A Feasibility Study of Techniques for Interplanetary Microspacecraft Communications

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Abstract. The increasing capabilities and low cost of microsatellites makes them ideal tools for new and advanced space science missions, including their possible use as interplanetary exploration probes. There are many issues that have to be resolved when it comes to employing microspacecraft on such missions. One problem is how to maintain a reliable communications link with the microspacecraft over long, interplanetary distances. Solutions to this problem include either improving the spacecraft transceiver/antenna, using a very large antenna on the ground, or using an array of small antennas on the ground. When looking at the feasibility and costs of these alternatives, it is shown that an array seems to be an ideal solution to the problem. By using several digital signal processing techniques, it should be possible to array a group of commercial-grade amateur ground stations together to synthesize a large-aperture antenna capable of communicating over interplanetary distances while keeping the costs low enough to be sustained by a microspace program. Future hardware experiments will be performed to confirm.

Introduction

The increasing capabilities and low cost of micorsatellite missions make them attractive for broadening the scope and number of space science and exploration missions. Several microsatellites launched by AMSAT, Surrey Satellite Technology Ltd (SSTL), SpaceDev, and other groups have performed science missions ranging from Earth observation to space astronomy. This summer, the Microvariablity and Oscillations of STars (MOST) microsatellite will be launched, becoming Canada's first space telescope. This was the first of many microsatellite projects in which the University of Toronto Institute for Aerospace Studies (UTIAS) will be involved.

Table 1: Example Microsatellite Data Rates (in bps)

	MOST	SSTL Microsat	SSTL Enhanced Microsat	FalconSat	Opal
Downlink	38k4	9k6 & 38k4	9k6 & 38k4	9k6	9k6
Uplink	9k6	9k6	up to 128k	9k6	9k6

However, despite numerous breakthroughs, microsatellites are presently limited to missions in low Earth orbit (LEO). This is due to several issues, including the availability of low-cost launches to higher altitudes and the higher radiation levels at altitudes beyond 1000 km. Another problem is how to maintain a reasonably wide-bandwidth data link between the ground and a microsatellite at a very high altitude. Most microsatellites in LEO can maintain a downlink data rate of no more than 128 kbps. See Table 1 for some examples. These limitations and others, including the requirement for on-board thrusters, must be overcome if we are to extend the microsatellite concept to include interplanetary microspacecraft that can be employed to perform fly-by or orbital science missions at the Moon, Venus, Mars, and one day the outer planets. This feasibility study will focus on the communications problem. The goal is to find solutions so that microspacecraft data rates can approach at least the minimum data rates of current planetary probes, as shown in Table 2. Even if it is years before any microspacecraft missions are launched, any solutions that are found can be quickly and easily applied to future microsatellites to improve their communication data rates to 1 Mbps and beyond.

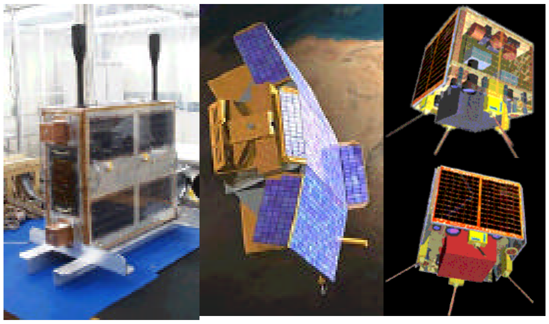
Table 2: Downlink Data Rates of Current Interplanetary Missions using the Deep Space Network

	Magellan	Mars Global Surveyor	Galileo	Cassini
Downlink	1k2 & 268k8	2k & 21k33	134k *	40 bps & 17k

* due to high gain antenna failure, actual data rate 10 bps with no arraying, 1000 bps with arraying

Spacecraft Radio/Antenna Improvements

Perhaps the most obvious solution to the problem is to improve the radio transceivers found on today's microsatellites so that they are capable of maintaining a wide bandwidth uplink/downlink over interplanetary distances. This involves increasing the effective isotropic radiative power (EIRP) of the radio. Ways to increase the amount of power available to the radio include the use of more efficient solar cells or the increase in available area for solar cells. Both these propositions prove to be difficult to implement for a small satellite/spacecraft program. Gallium-arsenide solar cells available today can achieve energy conversion efficiencies greater than 20%. However, using even more efficient solar cells might prove to be cost-prohibitive. As for larger spacecraft solar arrays, the small size of a typical microsatellite bus limits their maximum size. In fact, most microsatellites already have solar cells (and science instruments) covering most of their available surface area (see Figure 1). Proposed deployable solar arrays[1] might help increase the available power somewhat.



