

Enabling Affordable Communications for the Burgeoning Deep Space Cubesat Fleet*

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The low costs of development and launch, coupled with new propulsive technologies, have made cubesats increasingly popular for use in science investigations beyond geosynchronous orbit. As this deep space cubesat fleet grows in size, the challenge of trying to provide affordable communications for it grows commensurately. The mass, power, and volume constraints inherent to cubesats limit the antenna size and transmit power that they can use to close the deep space link. As a consequence, cubesats need to rely more heavily on ground antennas that are characterized by large aperture, low noise temperatures, and relatively high-power transmitters. Such antennas are not in great abundance, nor are they inexpensive to build. For this reason, NASA's Deep Space Network has been advocating a three-pronged approach to meeting anticipated cubesat demand: development of simultaneous, shared-beam multi-spacecraft communications capabilities, development of large-antenna cross-support arrangements with other agencies and universities, and development of less uplink-intensive navigation techniques.

This paper focuses on the pursuit of simultaneous, shared-beam multi-spacecraft communications capabilities. While the Multiple Spacecraft per Antenna (MSPA) technique has existed for over a decade, it has generally been limited to supporting downlink for just two in-beam spacecraft at a time. This limitation has largely been a function of the number and cost of available receivers. A relatively new technique that potentially overcomes this limitation is Opportunistic MSPA (OMSPA). Instead of relying on additional receivers, OMSPA makes use of a digital recorder at each ground station that is capable of capturing the intermediate frequency (IF) signals from every spacecraft in the antenna beam within the frequency bands of interest. When cubesat projects see one or more opportunities for their cubesat(s) to intercept the traditionally scheduled antenna beam of a "host" spacecraft, they can arrange for the cubesat(s) to transmit open loop during those opportunities. Via a secure Internet site, the cubesat mission operators can then retrieve the time- and frequency-relevant portions of the digital recording for subsequent demodulation and decoding, or subscribe to a service that does it for them. This "opportunistic" use of a host spacecraft's ground antenna beam potentially enables cubesat projects to make use of large ground antennas for downlink without having to compete with bigger, better-funded missions for antenna time in the formal scheduling process. In so doing, it also potentially enables cubesat projects to avoid the aperture fees associated with formally scheduled downlink time – fees that factor into the "bottom-line" of competitively-bid NASA missions and that actually get charged to non-NASA missions.

Taking advantage of these potential OMSPA benefits, however, will require cubesat projects to pursue mission designs that ensure at least periodic in-beam operations relative to a "host" spacecraft. In the case of a constellation of cubesats with inter-spacecraft distances that do not extend outside of the beam-width of the desired ground antenna at the given range, one cubesat can serve as the "host" and have a formally scheduled downlink while the rest of the cubesats can downlink essentially for "free" via OMSPA.

Deep space cubesats, of course, will need uplink in addition to downlink. Beyond commanding, this need is driven by the use of two-way ranging and Doppler for navigation. While OMSPA may not directly facilitate uplink, it does have the potential to free up antennas for those spacecraft that periodically require formally scheduled links for commanding and two-way radio metrics. NASA is also exploring the physical feasibility of an in-beam, simultaneous multi-spacecraft uplink technique. As with OMSPA, if successful, it will require little new equipment, further enabling affordable deep space cubesat communications.

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I. Introduction

THE growing popularity of cubesats is largely due to the fact that they are affordable. Their small size makes them relatively cheap to build, test, and launch. Instead of needing large teams of technicians and whole buildings for spacecraft assembly, a couple of knowledgeable individuals, benefitting from the cubesat standards developed by others over many prior years, can build up a cubesat on a desktop. For environmental testing, they can literally carry it to a small vacuum chamber sitting on a nearby desk for thermal-vacuum testing, place it on a nearby shaker table for vibration testing, and move it into a properly outfitted nearby “closet” for acoustic testing. Instead of needing a dedicated launch vehicle capable of hefting tons of payload into orbit, cubesats can “hitch a ride” as small secondary payloads on a rocket launching a much heavier traditional spacecraft. Even for those looking to send their cubesats beyond geosynchronous orbit, launch opportunities as secondary payloads are emerging as evidenced by the 13 cubesat slots that NASA recently awarded for the maiden flight of the Space Launch System (SLS), the rocket that will ultimately take astronauts beyond Earth orbit. And, as miniaturization technologies for key components and sensors improve, these small spacecraft are becoming increasingly capable from a scientific and commercial standpoint. This combination of affordability and growing functional potential is attracting a much broader swath of government, academia, and industry to cubesats than did their much larger, more expensive predecessors.

One area where costs do not always scale in proportion to the size of the spacecraft is operations. While the cubesat’s simplicity may lend itself to operating with fewer people than in the case of a traditional spacecraft, the end-to-end link difficulty associated with commanding the spacecraft and receiving its telemetry does not scale with spacecraft size. In fact, because the cubesat’s smaller size limits the solar array area and battery volume needed for transmission power, the area available for radiating the heat-load, and the space available for key telecom components like the antenna, the required ground-side telecom capability has to increase to offset the diminished flight-side capability. In short, cubesats generally need larger ground stations than traditional spacecraft to achieve the same data rates across the same link distance.

For cubesat missions beyond geosynchronous orbit, this need for larger ground stations becomes particularly apparent due to the inverse relationship between received signal power and the square of the distance between the spacecraft and the Earth. For instance, a cubesat in geosynchronous orbit receiving the same signal from the Earth’s surface as a cubesat in low Earth orbit, will receive that signal with roughly one ten thousandth the power that the low Earth orbit cubesat does.** A cubesat at the Moon will receive that same signal with roughly one millionth the power.†† And, a cubesat at Mars will receive that same signal with roughly three trillionths the power.‡‡ Of course, the magnitude of these challenges is the same whether one is uplinking from the Earth or downlinking to the Earth. Clearly, the further from Earth cubesat missions travel, the more they need a capability on the ground characterized by very high gain antennas, very low-noise amplifiers, and high-power transmitters. For this reason, an increasing number of deep space cubesat missions are looking to NASA’s Deep Space Network for communications support.

NASA’s Space Communications and Navigation (SCaN) Office funds and manages the Near-Earth Network, Space Network, and the Deep Space Network (DSN). The DSN consists of three complexes spaced roughly equally around the globe such that, for a spacecraft operating beyond geosynchronous orbit, at least one complex is almost always in view as the Earth turns. These three complexes are located near Goldstone, California; Madrid, Spain; and Canberra, Australia. Each complex includes a 70m antenna and multiple 34m antennas, such that there are currently, in total, 13 antennas across all three complexes. Each antenna makes use of low-noise amplifiers that are cryogenically cooled to within a few degrees of absolute zero, and each antenna is equipped with a 20 kW X-band transmitter.§§ All of the antennas are capable of receiving at X-band; a limited number are also capable of receiving at S-band.*** And, one 34m antenna per complex is capable of receiving at 26 GHz Ka-band, while two or more are

** Assumes a low Earth orbit of 400 km and a geosynchronous orbit of 35,786 km.

†† Assumes an average lunar distance of 382,500 km.

‡‡ Assumes an average Mars distance of 225,000,000 km.

§§ Six antennas are also equipped with 20 kW S-band transmitters. Three antennas are equipped with 250-watt, near-Earth S-band transmitters. NASA is also beginning the process of equipping a couple of 34m antennas per complex with 80 kW X-band transmitters. It is also planning on instituting one 3 kW 34 GHz Ka-band transmitter per complex.

*** NASA is in the process of phasing out its 34m HEF antennas and building new 34m BWG antennas, so the exact numbers are in flux and depend upon the timeframe of interest.

capable of receiving at 32 GHz Ka-band. So, the DSN is well-equipped to support the diverse communication needs of spacecraft operating between geosynchronous orbit and the furthest reaches of our solar system.

Unfortunately, the investment required to develop, operate, and maintain such capability is quite large. NASA's SCaN Office cannot afford to place tens of new 34m antennas per complex to accommodate the tens of new deep space cubesats that may be launching as secondary payloads every couple of years. Yet, with a current spacecraft-to-antenna ratio of roughly three-to-one and about a third of the spacecraft, on average, looking to communicate with the Earth at any given time, it is not too difficult to see that the DSN is currently operating near capacity. So, to accommodate the influx of new cubesats in the future, the DSN has begun pursuing a three-pronged approach: development of simultaneous, shared-beam multi-spacecraft communications capabilities, development of large-antenna cross-support arrangements with other agencies and universities, and development of less uplink-intensive navigation techniques.

Development of simultaneous, shared-beam multi-spacecraft communications capabilities involves investigating and implementing techniques that allow spacecraft that are within the beam of the same ground antenna to downlink through that antenna at the same time -- and, eventually, to uplink through it at the same time as well. The DSN's current simultaneous downlink capability is limited to two spacecraft, since only two receivers are associated with each antenna. In preparation for the cubesat secondary payload deployments anticipated for 2018, the DSN is working on expanding this capability to four simultaneous downlinks through the same antenna. And, techniques are currently under investigation that will ultimately allow for a virtually unlimited number of simultaneous in-beam downlinks. Some of these techniques lend themselves to opening up a new "self-service" paradigm for cubesat communications that promises not only to be more affordable for the DSN to provide, but also more affordable for the cubesat missions to use. These techniques and how to design cubesat missions to take advantage of them will be the primary focus of this paper.

For the sake of completeness, however, it is worth mentioning that the DSN is also investigating simultaneous multi-spacecraft uplink techniques. Such techniques are not only important from a spacecraft commanding standpoint but, also, from a navigation standpoint. Currently, one of the most important radiometric methods for navigating deep-space spacecraft is that of coherent two-way ranging and Doppler. Because of the timing precision needed to estimate the signal delay associated with a given spacecraft range, very precise, stable atomic clocks are needed. These clocks are generally too massive and too expensive to put onboard spacecraft. So, it has not typically been possible to reliably determine spacecraft range based on the signal delay from just the downlink, or just the uplink, over long durations.^{†††} Instead, spacecraft are usually outfitted with a transponder that coherently turns around the uplink ranging signal onto the downlink so that the end-to-end path-length-delay can be determined using the atomic clock on the ground. The Doppler shift in the signal during this signal transit can also be determined to provide range rate-of-change information. The point is that navigation drives the need for both an uplink and a downlink. So, having a technique for simultaneous multi-spacecraft uplink, in addition to downlink, is important.

To this end, the DSN is currently investigating three different techniques for multi-spacecraft uplink. One involves uplink to all of the in-beam spacecraft at the same frequency, using spacecraft identifiers in any commands to differentiate which spacecraft will actually be commanded, but allowing all to coherently turnaround the ranging signal on their downlinks. This technique necessitates that variable turnaround ratios are built into both the spacecraft radio and the ground system. A second technique involves using multiple exciters to send separate signals up through the same transmitter. And, the third technique involves modulating subcarriers onto the carrier in such a way that each subcarrier frequency can be assigned to a specific spacecraft for uplink. These latter techniques involve a variety of intermodulation, power, and signal processing challenges that still need to be overcome.

