Arraying Technique for Enhanced Multiplexing of Interferometric Signals (ARTEMIS): An Enabling Technology for Long Range or High Data Rate Microspacecraft Communications

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ABSTRACT: The Space Flight Laboratory of the University of Toronto Institute for Aerospace Studies has developed a prototype ground station antenna array correlator that offers advantages over previously employed approaches for weak signal communication. By using Orthogonal Frequency Division Multiplexing (OFDM) in the microspacecraft transmission, the array can perform frequency correlation in addition to time correlation (both techniques derive from Very Long Baseline Interferometry) to bring all the signals of the array into alignment. This removes the need for high accuracy local oscillators, such as hydrogen masers, to be used at each antenna to maintain frequency stability. In essence, expensive hardware requirements have been replaced with inexpensive software algorithms, allowing for the construction of low-cost ground station arrays made up of small antennas (eg. 3 m or 6.1 m diameters), perfect for use as a microsatellite ground station with a high data rate link, higher than what is currently possible. Recent hardware prototyping results have confirmed those obtained previously through simulation alone. These new results will be discussed and it will be shown how a small-antenna array ground station could be used to provide a high performance communications link for future microspacecraft missions flying to the Moon and other planets and bodies in the Solar System. The paper will also describe a planned flight demonstration mission currently being arranged through the Space Flight Laboratory's CanX nanosatellite program.

INTRODUCTION

Arraying as a Solution to Communications with Micropacecraft

Over the past few years, the Space Flight Laboratory of the University of Toronto Institute for Aerospace Studies has been studying methods that can be developed to improve microsatellite communications. Such techniques can be used to not only increase the link data rates of future microsatellite missions, thus improving the speed at which any science and other payload telemetry is sent to the ground, but also towards the development and launch of interplanetary microspacecraft capable of communicating with Earth ground stations from various locations in the Solar System.

As previously determined by the Space Flight Laboratory[1], the best solution is to significantly improve the ground station, rather than the microspacrcaft transceiver system, since limitations in mass and volume on the microspacecraft make it difficult to effect any major enhancements. The most effective way to improve the ground station solution that avoids dramatic price increases while still allowing for large aperture areas, and hence gains, is to array several smaller low-cost antenna dishes together and combine their signals. A flexible array design, allowing the users to locate the individual antennas, each with its own local oscillator, wherever preferable, can be constructed using Very Long Baseline Interferometry (VLBI) techniques developed for radio astronomy in the 1960's[2,3]. 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 at baseband, the array is made functional for a wide variety of RF bands.

Very Long Baseline Interferometry & Signal Correlation

Many relative offsets will be present between each antenna signal in this array. Some of these offsets are known *a priori* and can be corrected automatically. These offsets include:

- Time offsets due to the different geographic locations of each antenna (each antenna receives the signal at a different time)
- Frequency offsets due to Doppler shifts in the microspacecraft signal

However, this array must also be capable of correcting for changing, *unknown* offsets that can be present in each signal, such as:

- Time offsets (τ_{off}) due to errors in correcting for the different geographic locations of each antenna; time offsets due to the clocks of each antenna not being synchronized;
- Phase offsets (ϕ_{off}) introduced when downconverting the signal from RF to baseband;
- Frequency offsets (υ_{off}) between the various local oscillators of each antenna in the array and the microspacecraft, as well as errors in Doppler shift correction.

The first two offset errors can be detected and corrected using signal correlation. Many correlation techniques were developed by JPL and have been used on the DSN[4] for communicating with spacecraft such as Voyager and Galileo. With one method, Full Spectrum Combining (FSC, see Figure 1), the entire observed spectrum is downconverted in an open-loop manner, and performs symbol demodulation after the correlation stage. Since no carrier lock is required, an array employing FSC can correlate very noisy signals as compared to other techniques. Due to the low power signals that a microspacecraft will be transmitting, FSC is the best method to use for a microspacecraft ground station array.
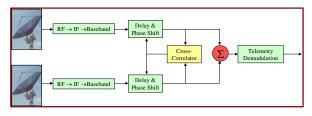

Figure 1: Full Spectrum Combining Block Diagram.