MOST

Dynacon/UTIAS/ UBC

CHIPSat

SpaceDev

Enhanced Microsatellite Bus

SSTL

Figure 1: Solar Panel Coverage of Three Microsatellites

In the end, just increasing the power available to the microspacecraft transceiver will not be enough due to the large increase in path loss interplanetary distances will introduce. Increasing the distance between the microspacecraft from 900 km (LEO) to 385 000 km (Lunar orbit) introduces a path loss of over 40 dB. Therefore, the EIRP of the transceiver must be increased by at least 40 dB. Clearly, this is infeasible. A better way to increase the EIRP of the microspacecraft would be to forego omni-directional communications and install a directional antenna (eg. a parabolic dish). Many microsatellites today are capable of three-axis stabilization (eg. CHIPSat, MOST) and pointing the antenna beam at the Earth would be feasible. A 30 cm parabolic antenna with an efficiency of 70% can provide a gain of around 20 dBi for S-band frequencies (~2 GHz). This gain increases to 40 dBi for K-Band frequencies (~20 – 30 GHz). For larger interplanetary distances, a larger antenna could be used. This leads to the problem of where to place the antenna on the microspacecraft. As previously stated, most of the microspacecraft surface area is already dedicated to solar cells and instruments. A deployable antenna might be possible, but then the problems of how to stow and deploy the antenna given the limited volume of the microspacecraft must be solved. Though a small high-gain antenna might provide part of the solution to microspacecraft communications over interplanetary distances, a better approach might be to look away from the microspacecraft and instead look at the Earth ground station.

Figure 2: Goldstone 70 m Ground Station

Earth Ground Station Solutions

In many ways, improving the Earth ground station is much easier than improving the microspacecraft transceiver. Power and available space are no longer limiting issues that they were for the microspacecraft. Ground station antenna sizes can range from 2 m to the 70 m Deep Space Network antenna found in Goldstone, California (see Figure 2). By increasing the size of the antennas used by current microsatellite groups, it would be possible to increase the receiver gain and thus communicate over longer interplanetary distances. However, ground stations become dramatically more expensive as antenna dish size increases. For example, a 5 m parabolic reflector used to track LEO satellites requires a ground station system costing upwards of US$300,000. The increase in cost for larger antennas is due to the requirements for better instrumentation and motors capable of pointing and holding the larger dish in place while resisting any environmental disturbances, such as wind. The 70 m Goldstone antenna cost US$ 150,000,000 (in 1972 dollars). Figure 3 gives a plot of the estimated antenna cost vs. size, showing the non-linear nature of the relationship. The cost numbers were determined by surveying several ground station manufacturers. Such cost increases will most likely be unaffordable for many small satellite groups, who do not have the money available for such expenses

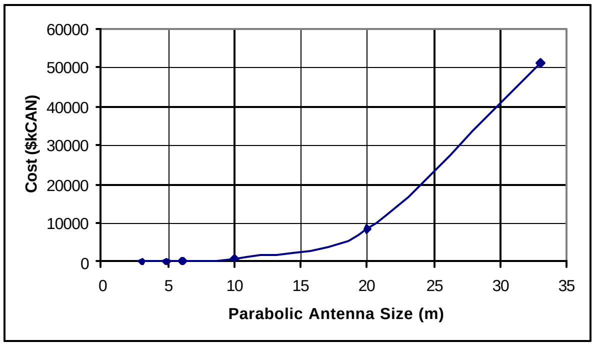


Figure 3: Parabolic Antenna Size vs. Cost

Solution: Antenna Arraying

One solution that avoids this dramatic price increase while still allowing for equivalent large antenna areas - and hence gain, is to array several low-cost antenna dishes together and combine their signals together. This allows for a linear increase in cost as more antennas are arrayed together and the overall gain is increased. The large antennas in the Deep Space Network (DSN) have used arraying techniques to communicate with the Voyager and Galileo spacecraft. If an array of equally sized antennas is used, each time the size of the array is doubled, the signal-to-noise ratio (SNR) of the received microspacecraft signal increases by a theoretical maximum of 3 dB (see Figure 4), thus making it possible for several small antennas to pull the microspacecraft signal out of the noise at a higher data rate. This SNR gain assumes that the signals from each antenna are combined in-phase; a slight phase difference will introduce a small amount of loss. If the array is made up a large antenna combined with several small antennas, the SNR improvement from adding the small antennas is somewhat less. For example, a 10 m parabolic antenna arrayed with a 3 m parabolic antenna leads to a received SNR increase of only 1.1 dB.