In the meantime, the DSN is pursuing two other approaches in its three-pronged approach to servicing the burgeoning cubesat fleet: large antenna cross support and less uplink-intensive navigation techniques. For the past couple of decades, the DSN has sometimes relied on the large antenna assets of other space agencies (e.g., ESA and JAXA) for support to specific missions when its own antennas were either not in view or were occupied with some other mission's critical-event support requirements. And, these other agencies have frequently relied on DSN antenna assets for the same reasons. Typically, such cross-support arrangements have occurred on a *quid pro quo* basis, involving no exchange of funds -- with the cross-support antennas actually appearing as schedulable assets in the supported agency's antenna scheduling system for the duration of the arranged cross support. For cubesat

^{†††} NASA currently has a technology development and demonstration effort underway for a Deep Space Atomic Clock (DSAC) that would be suitable to carry onboard a spacecraft of traditional size and cost. To the extent that the demonstration succeeds, it may "open the door" to reliable one-way Doppler and ranging for long-duration missions.

support, the DSN is currently working to extend this cross-support model to universities and other organizations possessing large antennas suitable for communicating with deep space missions. Having cross support available for cubesats is important since the simultaneous, multi-spacecraft communications techniques discussed earlier only apply when all the participating spacecraft reside in the same ground antenna beam. But, not all cubesat missions will reside within the half-power beamwidth of some other spacecraft's ground antenna for any significant duration. These cubesats will require individual antenna support. During occasional peak-load periods, the DSN will not always have antennas available for these individual supports. At such times, university and foreign agency cross support could help assume some of this peak-load demand. To this end, via funds provided by NASA's Advanced Exploration Systems Office, the DSN is working with Morehead State University on a pilot activity to bring its 21m antenna up to DSN cross-support standards and to apply the antenna in support of the EM-1 secondary payload cubesats anticipated for 2018. To the extent that this pilot activity succeeds, it will then become a model for establishing other university cubesat cross-support arrangements.

The third prong of the DSN's three-pronged approach to servicing burgeoning cubesat demand involves investigating less uplink-intensive navigation techniques. As noted earlier, one of the most important radiometric methods for navigating deep-space spacecraft is that of coherent two-way ranging and Doppler. That method requires an uplink to go with the downlink, and unfortunately, that is not always possible. When cubesats are in a position to make use of simultaneous, multi-spacecraft downlink techniques, they may not yet have proven, corresponding simultaneous, multi-spacecraft uplink techniques available upon which to rely. And, when circumstances necessitate relying on cross-support antennas for individual support, not all of those cross-support assets may be uplink-capable. So, it makes sense to look at ways for cubesats to cost-effectively navigate in deep space without the benefit of having a readily available uplink. While developments like DSAC look promising, it could be quite a while before the technology scales down to a cost, mass, volume, and required input power that is compatible with cubesats. In the interim, the DSN is looking into things like using coarse one-way Doppler measurements in conjunction with occasional very long baseline interferometry techniques that can depend on non-DSN, downlink-only assets. Similarly, coarse one-way Doppler supplemented with occasional onboard optical measurements (i.e., star camera measurements) represent another avenue of inquiry. When these and other techniques have been more thoroughly investigated, the findings will be made available to the cubesat community for further consideration.

The remainder of this paper focuses on how cubesat missions can make the most of existing and upcoming simultaneous, shared-beam, multi-spacecraft downlink techniques – particularly those that, as alluded to in the preceding discussion, lend themselves to opening up a new, low-cost “self service” paradigm for cubesat communication.

II. Simultaneous, Shared-Beam Multi-Spacecraft Communications Techniques

Development of simultaneous, shared-beam multi-spacecraft communications capabilities began over a decade ago to accommodate simultaneous downlink from multiple Mars orbiters without using up the antennas needed by non-Mars missions visible from the same DSN complex. Known as Multiple Spacecraft Per Antenna (MSPA) capability, this technique allows two spacecraft within the half-power beamwidth of a DSN antenna to arrange to simultaneously share that antenna for downlink.^{†††} This simultaneous sharing is made possible by the fact that each spacecraft is transmitting at a different frequency and that each antenna is associated with two receivers. So, one spacecraft can communicate down through the antenna to one receiver at one frequency, and the other spacecraft can communicate down through the same antenna to the other receiver at the other frequency. Because only two spacecraft have been simultaneously serviceable with this technique, it has sometimes been referred to as “2-MSPA” (Fig. 1).

In preparation for supporting the deployment of up to 13 cubesat secondary payloads from the Orion adapter on the upper stage of the SLS in 2018, the DSN has been working to implement “4-MSPA” on at least one antenna per complex. So, in this case, four spacecraft or cubesats will be able to downlink simultaneously through the same antenna, each at a separate frequency to a separate receiver. For uplink, the baseline plan is for the four spacecraft to share the antenna pass, such that the first spacecraft uplinks during the first quarter of the 4-MSPA downlink pass, the second spacecraft uplinks during the second quarter of the pass, the third spacecraft uplinks during the third quarter, and the fourth spacecraft uplinks during the final quarter. Sometimes referred to as “serial uplink swapping,” this technique (also shown in Fig. 1) is already used in conjunction with 2-MSPA downlink -- with one

^{†††} MSPA is also sometimes referred to as “Multiple Spacecraft Per Aperture.” At Mars at S- and X-band, everything is within the half-power beamwidth of a single 34m antenna.

spacecraft uplinking during the first half of the pass and the second spacecraft uplinking during the second half of the pass. So, even though both spacecraft cannot uplink simultaneously, they do each receive enough uplink time to allow for some commanding and two-way ranging and Doppler.

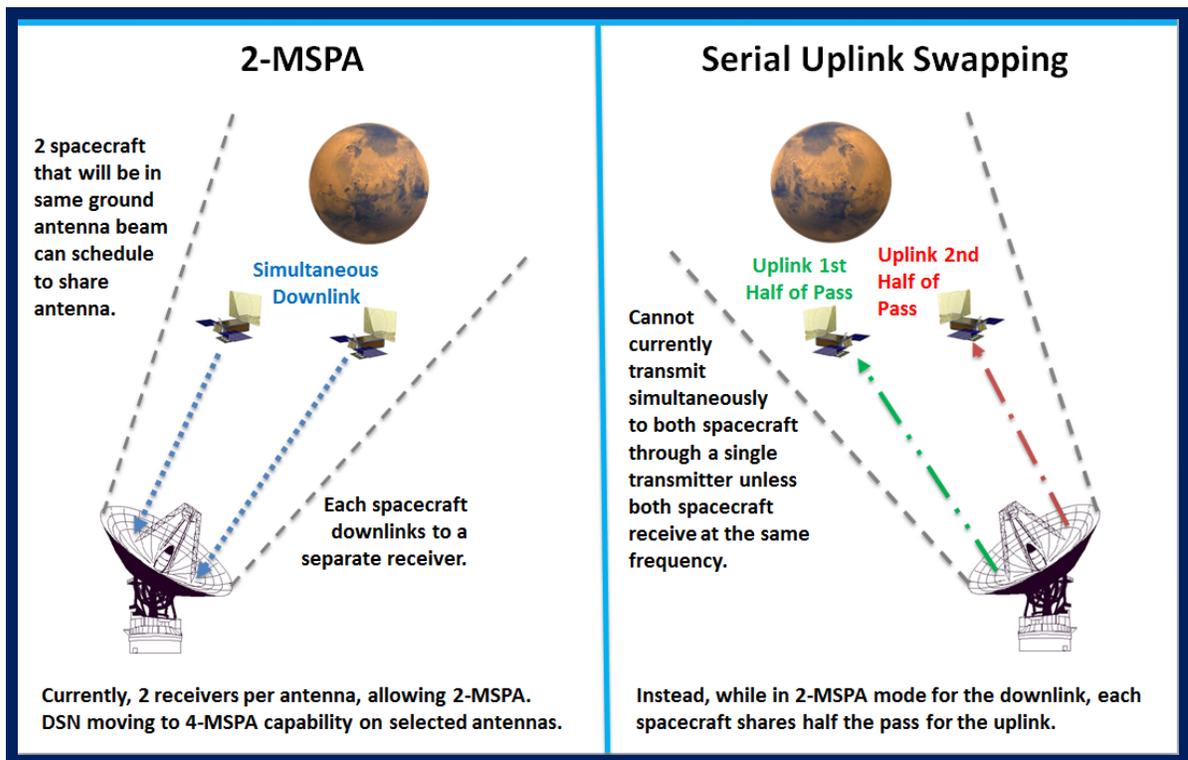


Figure 1. 2-MSPA and Serial Uplink Swapping.

Moving beyond 4-MSPA to n-MSPA (where “n” is some number greater than four) is currently difficult for a couple of reasons. Adding additional hardware receivers is expensive, and the current DSN is configured so that the intermediate frequency (IF) output from each antenna to the complex’s signal processing center is analog and only capable of being split into four copies. The DSN is moving toward a “Common Platform” architecture that will, among other things, enable digitization of the IF to occur at each antenna, with the potential to make as many digital copies of the IF as desired. These digital copies can then be routed to a bank of software receivers, each one capable of demodulating and decoding a particular spacecraft’s signal at a particular frequency. At that point, n-MSPA becomes quite doable. Serial uplink swapping, however, starts to become infeasible (for “n” significantly greater than 4 spacecraft) due to the very short amount of time available to each spacecraft for uplink (not to mention the challenges of maintaining the pass calibrations needed for the two-way ranging and Doppler). So, one or more of the simultaneous, multi-spacecraft uplink schemes briefly discussed earlier becomes a highly desirable complement to n-MSPA.

A higher latency, but lower-cost, approach to MSPA currently under investigation is that of Opportunistic MSPA.¹ Instead of adding additional receivers to accommodate each of the additional spacecraft sharing the ground antenna beam of a “host” spacecraft, a broad-band recorder is used to capture the IF signal across the frequency band(s) of interest – essentially “seeing” everything the antenna “sees.” Cubesats or other spacecraft within the half-power beamwidth of the “host” spacecraft’s ground antenna while it is actively tracking the “host,” can opportunistically transmit open-loop during that timeframe. These open-loop transmissions will appear in the IF signal being captured on the recorder. To recover the data in these transmissions, each of the cubesat Mission Operations Centers (MOCs) could register for, and subsequently interface with, a secure internet site providing access to the IF recording in the frequency range and timeframe of interest. After retrieving the appropriate portion of the recording, each of the MOCs could then apply software tools to demodulate and decode its cubesat’s signals and recover its data, or subscribe to a service that does it for them. Alternatively, each MOC could, through the same secure internet site, pre-arrange for a software receiver at the DSN complex to automatically demodulate and decode the recording at the frequency and across the timeframe of interest. The resulting transfer frames would then

be passed on to the MOC in much the same way that they are in the DSN's traditional downlink service. Both approaches are illustrated in Fig. 2 below.

