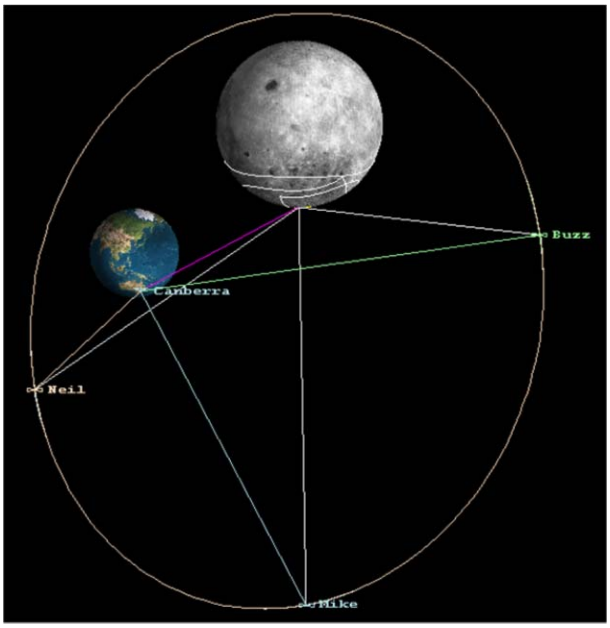

Figure 4. Three-satellite lunar relay configuration

The orbits are designed so that each satellite spends most of its time over the South polar region. Two of the three are in view of this region at any time. Although two such satellites could provide continuous coverage near the pole, having three provides continuous redundancy – important for human missions.

These satellites could also provide radiometric navigation services. While there will be fewer satellites in view than with GPS, because there will be only a few users, two-way Doppler and ranging services can be used to enhanced navigation accuracy.

Since developing this initial concept, much work has been performed along with NASA's Goddard Space Flight Center to further define this constellation[vii].

7. OTHER ELEMENTS

As mentioned in Section 2, there may be a need for lunar surface elements as part of this architecture.

A Malapert Mountain relay station could provide a continuous relay to missions in south polar craters.

Such a relay could be deployed as part of one of these use missions. The spacecraft could land on or near the mountain and deploy a rover that could configure itself into the relay. Alternatively, if landing accuracy is sufficient, the fixed landed portion of the mission might simply become the relay. Rovers would then be dispatched to explore the craters.

In addition to the Malapert relay, it might be beneficial to deploy a number of fixed lunar surface elements to serve as beacons for a lunar navigation system. Until there is a much better understanding of mission requirements, we will not be able to decide if these are justified.

8. COST SAVING ELEMENTS

This proposed architecture for lunar communications and navigation was devised to satisfy our assumed requirements at a minimal cost to NASA. The cost savings elements, and some thoughts on actual cost savings, include the following:

8.1. Use of DSN sites

New sites for Earth stations would require significant facilities investment for roads, power, and communications. There could be substantial additional costs to cover environmental impacts or other regulatory issues. In addition, there would be considerable up-front work required to identify and evaluate candidate sites.

Although there is no perfect algorithm for estimating the development of an entirely new site (and the costs vary considerable with location), experience has shown that these costs can be as high as $50M per site.

It is likely that the DSN will develop some new sites for its array. There are several reasons for this. First, there is insufficient land available at the current Spanish and Australian sites. Second, the weather at these two sites is not optimal for Ka-band links. Third, there has already been encroachment on spectral bands needed by NASA in Spain.

If the DSN develops new sites, they will still satisfy the criteria required for the lunar Earth station site selection. Hence, the lunar Earth stations would move with the DSN.

In any case, by collocating with the DSN sites (or even sharing some of the DSN array antennas) the entire cost of site development can be saved.

8.2. Use of smaller antenna Earth stations

If we were to use existing large DSN antennas as the Earth stations, we would encumber the larger operations costs associated with these stations. Since the extra performance is not required, it makes much better sense to use smaller antennas.

Estimates of the operations savings have been performed for the DSN array. Savings of something close to 70% should be attainable.

8.3. Use of DSN array antenna designs

By using major portions of the component design for the DSN array antennas, we can save most of the non-recurrent engineering investment. With the array project already designing the antennas, feeds, amplifiers, and signal processing, there will be very little cost remaining for this architecture. This can easily amount to a savings of more than $10M.

8.4. Tracking multiple users per beam

By equipping the Earth stations with systems that can track up to four user spacecraft at a time within their beam, coupled with the fact that their beams will include the entire Moon at S-band (2.2-2.29 GHz), we will save the cost of three 12m antennas at each of the three sites. These nine antennas would otherwise have cost at least $5M in replication costs. There is also a savings in maintenance and operations.

8.5. Minimal lunar relay constellation

By deploying a three-satellite lunar relay constellation rather than a six-satellite one, we will save the cost of three satellites. These are quite expensive – maybe as much as $100M apiece including launch, spacecraft, and payload costs. In addition, we would save 50% of the operations and replenishment costs.

8.6. Use of surface relays

The use of lunar surface relays, such as a Malapert Mountain relay, could reduce the need to lunar relay orbiters. Even so, it may be more expensive to deploy such a surface relay than an orbital relay. However, when one takes into account the longevity of the device and the operations costs, it may be less expensive to develop the surface asset.

Also, it may be less expensive to do this if the surface relay can be deployed as a part of a lander exploration mission.

9. CONCLUSIONS

We have developed an architecture to provide communication and navigation support to NASA's lunar exploration program. The architecture can be deployed quickly to support LRO and can grow to provide support to human explorers at the Moon. Because this architecture is based heavily on the DSN array, it can also grow to support human exploration of the planets.

The architecture, which consists of both Earth stations and lunar relays, has been developed to minimize cost to NASA.

10. REFERENCES

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