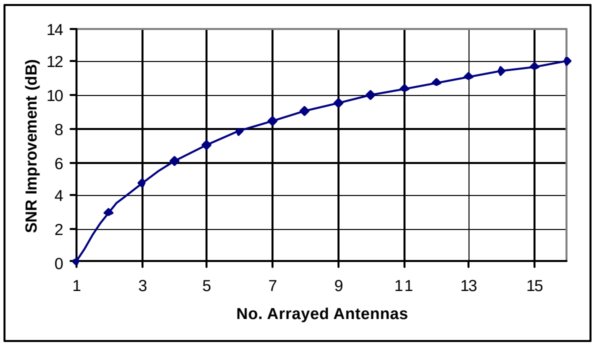


Figure 4: Array SNR Improvement

A plot of ground station cost vs. SNR improvement comparing an ideal 3-m parabolic antenna array to a single dish ground station (with the size of the dish increasing with the cost) is shown in Figure 5. The downlink is at 2.2 GHz, and a central array site cost of US$50,000 (CDN$70,000) is included in the array plot (hence the larger jump in price from the first point to the second). It is clear that using a larger array is more cost effective than using a larger single dish. Similar results can be found even when using higher downlink frequencies. Arraying seems to be the way to go for developing a low-cost microspacecraft ground station.

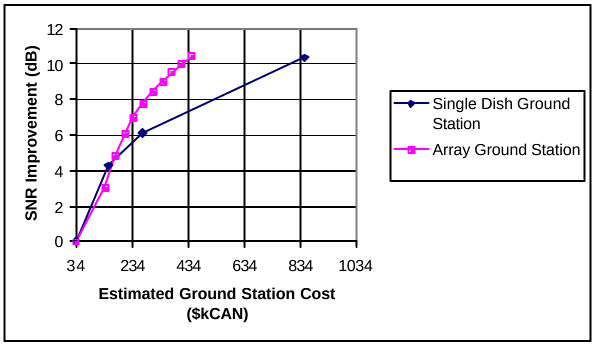


Figure 5: Cost vs. SNR gain Comparison Between an Array and a Single Dish Ground Station

Several arraying techniques are available. The simplest method, one used by amateur radio operators, is to directly tie the outputs of the individual antennas to a combiner. The output of each antenna is usually at an intermediate frequency (IF) heterodyned down from the initial RF. Assuming each antenna in this compact array is using the same local oscillator (LO), then no phase errors will be introduced in the heterodyne process. Phase coherence is maintained by making sure that the cable lengths linking each antenna to the combiner are exactly the same length. The tolerance requirements for errors are directly proportional to the frequency of the signal being combined. Therefore, some arrays combine the signals at baseband frequencies, ie. the modem data rate, to make signal combination easier. The limitation to this array is that since each antenna must share the same local oscillator, they all must be located very close to one other. This limits the sky coverage of the array and limits the flexibility in the design of the array and where the various antennas can be located.

VLBI & Signal Correlation

A more flexible array design would allow the users to locate the antennas, each with its own LO, wherever they wish. This array would be capable of