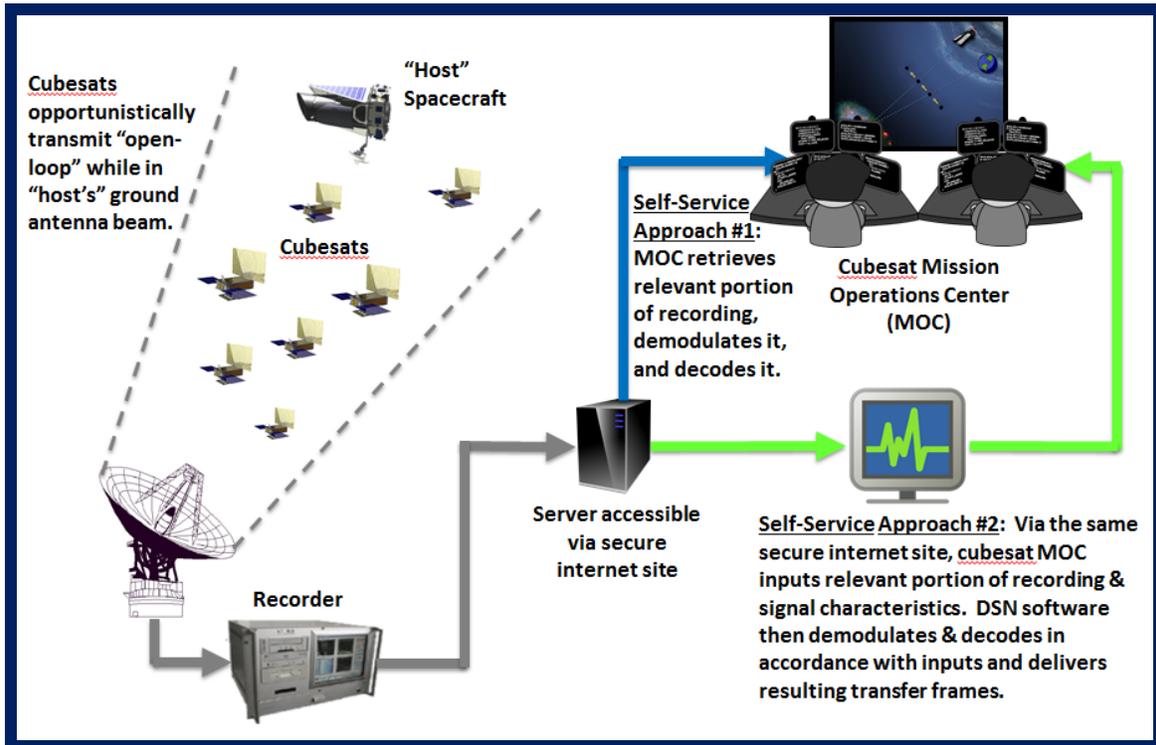


Figure 2. Opportunistic MSPA (OMSPA) and Two Possible Service Provision Approaches.

Toward the end of FY 2014, an OMSPA proof-of-concept demonstration was undertaken with respect to the first self-service approach.² This demonstration sought to provide prospective smallsat users and the DSN, as the prospective service provider, with demonstrable proof that the OMSPA concept is, in fact, an operationally viable, low-cost means for obtaining routine downlink telemetry. To that end, the demonstration sought to show four things:

1. Given access to the DSN station schedules, associated trajectory files, and an appropriate tool, a user mission can compute the beam intercept times for its trajectory relative to that of a host spacecraft such that it has the capability to arrange its downlink operations to accord with those times.
2. Given the tool in item #1, a user mission can successfully retrieve the portions of the wideband recordings corresponding to its signal via a secure internet site.
3. Given an appropriate tool, a user mission can successfully demodulate, decode, and recover its data from the retrieved recordings within a timeframe that is operationally reasonable for the user mission.
4. A user mission can successfully do these things irrespective of which DSN complex is in view during the pass.

To do all of this, the demonstration began by treating Mars Odyssey as a "smallsat" and Mars Reconnaissance Orbiter (MRO) as the "host" spacecraft. Mars Odyssey was scheduled to transmit to another antenna (not the MRO antenna) to assure that it was transmitting during the demonstration. Using a specially created Beam Intercept Planning System (BIPS) and a DSN 7-Day Schedule Cross-Comparison tool (7-DSC), opportunities were identified when Mars Odyssey would be transmitting while in MRO's ground antenna beam. Existing Very Long Baseline Interferometry (VLBI) Science Receivers (VSRs) were used to record the Mars Odyssey downlink telemetry during these opportunities. The recordings were played back to a secure server outside the Flight Operations Network firewall, but inside the JPL firewall. The demonstration team's signal processing personnel retrieved the recordings from this secure server and downloaded them to a workstation containing an OMSPA Software Demodulator (OSD) tool to demodulate and decode the Mars Odyssey signal. Validation of the recovered data was then accomplished by

comparing the transfer frames obtained through OMSPA with those recovered via Mars Odyssey's formally scheduled downlink.

The demonstration successfully achieved all four of its objectives. BIPS and 7-DSC predetermined OMSPA opportunities to within a minute or less of the formally scheduled downlink times. The demonstration team was able to successfully playback the VSR recordings to the secure server outside the Flight Operations Network firewall in timeframes ranging from 1 hour and 23 minutes (Goldstone) to 9 hours and 41 minutes (Madrid). The recordings were then transferred to the OSD workstation in approximately 53 minutes. Demodulation and decoding were then achieved in 5 to 6 hours, with at least 99.95% of the transfer frames being successfully recovered from each demonstration recording.

While the turnaround time for recovering the transfer frames from the recording was well within the single-day goal set for the demonstration, the desire to further reduce the latency prompted subsequent investigation into some of the longer data transfer times from the overseas complexes. This investigation suggested two factors that led to the long data transfer times. The first had to do with a low-priority setting for the VSR data relative to the other data being transferred from the complexes to JPL. The second had to do with the fact that the VSR (being significantly older than other types of DSN science/VLBI receivers) did not have the data-playback-rate capability needed to take advantage of the wide area network bandwidth when fully available. Both factors could easily be mitigated in the future by associating the data with a higher priority and using more modern receiver/recording equipment with faster playback capability. So, the achievable end-to-end latency for the OMSPA self-service approach #1 in the future is more likely to be limited by the time needed for demodulation and decoding than by the time needed for data playback from the recorder.

III. MSPA and OMSPA: The Value Proposition

In the preceding section, we introduced the MSPA and OMSPA concepts, discussed some of the past applications of these concepts, and pointed to how they might be implemented in the future. In this section, we will focus more on why these techniques may be of particular value to cubesat missions. Clearly, they are not a panacea for all of a mission's communication and navigation needs. They apply only to downlink and apply only when multiple spacecraft happen to all be within the half-power beamwidth of a ground antenna at the same time. Until simultaneous, shared-beam multi-spacecraft uplink becomes available, these techniques will have to be used in conjunction with serial uplink swapping and/or traditional uplink and downlink services in order to command the spacecraft and navigate it via two-way ranging and Doppler. OMSPA further constrains the user to operations that can tolerate substantial latency in the recovery of the downlinked data. In short, it is highly unlikely that any mission can use MSPA or OMSPA to the exclusion of all other communications services. So, why bother with either technique?

A. Enhanced Antenna Availability

As discussed in earlier sections, the large antennas needed for communicating at deep space distances do not come cheaply. At a cost of a few tens of millions of dollars per antenna, NASA cannot afford to meet burgeoning cubesat communications demand by building tens of additional antennas at each DSN complex. So, with a relatively fixed number of deep space antennas available, some amount of antenna sharing between missions has to occur. Otherwise, some missions simply will not be tracked.

Antenna availability can particularly be an issue when multiple cubesats are being deployed as secondary payloads from the upper stage of a launch vehicle – a means of deployment that contributes significantly to reducing the cost of cubesat missions. As currently envisioned for the EM-1 secondary payload deployments off the Orion adapter on the SLS's Interim Cryogenic Propulsion Stage (ICPS), at least three or four of the 13 or so cubesats will be deployed at set intervals. Within each interval or "bus stop" as it is sometimes referred to, the three to four cubesats are released in rapid succession. Presumably, each cubesat project will want to establish that its cubesat has deployed correctly, that it is functioning nominally, and that it is on a course consistent with its planned trajectory. Shortly after that, each cubesat project may want to command its cubesat to set up for and then execute one or more trajectory correction maneuvers (TCMs) to keep it on its planned trajectory as it flies past the Moon. But, it is possible that only one DSN complex at a time will be in view while all of this is happening. The complex will only have three to four antennas. Two of those antennas will likely be trained on EM-1's maiden flight of Orion -- one as a prime antenna and one as a "hot backup." So, there may only be one or two antennas remaining. One of those may be tied up supporting one or more traditional robotic spacecraft, leaving only one antenna to share amongst the three to four cubesats. With each antenna pass requiring about 45 minutes for setup and another 15 minutes for tear-down, servicing each cubesat in separate, serial passes would significantly limit the amount of

communication time available for assessing spacecraft health, determining its course, and introducing trajectory corrections. Analyses by two of the authors, however, have shown that all of the released cubesats will likely be within the half-power beamwidth of a single 34m ground antenna for at least several hours.^{§§§} So, 4-MSPA with serial uplink swapping would be capable of providing simultaneous, real-time downlink from all of the deployed cubesats within the same antenna pass, as well as serial uplink opportunities within that pass for two-way ranging and Doppler, spacecraft commanding, and TCM execution.

Even when the cubesats have gone their separate ways and are no longer within the beamwidth of a single 34m antenna, both MSPA and OMSPA have a potential role to play – in this case, freeing up antennas for the cubesats through application to other missions that happen to be within the beamwidth of a single 34m antenna. As mentioned earlier in the paper, missions at Mars are always within the beamwidth of a single 34m antenna, and they already make use of 2-MSPA for most routine downlink passes. With 4-MSPA, twice as many Mars spacecraft could potentially be serviced with a single antenna for routine downlink. And, with OMSPA, as long as the higher latency could be tolerated, a virtually unlimited number of spacecraft could downlink to a single antenna. While the antennas freed up from the Mars missions might not always be in view of cubesats headed toward the Moon, the analysis results shown in Fig.3 below suggest that the view periods overlap with sufficient frequency and duration where there could be tangible benefit.

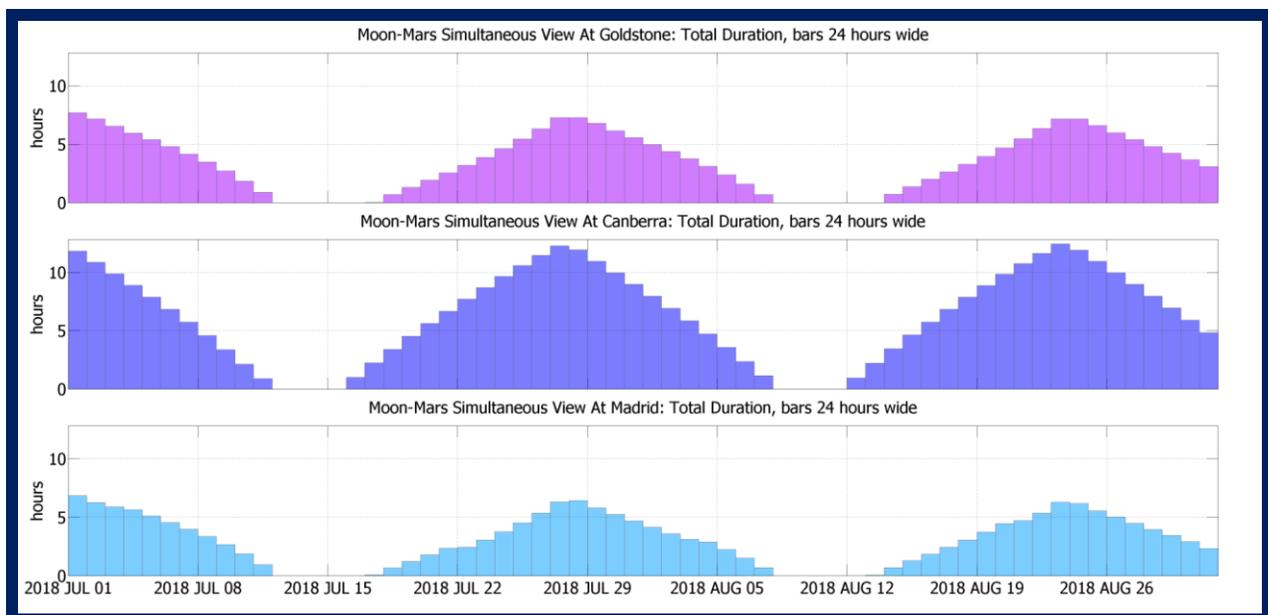


Figure 3. Moon-Mars Visibility Overlaps for Each of the DSN Complexes in July-August 2018.

B. Reduced Antenna Scheduling Coordination

Clearly, by enhancing antenna availability via MSPA and/or OMSPA, the potential for contention with other missions in the DSN’s scheduling process should go down. However, for routine downlink passes, OMSPA also has the potential to free cubesat projects from the DSN scheduling process altogether. Remember that the proposed OMSPA technique in Fig. 2 works by: identifying a “host” spacecraft in whose ground antenna beam the cubesat will reside, figuring out when the “host” will be communicating with the ground antenna, transmitting open-loop from the cubesat during those times, and retrieving the appropriate portions of the recording from that ground antenna’s recorder for subsequent demodulation and decoding. To the extent that the antenna is always open-loop recording, there is no need to schedule it. The antenna has already been scheduled by the “host” mission. The cubesat is just making opportunistic use of the antenna’s beam. And, as long as the cubesat project has properly worked through the required National Telecommunications Information Agency (NTIA) process to obtain its authorized frequencies, there should be no potential for radio-frequency interference, nor any associated need to

^{§§§} NASA-internal study by Bruce E. MacNeal and David P. Heckman entitled “EM-1 CubeSat Deployment Analysis,” October 1, 2015.

coordinate with the “host” spacecraft.^{****} The only interaction with the DSN scheduling system would be via a tool (e.g., 7-DSC) provided on the proposed OMSPA secure internet site to ascertain when the “host” will be actively communicating with a ground antenna, and on which antenna.

Of course, most cubesat missions will likely need more than just routine downlink at various points in their mission. They may need traditionally scheduled passes for commanding, two-way ranging and Doppler, or for critical events in which downlink with negligible latency is required. These types of passes would require participation in the DSN’s antenna scheduling coordination activities. Nonetheless, it is possible to conceive of cubesat missions characterized by long periods of routine downlink when these other pass types are not needed. Such mission concepts will be discussed in the next major section of this paper.

C. Reduced Aperture Fees

Both MSPA and OMSPA offer the potential for significantly reduced fees for antenna time.^{††††} NASA missions do not actually pay these fees, but the fees do count toward the mission’s total cost while it is being proposed. Non-NASA missions that are not part of some sort of *quid pro quo* arrangement with NASA are referred to as “reimbursable” missions and do pay the full aperture fees. Other government agency missions, commercial missions, some foreign agency missions, and university missions that are not NASA-sponsored fall into this “reimbursable” category. Because the aperture fees for a year’s worth of tracking can be of the same order of magnitude as the total development cost for a deep space cubesat mission, reimbursable missions and missions proposing for NASA’s competitively-bid opportunities are particularly motivated to reduce such fees wherever possible.

According to the *Deep Space Network Services Catalog*, current 2-MSPA users are entitled to a 50% reduction in aperture fees while sharing an antenna with another user in a downlink-only mode.³ While not yet decided, 4-MSPA users presumably would be entitled to a 75% aperture fee reduction when sharing an antenna with three other users in a downlink-only mode, and n-MSPA would presumably enable similar, proportionally scaled fee reductions. So, for situations where low data latency is desired, beam sharing via 4-MSPA and, eventually, n-MSPA may provide cubesat projects with a viable technique for keeping their downlink costs low.

While OMSPA and the details of its implementation are still under consideration, the self-service approaches discussed in this paper would probably qualify for some sort of flat monthly fees that would be even more affordable than the aperture-time-dependent fees for n-MSPA. These monthly fees would go toward the implementation and maintenance of the recorders at each antenna, the provision of the secure internet site for accessing the necessary tools/services and relevant portion of the recordings, and the provision of the tools/services themselves for planning the recordings and recovering data from them. A reduced aperture-based fee would not make as much sense as a flat monthly fee since, in the OMSPA mode, it matters neither how many users there are, nor how long those users take advantage of the service. DSN equipment and labor costs do not scale up with the number of users or with their durations of use. OMSPA takes one recorder at each antenna, whether there are two in-beam users or a thousand in-beam users and whether they transmit once a month for 8 hours or 10 times a day for one hour. So, a modest, flat monthly fee for OMSPA service subscription would tend to make a lot of sense. For low-budget cubesat missions in routine downlink situations where data latency is manageable, this flat monthly fee structure would enable a dramatic reduction in their communications costs.

Taking advantage of these potential communications cost reductions, however, requires cubesat mission designers to surmount at least two key challenges. The first challenge is to design missions in a manner that maximizes shared-beam opportunities. Without some other spacecraft with which to share a ground antenna beam, neither MSPA nor OMSPA can apply. The second key challenge is to design the mission in a manner that maximizes routine downlink time and minimizes required uplink time. Until shared-beam, simultaneous, multi-spacecraft uplink capability exists, any required uplink is going to necessitate the traditional, full-price communications service over the duration of the required uplink time. In the section that follows, we present some example mission design concepts that maximize beam sharing opportunities, maximize routine downlink time, and minimize required uplink time.

^{****} NASA and other government agency missions must obtain authorized frequency assignments through NTIA. U.S. commercial and university missions (not sponsored by a U.S. government agency) must obtain authorized frequency assignments through the Federal Communications Commission (FCC). NASA-sponsored cubesat missions should consult with their NASA Center Spectrum Managers for additional information.

^{††††} Aperture fee information, as well as other useful information regarding DSN services, is available at: <http://deepspace.jpl.nasa.gov/advmiss/missiondesigndocs/#>.

IV. Example Mission Design Concepts Amenable to Beam Sharing

As noted in the previous section, designing one’s cubesat mission to maximize beam sharing opportunities with other spacecraft can potentially improve antenna availability (and, in the case of OMSPA, reduce antenna scheduling coordination) while significantly reducing attributed fees for antenna time. Achieving such a design might begin with asking, and answering, the following questions:

- 1) What are my science or exploration goals?
- 2) Given a deep space cubesat’s probable mass, power, and volume constraints, associated onboard telecom system, and likely launch opportunities, at what destinations in the solar system could I possibly achieve those science or exploration goals?
- 3) Will other spacecraft be operating at any of these destinations in the timeframe of interest?
- 4) For the destinations where they will be, what ground antennas will they be communicating with?
- 5) Would my probable cubesat telecom system, at those destinations, support a communications link with the associated ground antennas at the required data rates?
- 6) For those destinations where the link would close, what is the half-power beamwidth of the associated ground antennas?
- 7) Will the diameter of the ground antenna beam at the destination(s) of interest be sufficiently large to encompass both my cubesat and the other spacecraft?
- 8) Will this in-beam condition occur frequently enough and/or long enough to support my communications needs?

To the extent that the answers to these questions identify multiple candidate destinations, trade studies can then be conducted to determine which locations impose the least stringent navigation and station-keeping requirements, thereby minimizing required uplink for commanding and two-way ranging and Doppler. These results, of course, also have to be traded off against other mission design considerations (e.g., maximum science value, solar illumination, required onboard consumables, operational complexity, spacecraft design life, etc.) and their associated costs.

In the subsections that follow, we attempt to provide some example destinations and their implications relative to questions three through eight – assuming DSN ground antennas and certain specific onboard telecom assumptions.

A. Mars, Venus, and More Distant Planets

As already alluded to in earlier sections of this paper, just about anything at Mars is typically within the half-power beamwidth of the DSN’s 34m and 70m antennas.^{****} Table 1 shows the approximate beam diameter for different Mars ranges as a function of antenna diameter and downlink frequency.

Table 1. Beam Diameter in Terms of Mars Radii for Minimum, Average, and Maximum Mars Range.

Antenna Diameter (m)	Freq Category	Band	Downlink Frequency (GHz)	Wavelength (m)	HPBW (deg)	HPBW (rad)	Beam Diameter in Mars Radii		
							Mars Min	Mars Ave	Mars Max
70	Cat B	S	2.295	0.1306	0.1180	0.00206	17	78	122
70	Cat B	X	8.42	0.0356	0.0320	0.00056	5	21	33
34	Cat B	S	2.295	0.1306	0.2420	0.00422	35	159	249
34	Cat B	X	8.42	0.0356	0.0660	0.00115	10	43	68
34	Cat B	K32	32	0.0094	0.0170	0.00030	2	11	18

There are already a significant number of spacecraft at Mars that routinely communicate with these DSN antennas. Such spacecraft include Mars Odyssey, Mars Reconnaissance Orbiter, MAVEN, Opportunity, Curiosity, ESA’s Mars Express, and India’s Mangalyaan.^{****} While some of these spacecraft may no longer be operating

^{****} An antenna’s half-power beamwidth can be approximated using $HPBW(deg.)=70.8(\lambda/D)$ where λ is the wavelength associated with the radio frequency and D is the antenna diameter. Results can vary somewhat, depending, among other things, on how much of an antenna’s stated diameter is actually relevant reflector and not just structure.

^{****} The Opportunity and Curiosity rovers generally rely on Mars Odyssey and Mars Reconnaissance Orbiter to relay their data back to Earth, but they do periodically communicate direct to Earth as well.

several years hence, new Mars spacecraft are currently under development that will ultimately replace them. ***** At Mars, future cubesats are therefore likely to have plenty of opportunities to schedule MSPA passes in conjunction with such spacecraft. And, because such spacecraft will primarily rely on scheduled passes, they represent potential “hosts” for OMSPA – i.e., with the cubesats making opportunistic use of their passes without having to schedule their own. The fact that cubesats will need occasional two-way ranging and Doppler and uplink commanding for orbit maintenance and science execution may also present mainline Mars missions with occasional opportunities for exploiting the cubesats as “hosts.” During these times, the mainline missions would, when not occluded by Mars, transmit open loop in the cubesats’ ground antenna beams.

Mars is not the only planet where these beam sharing opportunities abound. As Fig. 4 shows, the half-power beamwidth of the DSN’s 34m antennas at Venus range distance is sufficiently large to encompass most missions operating at deep space S- and X-band. Ka-band missions in relatively tight orbits around Venus would also fall within this beamwidth. While JAXA’s Planet-C/Hayabusa mission is currently the only mission operating at Venus, additional missions are likely to follow. Two of the five mission concepts currently being evaluated for NASA’s Discovery-13 mission, VERITAS and DAVINCI, are Venus missions. So, it is quite possible that MSPA and OMSPA opportunities similar to those at Mars may be available for future cubesats at Venus.