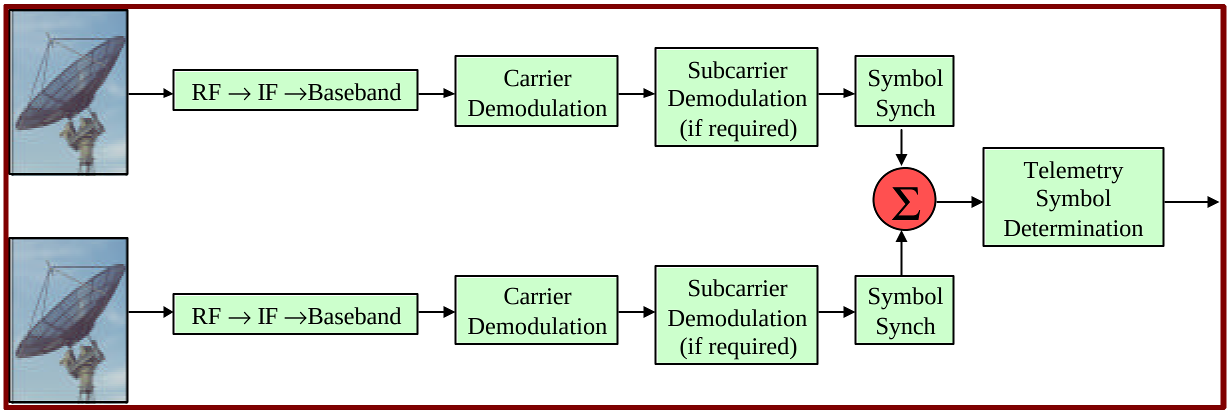


Figure 6: Symbol Stream Combining Block Diagram

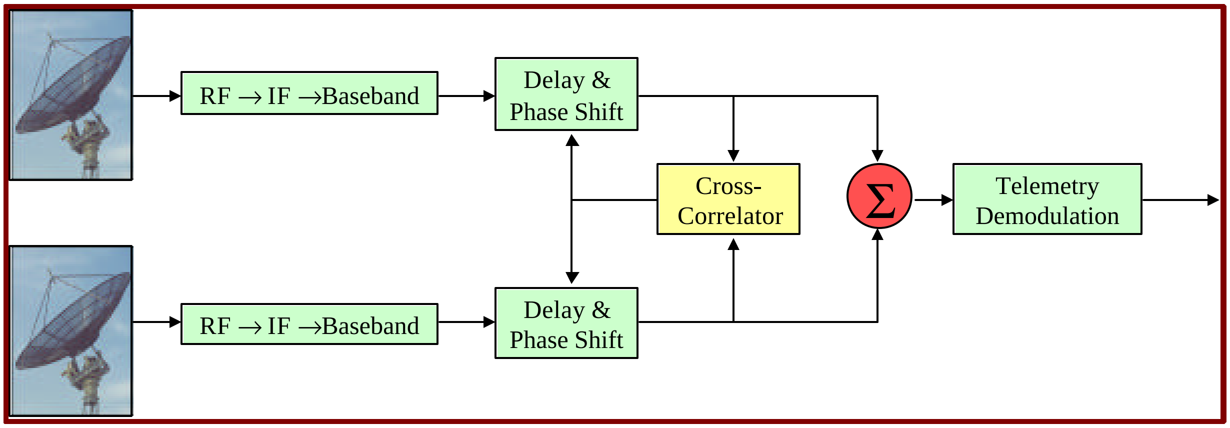


Figure 7: Full Spectrum Combining Block Diagram

combining the received baseband signals and pulling a wide bandwidth microspacecraft signal out of the noise while compensating for time and frequency phase errors introduced by such sources as:

- the fact that each antenna receives the signal at a different time due to their different geographic locations.
- the maximum accuracy when downconverting to baseband
- frequency and phase offsets between the various LOs

The flexibility of this array would allow for the construction of a ground station array using existing ground stations located across a large surface area, increasing the sky coverage of the ground station. As well, by combining the signals in baseband, this makes the array functional for a wide variety of RF bands.

Such a microspacecraft ground array can be constructed using Very Long Baseline Interferometry (VLBI) techniques developed for radio astronomy. When first developed and used in the 1960's[3,4], antennas in a radio astronomy VLBI array independently collected signal data on the same region of the sky. The data was then recorded and time stamped on magnetic tape at each site. The tape from each site was then brought to a central correlation site. With the geographic locations of the antennas known, the tapes could then be properly cross-correlated and combined to produce a received signal with a SNR higher than each individual antenna and with a spatial resolution equal to the minimum distance between the antennas.

Several of the techniques used in VLBI can be implemented in a microspacecraft ground station array to make interplanetary communications possible. Today, any time-stamped data collected by the array can be sent directly to the central correlation site in real-time over an ADSL or other high-speed data link. As well, low-cost commercial GPS receivers can be used to determine the position of each antenna within a few centimeters, thus allowing for the central site to correct time-phase errors due to the fact that each antenna receives the signal at a different time.