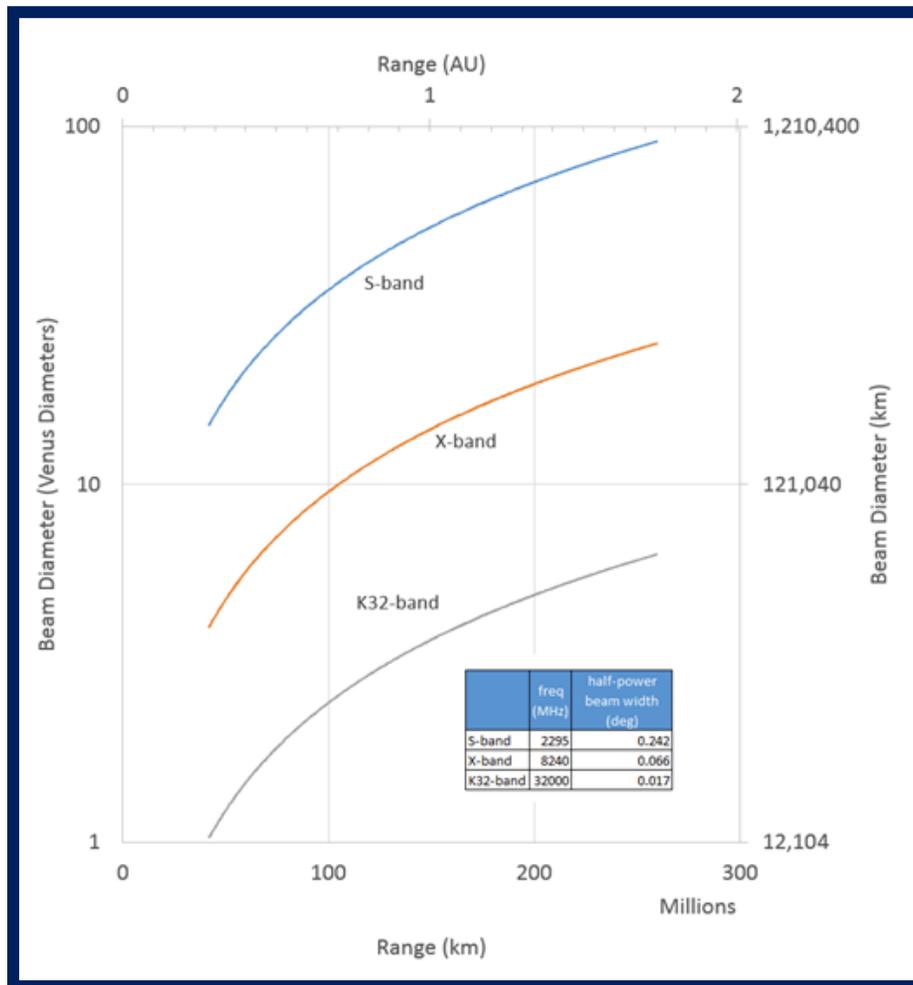


Figure 4. 34m Beam Diameter at Venus as a Function of Frequency Band and Range Distance.

***** ESA’s ExoMars 2016 and 2018 Mars missions are nearing launch. NASA’s Mars 2020 Rover is approved and under development. A Mars 2022 Science Orbiter is under study. And, a number of other countries (e.g., Japan, India, UAE, etc.) are pursuing plans for Mars probes in the 2018-2022 timeframe.

To the extent that DSN antenna beams encompass most missions at Venus and just about any at Mars, the beam diameter at more distant planets will encompass most everything in their vicinity. The one question we have not yet addressed is what the data rate performance might be like at all of these locales. Figure 5 provides a solar system wide view of the anticipated data rate performance for a MarCO-like cubesat telecom system as a function of frequency band and range distance.^{††††} So, for instance, at average Mars range distance, tracing up to the red X-band line, we see that the intersection point on the left vertical axis corresponds to a cubesat data rate of a couple of kilobits per second. The figure also shows the 34m beam diameter as a function of range distance and frequency band. So, again, tracing up from average Mars range distance, this time to the green X-band line, we see that the intersection point on the right vertical axis corresponds to a beam diameter well in excess of 100,000 km.

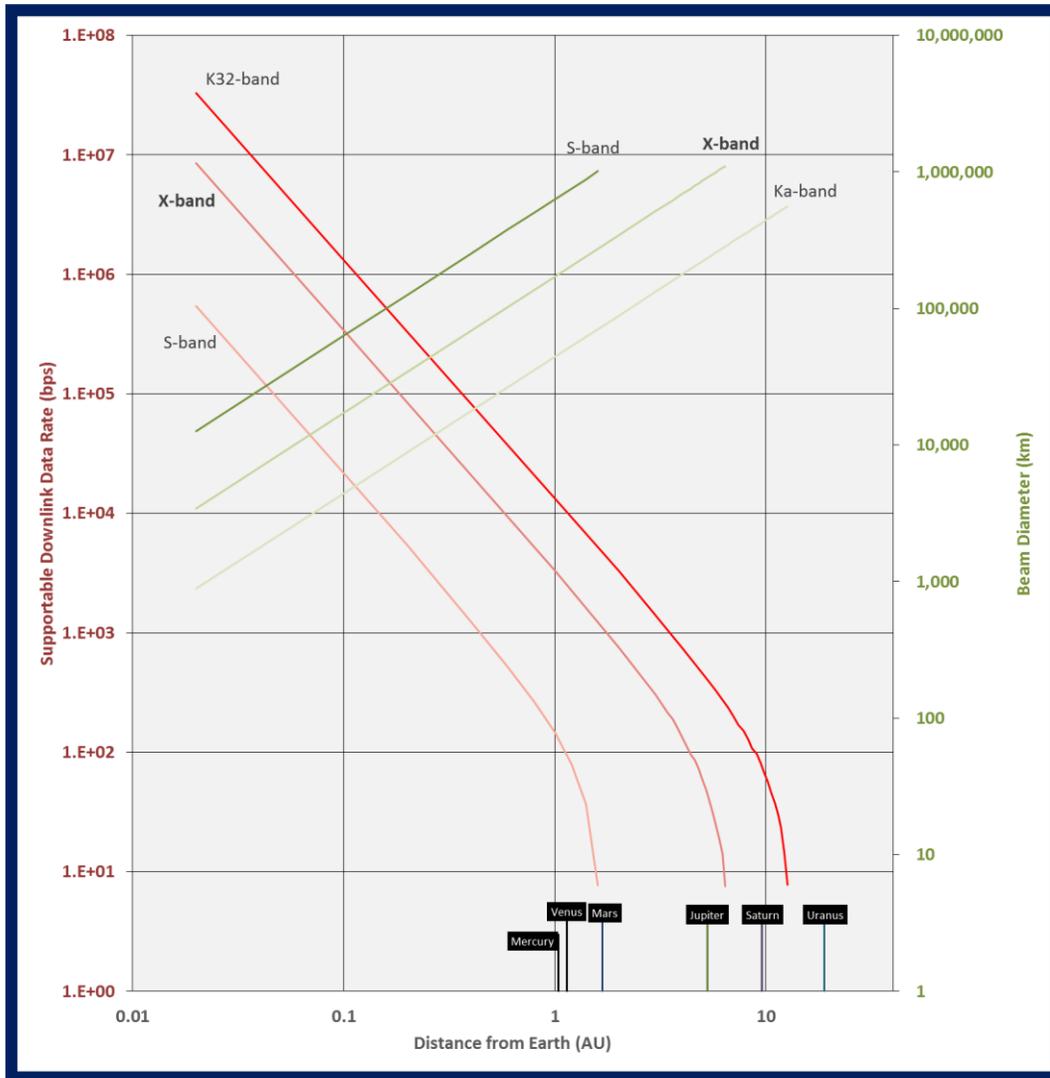


Figure 5. 34m Data Rate Performance and Beam Diameter Across the Solar System.

^{††††} MarCO stands for Mars Cubesat One. This mission consists of two deep space cubesats designed to serve as relays for NASA's InSight lander during Mars entry, descent, and landing. The MarCO cubesats make use of an X-band Iris radio to communicate direct to Earth (subsequent versions of Iris will also be S- and Ka-band capable). The radio also provides a UHF proximity link capability for relaying from InSight. The MarCO spacecraft launch as secondary payloads on the upper stage that sends InSight on its way to Mars. Launch was due to occur in March of 2016, but difficulties with InSight's seismometer forced a delay until the next launch opportunity in 2018.

A Venus mission would allow slightly higher data rates at X-band than at Mars, but with a slightly decreased beam diameter in which to operate (but still well over 100,000 km). Perhaps surprisingly, Mercury's average distance from Earth is actually closer than Venus's average distance, enabling a somewhat higher data rate (on average) and a beam diameter close to 100,000 km. The thermal and radiation environment at Mercury, however, might not be very conducive to a long-lived cubesat mission, and the absence of any current or planned mainline missions to Mercury suggest that MSPA and OMSPA opportunities would be wholly lacking.

At Jupiter, the supportable data rate would be around a hundred bits per second (assuming that the cubesat's solar arrays could somehow be sufficiently enlarged to provide the telecom system with the necessary power), and the beam diameter in which to operate would be immense, approaching a million kilometers. Two mainline missions are currently planned to venture out to the Jupiter system near the beginning of the next decade – ESA's JUICE mission and NASA's Europa mission. JUICE will focus on Ganymede which is about a million kilometers from Jupiter. The Europa mission, of course, will focus on Europa which is about 671,000 km from Jupiter. So, any cubesats launched as secondary payloads from the upper stages of these missions would likely remain within the beamwidth of the DSN's antennas over much of the mission. While such cubesats would probably tend to relay their data back to Earth via JUICE and/or Europa, there might be radiation considerations that would cause them to assume more distant orbits than those used for the mainline missions. If so, the distance between the cubesats and these other spacecraft might be too great to support proximity links, yet might still be close enough to allow very low data rate communications direct to Earth via MSPA or OMSPA.

Beyond Jupiter's range distance, realizable data rates at X-band appear to be too low for a MarCO-like cubesat to be feasible. While Ka-band might improve the realizable data rate, there would not be enough solar illumination to power the cubesat sufficiently for the Ka-band communications to occur.

So, in terms of planetary destinations, Mars and Venus appear best suited to deep space cubesats and their sustained use of MSPA and/or OMSPA. In the next decade, Jupiter-bound missions might also provide some very limited cubesat "rideshare" opportunities and associated MSPA/OMSPA communications potential.

B. Earth Trailing Orbits and Constellations of Cubesats

Not all deep space cubesats are likely to be focused on planetary exploration. They may also have a significant role to play in making heliophysical, astrophysical, or other types of observations. To these ends, heliocentric Earth Trailing Orbits (ETOs) and Earth Leading Orbits (ELOs) may prove attractive "destinations" for cubesats. The notion of an ETO first originated with the Spitzer Space Telescope in the early 1990s.⁴ At that time, the Spitzer Project was planning on using an earth-escape orbit to Sun-Earth Lagrange Point 2 (SEL2). However, the orbit for a spacecraft positioned at SEL2 is not quite stable. So, the Spitzer Space Telescope would have required station-keeping maneuvers every few months. This in turn would have driven up the spacecraft's complexity, mass, and associated launch costs. Faced with significant budgetary pressures at the time, the Spitzer Project began looking for a more cost-effective orbit. This search culminated in the heliocentric ETO.

Using iterative simulations of an earth escape orbit involving varying energies and directions, the Project found a minimum drift rate orbit with a very low escape energy of about $0.4 \text{ km}^2/\text{s}^2$.⁵ This heliocentric orbit is slightly larger than the Earth's with a period of about 373 days. Because of this larger orbital period, the spacecraft generally trails the Earth, drifting roughly 0.1 AU further from the Earth each year out to a maximum of ~2 AU (after which the Earth will once again begin to approach the spacecraft).^{****} The orbit is scientifically attractive because it provides a relatively unobstructed view of the sky, allows a consistent solar flux density for solar power roughly comparable to that at the Earth, resides outside of the Earth's radiation belts, and is largely free of torque-producing gravity gradients, allowing a stable pointing attitude. This latter benefit also makes navigation a lot easier, with the only requirement being to have enough knowledge of the telescope's location to allow the DSN's antennas to point at it.⁶ For the Spitzer Project, which originally had a science-driven tracking requirement of 30 minutes every 12 hours, the orbit knowledge it derived from this tracking was two orders of magnitude greater than what was needed to point at the DSN's antennas.

Clearly, heliocentric ETOs have much to offer spacecraft of all sizes. The Kepler mission, in its search for extra-solar planets, employed a very similar trajectory to Spitzer's. And, the Solar Terrestrial Relations Observatory (STEREO) used a variation for its two spacecraft that involved phasing orbits and a lunar flyby to insert one into an

**** Due to the lack of alignment between Earth's perihelion and Spitzer's, Spitzer actually moves closer to Earth for roughly one month a year. But, overall, it drifts away from Earth.

Earth Trailing Orbit and the other into an Earth Leading Orbit.^{§§§§§},⁷ On the upcoming EM-1 launch, BioSentinel, a 6U cubesat devoted to the study of ambient space radiation effects on yeast growth, is planning on being deployed into a ELO following its lunar flyby that leaves it at between 0.98 and 0.92 the Earth's distance from the Sun.⁸ So, the potential benefits of ETOs and ELOs have not gone unnoticed.

From a beam sharing perspective, however, none of these missions provide sustained MSPA or OMSPA "host" opportunities for future missions. The main reason for this is that they all drift in very different positions around the sun relative to the Earth. So, they're rarely, if ever, within the half-power beamwidth of the same ground antenna. And, by the time they once again approach the Earth, their lifetime constraints will likely preclude them from being viable "hosts" for a cubesat trying to launch into a coinciding orbit.

For constellations of cubesats, however, ETOs and ELOs offer a potential means for putting the constellation's multiple spacecraft into a relatively disturbance-free orbit that gets well away from the Earth, requiring few maneuvers and little associated commanding and navigation. Assuming that the cubesats are deployed in roughly the same direction from an upper stage that has inserted into a heliocentric ETO or ELO, they should all reside within the half-power beamwidth of a ground antenna for the duration of the mission. In such a case, the cubesats could all arrange to MSPA during deployment and checkout and during any subsequent critical events. For routine downlink, OMSPA could be employed. One cubesat could schedule a traditional communications link with the ground antenna and the other cubesats could opportunistically take advantage of the scheduled cubesat's ground antenna beam by transmitting open loop at their individually assigned frequencies – with the open loop recordings being captured on the ground antenna's recorder for subsequent retrieval, demodulation, and decoding. Such an arrangement would make very efficient use of the DSN's ground antennas, and it could significantly reduce the mission's attributed aperture fees.

Of course, the constellation could choose to employ one of the cubesats as a relay instead. Future versions of the Iris radio are planned that will provide a two-way UHF proximity link capability, as well as a Delay Tolerant Networking (DTN) capability.⁹ Each of the cubesats in the constellation could communicate with the cubesat relay via the UHF links, and the cubesat relay could provide trunkline communications back to Earth with its X-band capability. In this case as well, the arrangement would make very efficient use of the DSN's ground antennas, and it could significantly reduce the mission's attributed aperture fees. However, the constellation's cubesats, in this case, would have to be built with the capability to properly store, route, and forward data along the most expeditious and reliable path. Whether this would entail less cost and risk than the MSPA/OMSPA approach would need to be the subject of a mission-specific trade study.

Another possible variation on the constellation theme particularly amenable to the MSPA/OMSPA approach would be the case where multiple unrelated missions band together to take advantage of an ETO/ELO deployment opportunity (Fig. 6). In this case, the cubesats might all be built by different organizations and have very different science objectives and associated designs, but they would all be drifting along the same trajectory. To the extent that this "flotilla" would be within the half-power beamwidth of a single ground antenna, it would tend to make more sense for the cubesats to use MSPA and/or OMSPA than for each to individually downlink to separate ground antennas. The cubesats could all arrange to MSPA during deployment and checkout when low-latency is desirable. After that, they could each, in turn, schedule traditional communications links for those occasional times when they need commanding and/or two-way ranging and Doppler. The other cubesats, with only routine downlink needs during those times, could make use of OMSPA – opportunistically taking advantage of the scheduled "host" cubesat's ground antenna beam to transmit open loop, with subsequent retrieval of the recordings for demodulation and decoding. Such an arrangement would require very little coordination between the respective cubesat projects. They would simply need to pay attention to when specific cubesats have scheduled downlinks, so as to know when to transmit open loop. Each cubesat mission could carry out its own processes without worrying about what the other cubesats are doing. Some could be making astrophysical observations in IR wavelengths; others could be making observations at radio, visible, and UV wavelengths; others could be monitoring the solar wind, while still others could be mapping magnetic fields. Yet, via these beam sharing techniques, all could benefit from enhanced ground antenna availability and reduced attributed aperture fees.

^{§§§§§} The Earth Leading Orbit (ELO) is similar to the ETO, except the orbital period around the Sun is slightly less than Earth's.

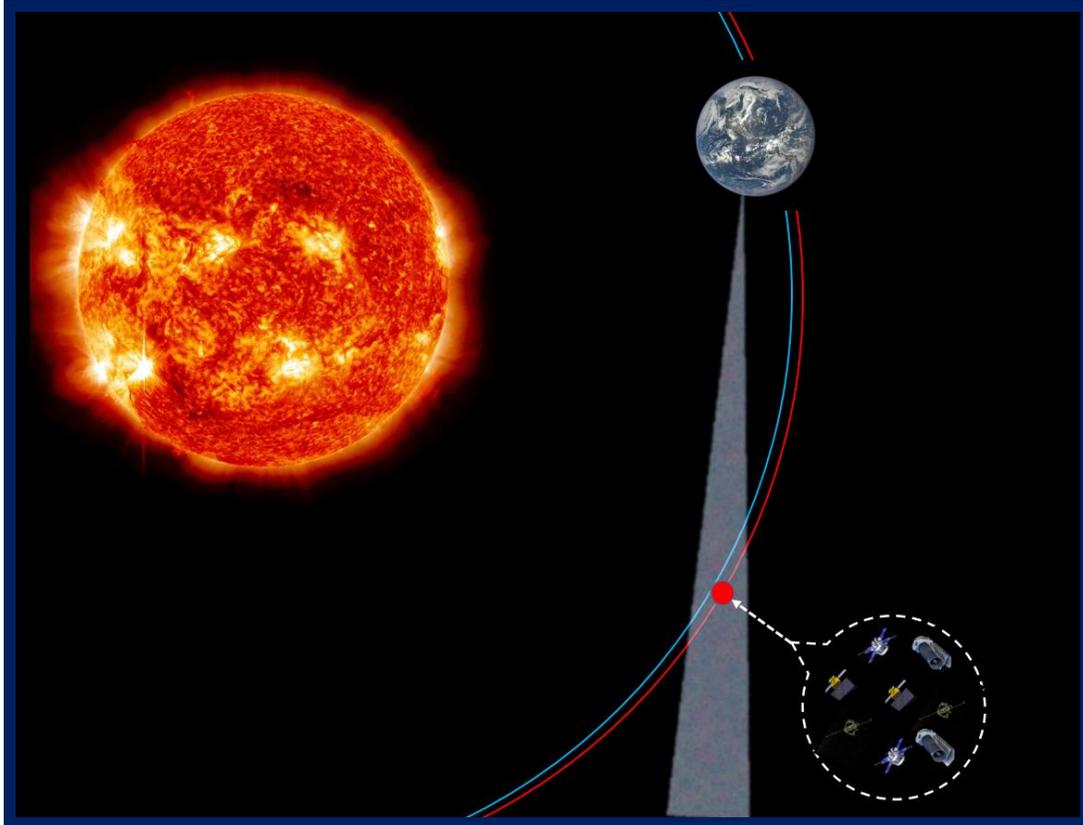


Figure 6. Beam Sharing by a “Flotilla” of Unrelated Cubesats Deployed Together in an ETO.

What we have not yet addressed in this discussion is what the supportable data rates and beam diameters might look like. Obviously, the further from Earth the cubesats drift, the lower the supportable data rate. However, as Fig. 7 suggests, the supportable data rates for a MarCO-like cubesat during the first six months in a Spitzer-style ETO are quite high – in the megabit-per-second range. At the same time, the beam diameter available for the cubesats to share is on the order of 1000 km or more. Even a year into the orbit, supportable data rates are still in the hundreds of kilobits per second, while the available beam diameter expands into the tens of thousands of kilometers. With data rates that high and antenna beams that big, supporting low-latency, critical-event downlink from constellations or “flotillas” of cubesats via MSPA, and routine downlink via OMSPA, should be quite doable. Coupled with the relatively unobstructed views, consistent solar illumination, and reduced navigation requirements associated with heliocentric ETOs and ELOs, this finding suggests that beyond-GEO cubesat mission proposers may want to give more thought to these types of orbits and associated beam sharing arrangements in the future.

C. Sun-Earth Lagrange Points and Potential Observatory Spacecraft “Hosts”

As attractive as heliocentric ETOs and ELOs may be, the sustained Sun-Earth alignment that SEL1 and SEL2 can offer to solar and astrophysical observatories, respectively, makes them very attractive as well. All Lagrange points in the Sun-Earth system are “balance points” at which the centripetal acceleration necessary to maintain a solar orbit having the same period of Earth’s orbit is exactly supplied by the mutual gravitational acceleration of the Sun and the Earth together. The SEL1 and SEL2 points are both on the Sun-Earth line at all times, with SEL1 closer to the Sun than the Earth and SEL2 farther away than the Earth. At SEL1, the “inward” pull of the Sun’s gravity, combined with the opposing “outward” pull of the Earth’s, together provide exactly the centripetal acceleration necessary to remain at the Sun-orbiting SEL1 point. Similarly, at SEL2, the two combined “inward” attractions of the Sun and the Earth together provide the necessary centripetal acceleration to remain in solar orbit at SEL2. Due to these balancing acts, solar observatories at SEL1 can keep their instruments Sun-pointed and their communications Earth-pointed, and astrophysical observatories at SEL2 can keep their instruments pointed into deep space (totally away from the Sun) while keeping their communications Earth-pointed. These features have attracted several missions to both destinations. The Advanced Composition Explorer (ACE), the Solar and Heliophysics Observatory (SOHO), and the Deep Space Climate Observatory (DSCOVR) exemplify current SEL1

missions. The Wilkinson Microwave Anisotropy Probe (WMAP) and ESA’s Herschel Space Observatory (HSO) exemplify past SEL2 missions, with ESA’s Gaia mission being the current SEL2 mission. In 2018, NASA will deploy the James Webb Space Telescope (JWST) at SEL2. So, both SEL1 and SEL2 will have mainline spacecraft operating there through much of the next decade.