At the central site, there are different ways in which the array signals can be processed before cross-correlation. Two techniques developed by JPL that have been used on the DSN are called Symbol Stream

Combining (SSC – see Figure 6) and Full Spectrum Combining (FSC – see Figure 7)[2]. SSC is easier to implement since the approach involves cross-correlating data signals that have already gone though a closed-loop downconversion to baseband and a "soft" symbol demodulation at each individual antenna, eliminating most of the time phase errors present before correlation is even done. However, it requires that each antenna have a carrier lock on the signal, limiting the individual receiver SNR to around 0 dB, making it difficult to array very noisy signals that have either a very wide bandwidth or are coming from a very long distance away. In contrast, FSC downconverts the entire observed spectrum in an open-loop manner, and performs symbol demodulation *after* the cross-correlation stage. This means that any time and frequency errors introduced by the open-loop downconversion to baseband must be captured and corrected in the cross-correlation stage. However, since no carrier lock is required, an array employing FSC can recover microspacecraft signals that are buried much deeper into the noise. Due to the low power signals that a microspacecraft will be transmitting, it is most likely that FSC will have to be employed in the microspacecraft ground station array.

In developing a low-cost ground station array using currently available VLBI and FSC techniques, though many of the time-phase errors will be corrected, other errors must still be captured and corrected at the central site before the signals can be combined. One source of error previously mentioned is the local oscillator (LO) frequency and phase drift rate. For radio astronomy and DSN arraying, atomic clocks with accuracies of better than 10^{-10} times the received radio frequency are used as the LOs. Thus, frequency-domain errors are kept to a minimum. However, commercial low-cost radio equipment accuracy was determined to be no better than 10^{-5} – 10^{-7} times the received frequency. For S-Band, this would lead to a frequency drift error ranging from 0.2 to 20 kHz. If not corrected, this LO frequency drift error will lead to signal decorrelation at the central site. A way must be developed to determine and correct for any frequency spectrum error before VLBI-FSC cross-correlation and combining is performed.

Another limitation that will be present in this low-cost ground station array is the maximum data rate that can be received due to the limited accuracy of commercial radio equipment. For example, to prevent decorrelation, the accuracy of the central site cross-correlator must be around 10% the symbol time. Given the accuracy of commercial equipment, the timing accuracy of the correlator was estimated to be on the order of several µs (ie. around 10 MHz). Therefore, the maximum data bandwidth that can be correlated by the array is 10 kHz. A way must be found around this limitation if higher data rate microspacecraft transmissions are to be properly received and processed by the ground station array.

Array Simulations & Experiments

To see if these limitations can be overcome, several spread-spectrum techniques are in the process of being researched and simulated at the University of Toronto's Space Flight Laboratory to reduce the required correlation timing accuracy of the array, thus allowing for higher data rate downlinks from the microspacecraft. As well, a method of performing frequency-domain correlation has been developed and simulated to prevent LO drift from causing decorrelation. VLBI-FSC is used by the simulated arrays, thus allowing for noisier signals to be detectable compared to what SSC can detect. The baseband array signals are digitized before cross-correlation to make future hardware implementations of the array easier to develop using available digital signal processors (DSPs). Several digital sampling and filtering techniques are the subject of current research to help reduce the noise present in each individual antenna signal before they are cross-correlated and combined.

These simulations are currently being used to develop low-cost ground station array designs for several microspacecraft missions, including LEO, Lunar orbit, and Martian orbit. A low power transmitter (e.g. 5W) and an omindirectional downlink antenna pattern are assumed in all cases. For each mission, the best possible downlink data rates are identified and the cost of the array is compared to an equivalent single-antenna ground station to confirm that an array is more cost-effective. The advantages (if any) of using a ground station array in uplinking a command to the microspacecraft is also under study.

The next step after the simulations will be to develop laboratory hardware experiments using equipment that can simulate noise, array time differences, and LO frequency drift. These will range initially from simple "flatsat" experiments to systems that will be used in an actual microsatellite communication link experiment as a spacecraft payload and/or a ground station array.

Conclusions

To enable the development of microspacecraft that can be used for interplanetary missions, several engineering problems must be overcome. Proposals for improving the communications link have been studied here and the most feasible improvement appears to be the development of a low-cost ground station array using new or currently existing antennas. The size of each individual antenna can be relatively small (less than 5 m) while still maintaining a wide bandwidth downlink. Some issues dealing with the time and frequency accuracy of commercial low-cost radio equipment must be resolved. However, it is believed that the application of available spread spectrum and digital signal processing techniques can resolve them. Ground station improvements are much easier to implement than trying to find ways of improving the microspacecaft radio/antenna, such as including a deployable directional antenna, due to the limited power and volume available, and the cost and complexity involved.

Though interplanetary microspacecraft missions might be years away, if hardware experiments are successful, the techniques developed can also be used to increase the data bandwidth of LEO microsatellites to 1 Mbps and beyond.

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