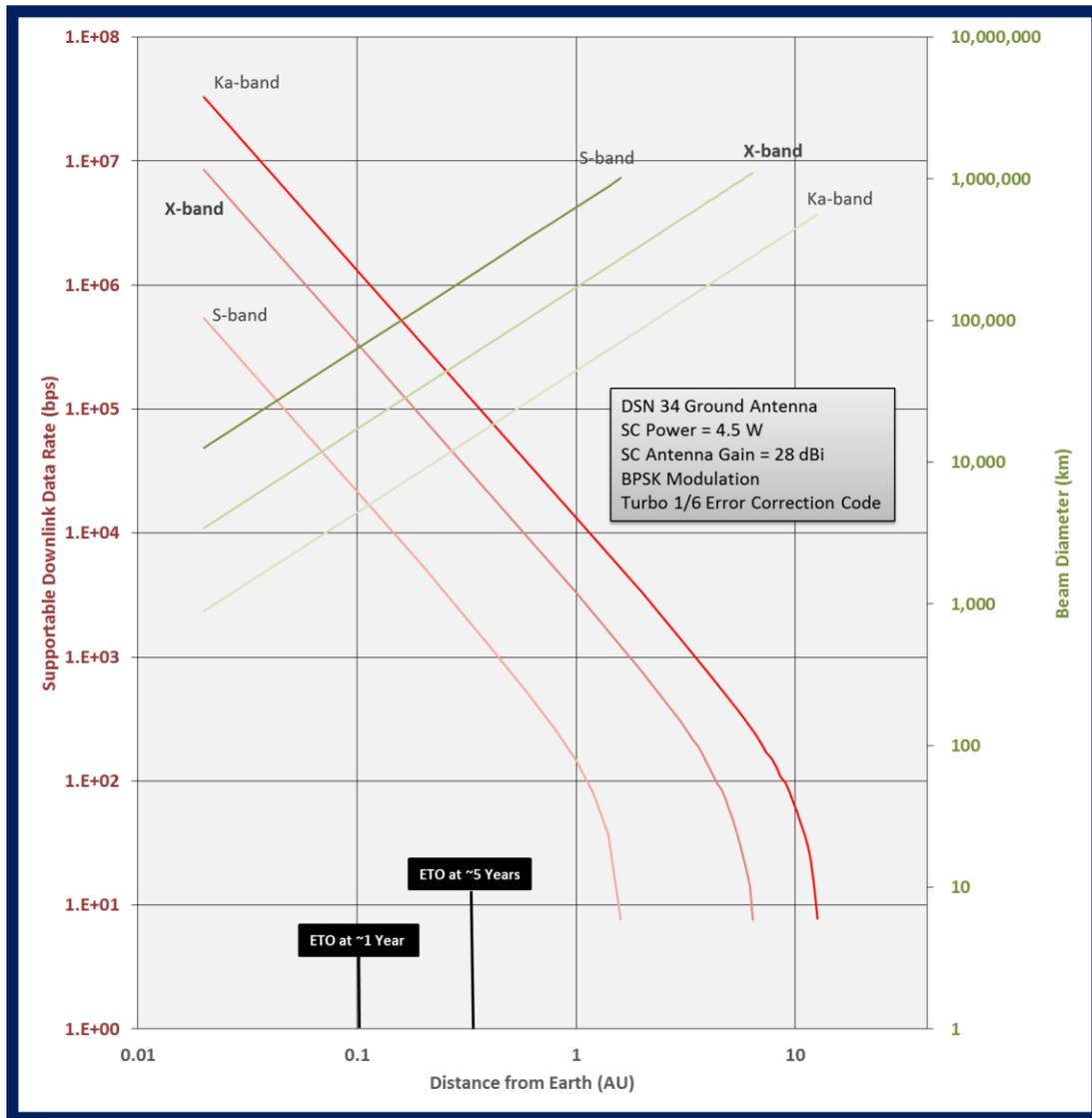


Figure 7. 34m Data Rate Performance and Beam Diameter for a Spitzer-Like ETO.

Thanks to the development of low-energy trajectories during the 1970s and ‘80s, SEL1 and SEL2 may also hold some attraction for cubesats as well.¹⁰ As Jeffrey Parker and Rodney Anderson explain in their book, *Low-Energy Lunar Trajectory Design*, “The field of low-energy mission design relates to the study of trajectories that traverse unstable three-body orbits and take advantage of the dynamics to perform orbit transfers using very little fuel.”¹¹ The only down side to such traversals is that they can take a few months to execute. For cubesats that may be secondary payloads on a lunar-bound launch to start with, the extra traversal time might be worth the associated propellant-cost savings.^{*****12} This could be particularly true if the propellant cost-savings for getting out there

***** In their 1991 paper, “To the Moon from a B-52: Robotic Lunar Exploration Using the Pegasus Winged Rocket and Ballistic Lunar Capture,” Edward Belbruno, Rex Ridenoure, and Jaime Fernandez also describe how to get into orbit around the Moon with low-energy transfer techniques they refer to as “Weak Stability Boundary” transfers. In

outweighs the propellant expenditures needed for station-keeping while there. Other advantages to the low-energy trajectories include greater flexibility in choice of orbit, arrival time, launch window, and trajectory correction maneuver timing.¹³

As the example Genesis trajectory in Fig. 8 suggests, missions do not typically choose to stay precisely at a Lagrange point. Instead, they expend enough station-keeping propellant to remain in quasi “orbits” around the Lagrange points. These “orbits” can sometimes be rather large with radii on the order of hundreds of thousands of kilometers. It is for this reason that SEL1 and SEL2 telecommunications relay proposals are typically deemed impractical.

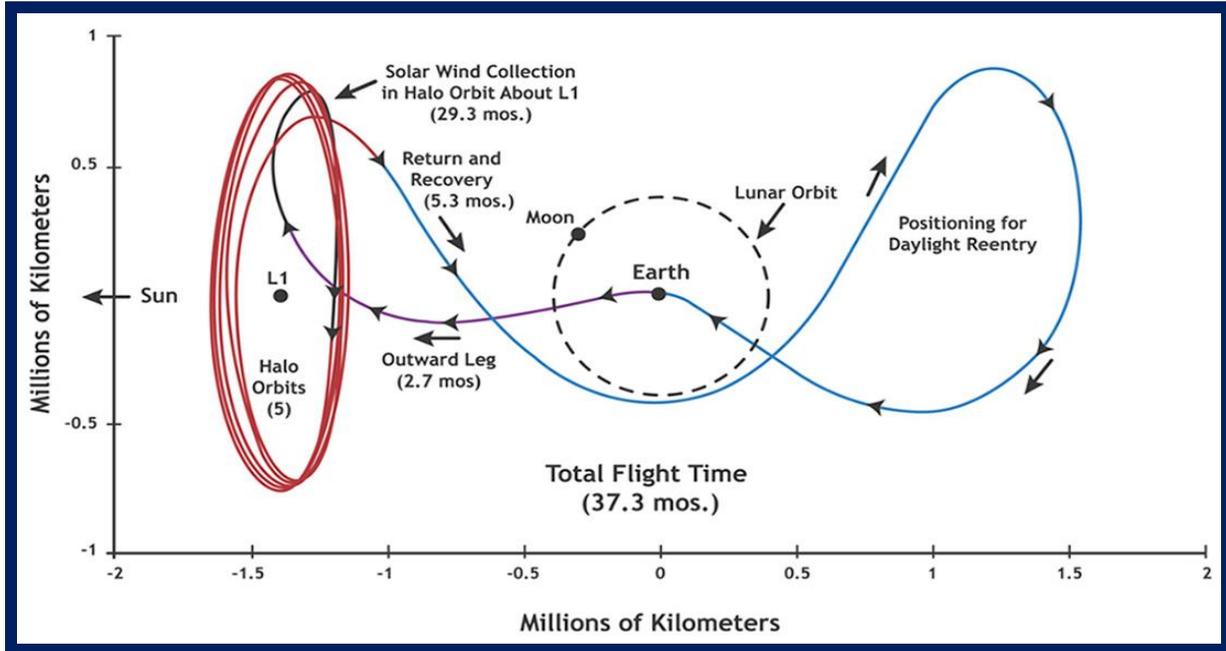


Figure 8. Genesis Mission Trajectory. Source: genesismission.jpl.nasa.gov.

Similar reasoning leads one to conclude that SEL1 and SEL2 cannot be encompassed by the half-power beamwidth of a single 34m antenna. Instead, any beam-sharing has to focus on the identification of a mainline mission “host.” Unlike with the ETOs, it is possible to design trajectories that will cost-effectively deliver a cubesat into an orbit coinciding with a previously deployed mainline mission. As indicated in Fig. 9, the anticipated 34m X-band beam diameter at these locales is between 1,000 and 2,000 kilometers. So, a cubesat would need to be delivered within this range, relative to a mainline mission, in order to make use of MSPA and/or OMSPA. For cubesat missions in the post-2018 era, some of the newer mainline missions would probably make for the best “hosts.” So, DSCOVR would probably constitute the best “host” for SEL1 and JWST the best “host” for SEL2. Given the importance and long-lived nature of these mainline missions and the fact that the SEL 1 and 2 “orbits” require some active station-keeping, any cubesat missions aspiring to deploy near the mainline “hosts” might need to give some thought as to whether or not there will be any collision risk following end-of-life and, if so, how to mitigate it.

2018, some of the lunar orbiting cubesats being launched as secondary payloads on EM-1 may use variations on these techniques to get into their desired lunar orbits.

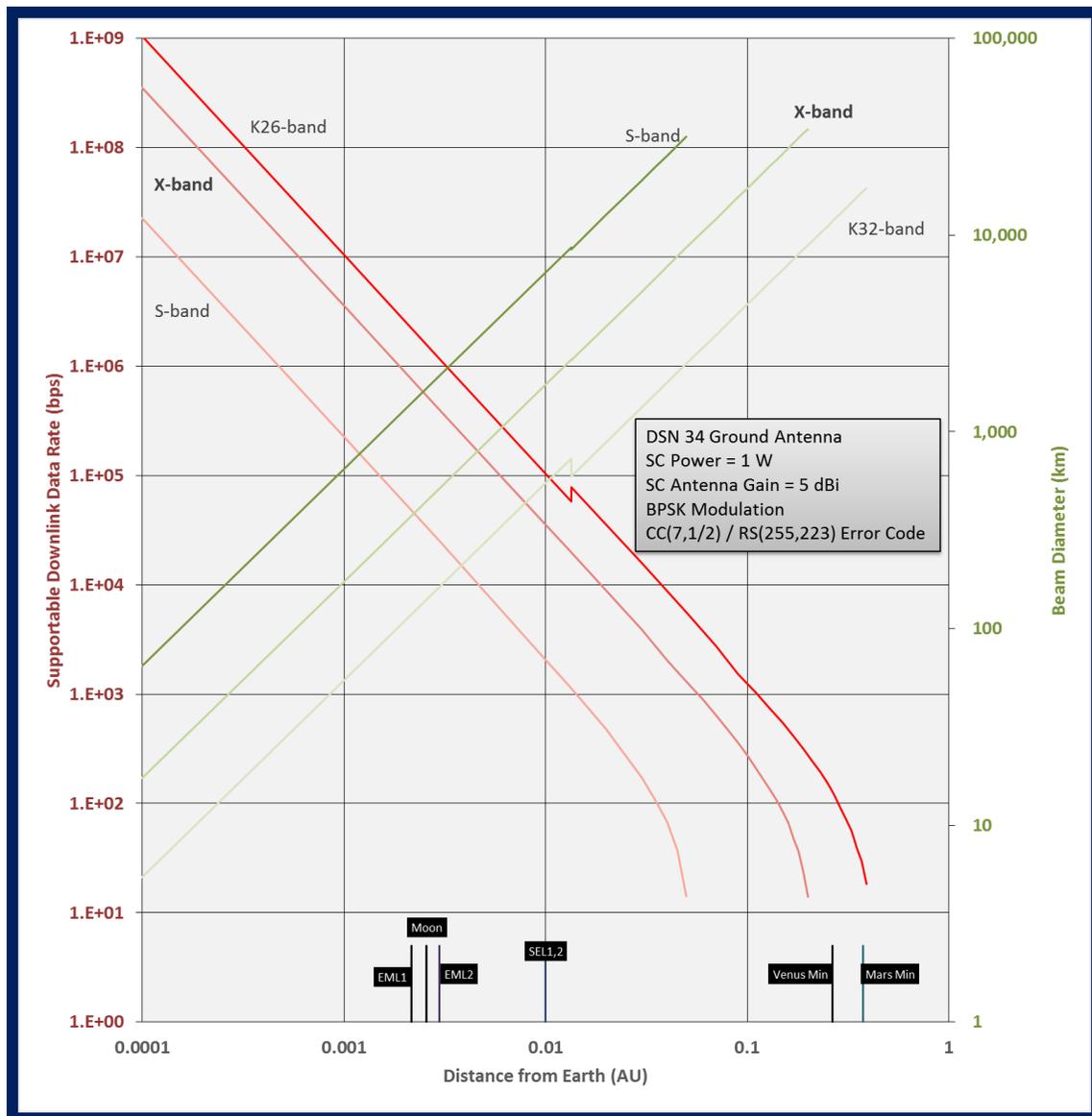


Figure 9. 34m Data Rate Performance and Beam Diameter, Assuming Lunar Flashlight-like Cubesat.

As for data rate performance, Fig. 9 shows that a Lunar Flashlight-like telecommunications system is capable of supporting tens of kilobits per second.^{†††††} A more robust MarCO-like telecommunications system would likely support tens of megabits per second -- though one would have to be careful to fit within the 10 MHz of allowable spectrum bandwidth that X-band missions are typically authorized to use in this region of space. So, SEL1 and SEL2 offer cubesat mission planners destinations where the supportable data rates are quite conducive to solar and astrophysical observations and do not change over time the way the data rates associated with ETOs and ELOs do. These data rate advantages, combined with SEL1 and SEL2's consistent level of solar illumination, the very low propellant costs to reach them via low-energy trajectories, and the presence of potential long-lived mainline mission "hosts" for MSPA and OMSPA, suggest further consideration by deep space cubesat mission proposers. Mission proposers, of course, will want to weigh these advantages against the increased mission duration, navigational complexity, and station-keeping requirements likely to accompany getting to and operating at SEL1 or SEL 2.

^{†††††} Lunar Flashlight is a 6U cubesat that will look for volatiles in the shadowed craters near the Moon's south pole. It will be one of the 13 cubesats being launched as secondary payloads on the SLS upper stage that will send EM-1 on its lunar trajectory in 2018.

V. Summary

Cubesats have become increasingly popular due to their affordability and, as technology advances, their growing capability. Their small size has been key to their affordability, primarily because development costs and launch costs tend to scale with spacecraft size. However, in the communications arena, operations costs do not tend to scale with spacecraft size. In fact, the required communications capability on the ground tends to grow with cubesats due to the smaller mass, power, and volume available for onboard communications capability. This is particularly true as cubesats begin to venture beyond geosynchronous orbit into deep space. Unfortunately, the large antennas, cryogenic amplifiers, highly-sensitive receivers, and large transmitters needed to support such missions are not cheap to build or operate. So, as the number of cubesats venturing into deep space grows, NASA cannot afford to buildup ground capability at a rate that will match this number -- nor can it provide traditional uplink and downlink services with these assets at an attributed cost that is substantially less for cubesats than it is for traditional mainline missions. However, NASA's DSN has been working to develop techniques for sharing antennas across multiple spacecraft at the same time in an effort to improve the availability and affordability of its communications services.

For downlink, two of these techniques, Multiple Spacecraft Per Antenna (MSPA) and Opportunistic MSPA (OMSPA), offer significant promise for the burgeoning cubesat fleet. Both techniques require all of the participating spacecraft to be within the half-power beamwidth of a single ground antenna. The number of spacecraft that the MSPA technique can service under this circumstance is limited, among other things, by the number of available receivers. However, the latency with which the downlinked data can be demodulated, decoded, and routed to the participating spacecraft is comparable to that for the traditional, single-spacecraft downlink service, making it particularly useful for mission-critical events when time is of the essence. And, the attributed aperture fee (when no uplink is involved) is less -- essentially the single-spacecraft fee divided by the number of MSPA participants.

The second technique, OMSPA, is not limited by the number of available receivers. Because it relies on a recorder at the antenna, the number of in-beam spacecraft that can be simultaneously serviced is virtually unlimited, and the costs for providing the service do not scale up with the number of users as they do in the receiver-dependent MSPA. This feature suggests that, if offered as a service in the future, this technique would involve some sort of nominal monthly flat fee to pay for the associated infrastructure and would not incur any sort of attributed aperture fee. And, because OMSPA involves opportunistically transmitting open-loop while in the ground antenna beam scheduled by another mission for a traditional communications link, it offers the possibility of significantly reducing the extent to which users of this technique would have to participate in the DSN's formal scheduling system. But, unlike MSPA, there might be some significant latency involved in retrieving the appropriate portion of the antenna's recording, demodulating it, decoding it, and recovering the data. For this reason, OMSPA would likely be better suited for routine downlink when time is not of the essence.

For cubesat missions to maximize the benefits from MSPA and OMSPA, however, they will need to maximize the amount of time they reside within the ground antenna beam of other missions. Certainly one way to do this is to design a cubesat trajectory that coincides with a pre-existing spacecraft's trajectory such that it is always within the beam of this "host" spacecraft. But, not all such trajectories may be feasible or affordable. In this paper, we provide three example mission destinations where in-beam time and supportable data rates look promising.

For planetary cubesats, Mars and Venus missions look promising, since cubesats that are able to insert into orbits around these bodies will always be in-beam (at X-band) relative to any other spacecraft residing at those locations. And, there are missions to one or more of these destinations in the future that could potentially provide cubesats with secondary payload opportunities on their upper stages.

For astrophysical, heliophysical, and other types of cubesat investigations, "flotillas" of cubesats in heliocentric ETOs and ELOs look promising, particularly if the cubesats are secondary payloads on an upper stage injecting into that kind of minimal escape orbit. In such a case, individual cubesats could take turns serving as the "host" spacecraft, while the other cubesats take advantage of MSPA and/or OMSPA. And, the cubesats would benefit from the fact that the only real navigation driver in these types of orbits is antenna pointing, which greatly relaxes the amount of two-way ranging and Doppler that might otherwise be needed.

Another promising option for heliophysics or astrophysics cubesats involves SEL1 or SEL2, respectively. If launching as a secondary payload on a lunar-bound upper stage, low-energy trajectories to SEL1 or SEL2 could conceivably be pursued at very low propellant cost. However, due to the large locational variations that occur with spacecraft residing at these unstable Lagrange points, the cubesat trajectories would need to be planned to coincide with the SEL1 or SEL2 locations of mainline spacecraft in order to make use of MSPA and/or OMSPA. This would require more precise navigation than ETOs and ELOs, and the propellant needed for station-keeping in these

unstable regions would need to be traded against the propellant savings that the low-energy trajectories confer in getting there.

As we progress in developing and proving simultaneous, multi-spacecraft uplink techniques to complement MSPA and OMSPA, the uplink needed for two-way ranging and Doppler, as well as commanding, may prove less of a concern for those trying to minimize asset contention and attributed aperture fees. Even then, such techniques will still require that cubesat mission proposers be vigilant about pursuing mission designs that maximize their shared-beam opportunities.

Acknowledgments

The authors would like to thank Lincoln Wood of JPL's Mission Design & Navigation Section for his helpful review of this paper, particularly with respect to the example mission design concepts amenable to beam sharing. The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The research was supported by NASA's Space Communications and Navigation (SCaN) program.

References

- ¹Abraham, D. S. and MacNeal, B. E., "Low-Cost Communications Concept for Smallsats: Opportunistic MSPA," *NASA Tech Briefs*, Vol. 38, No. 5, May 2014, pp. 56 and 58.
- ²Abraham, Douglas S., Finley, Susan G., Heckman, David P., Lay, Norman E., Lush, Cindy M., and MacNeal, Bruce E., "Opportunistic MSPA Demonstration #1: Final Report," *Interplanetary Network Progress Report*, Vol. 42, No. 200, URL: <http://ipnpr.jpl.nasa.gov/> [cited 10 February 2016].
- ³Pham, Timothy, *Deep Space Network Services Catalog*, DSN No. 820-100, Rev. F, JPL D-19002, Jet Propulsion Laboratory, Pasadena, CA, 2015, pp. 6-2 to 6-5, URL: <http://deepspace.jpl.nasa.gov/advmiss/missiondesigndocs/#> [cited 10 February 2016].
- ⁴Kwok, Johnny H., Garcia, Mark D., Bonfiglio, Eugene, and Long, Stacia M., "Spitzer Space Telescope Mission Design," *Proceedings of Optical, Infrared, and Millimeter Space Telescopes*, edited by John C. Mather, Vol. 5487, SPIE, Bellingham, WA, 2004, p. 201, URL: <http://proceedings.spiedigitallibrary.org/ConferenceProceedings.aspx> [cited 25 January 2016].
- ⁵Kwok et al., pp. 205-207.
- ⁶Kwok et al., p. 209.
- ⁷Dunham, David W., Guzman, Jose J., and Sharer, Peter J., "STEREO Trajectory and Maneuver Design," *John Hopkins APL Technical Digest*, Vol. 28, No. 2, 2009, pp. 104-120.
- ⁸Ames Research Center, "BioSentinel," *NASAfacts*, FS#2015-03-04-ARC, URL: <http://www.nasa.gov/centers/ames/engineering/projects/biosentinel.html> [cited 10 February 2016].
- ⁹Duncan, Courtney, "Iris V2 CubeSat Deep Space Transponder," JPL 400-1604, July 2015.
- ¹⁰Davis, Kathryn and Anderson, Rodney L., "Libration Point Orbits and the Three-Body Problem," *Encyclopedia of Aerospace Engineering*, Vol. 5, edited by Richard Blockley and Wei Shyy, John Wiley & Sons, Ltd., 2010, article 257.
- ¹¹Parker, Jeffrey T. and Anderson, Rodney L., *Low-Energy Lunar Trajectory Design*, Deep Space Communication and Navigation Series, Jet Propulsion Laboratory, California Institute of Technology, 2013, p. 41.
- ¹²Belbruno, Edward A., Ridenoure, Rex W., and Fernandez, Jaime, "To the Moon from a B-52: Robotic Lunar Exploration Using the Pegasus Winged Rocket and Ballistic Lunar Capture," 5th Annual AIAA/Utah State University Conference on Small Satellites, Utah State University, Logan, Utah, August 1991, p.2, URL: <http://digitalcommons.usu.edu/smallsat/1991/all1991/4/> [cited 10 February 2016].
- ¹³Parker and Anderson, p.4.