The signal-to-noise ratio (SNR) of the received transmission will drop as the transmission distance increases, the signal power drops, and the data rate increases. The minimum signal SNR that can be correlated depends on the correlation time, or window. For FSC, as the noise power increases, the correlation window time (Δt_c) must be increased in order to include more of the signal in the cross-correlation calculation.

As more of the signal is included in the calculation, the peak in the cross-correlation function will become more prominent above the noise floor, making it possible to accurately determine any time offsets present between the signals received by any pair of the antennas in the array (see Figure 2). Theoretically, Δt_c can be made as large as necessary to handle any SNR. In practice this will lead to correlation window times that are too long to allow for a functioning system. In addition to this, The troposphere will cause delay effects depending on weather conditions, and these delay effects will be different at each antenna given a wide enough separation. This will place a limit on the maximum correlation window time that can be used, based upon the time constant of the atmospheric changes. For S-Band and X-Band radio frequencies, this can be on the order of 10 seconds to one minute[5,6].
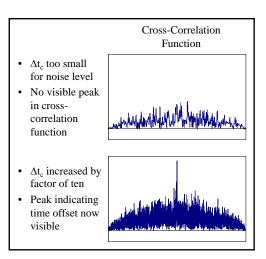

Figure 2: Affect of Δt_c on Time Domain Cross-Correlation Curve

Issues with Full Spectrum Combining

For FSC to function properly, τ_{off} must also fall below a certain tolerance before time correlation is performed. Otherwise, inter-symbol interference (ISI) will still cause time correlation to fail for a signal with a low enough SNR. ISI is interference caused by a neighboring data symbol partially intruding into the correlation window. Experience in using the DSN array has shown that the maximum value of τ_{off} that can be tolerated is 10% of the data period. Assuming the two antennas do not share the same clock source (impossible for remote sites in a VLBI array), GPS can be used to keep the clocks synchronized and provides accurate geographic information. According to an evaluation of typical commercial GPS receivers[7], the approximate timing synchronization accuracy is around 1 μs for a 1 pulse per second (PPS) receiver. Given the

high *position* accuracy of current GPS receivers, 30 m and even 3 m, it is the timing accuracy of the GPS receiver that will limit the maximum data rate that the array can handle. If the maximum time offset before correlation must be 10% of the data period, then the maximum GPS limited data rate is 100 kbps. It should be possible to find GPS equipment, at a certain expense, to increase the timing accuracy to 10 μs, thus increasing the maximum data rate to 1 Mbps. In reality, however, prediction errors in the satellite position as well as errors in predicting the beginning of the transmission during symbol boundary determination will lead to larger initial time offsets. For example, if the best guaranteed timing accuracy before correlation at any point is only 0.1 μs, then the maximum tolerable data rate is reduced to 10 kbps, or only 1 kbps if prediction errors of 100 μs are present (such a large error is only expected when the array first starts receiving the transmission). For data rates less than 1 kbps, timing synchronization between the antennas is less of an issue because even the most inaccurate of clocks can keep the antenna clocks synchronized to within 10% of the data period. However, other unknown time offsets might still introduce problems.

One source of error that is still present in the correlator is the unknown frequency offset, υ_{off}. A maximum υ_{off} value of 10% of the data bandwidth before time correlation is typically mandated. The use of specialized, highly stable oscillators, and transmitting at lower RF frequencies, helps mitigate this problem. For the DSN array, this is achieved by using a hydrogen maser as the frequency and timing standard, though current experiments are underway to improve timing and frequency accuracy by using linear ion trap (LIT) standards[8] or crystal sapphire oscillators[9]. For radio astronomy and DSN arraying, oscillators with accuracies of better than 10^{-10} times the received radio frequency are used. Thus, frequency offset errors are kept to a minimum. For S-Band RF, frequency offsets will not be an issue for data rates higher than 2 bps, or 10 bps for X-Band RF. However, commercial low-cost radio equipment accuracy was determined to be no better than 10 ppm to 0.1 ppm, especially when the microspacecraft oscillator is included. For S-Band RF, this would lead to a frequency error ranging from 200 Hz to 20 kHz (1 kHz to 100 kHz for X-Band RF). If not corrected, this local oscillator frequency error will lead to time correlation failure and a bit-error increase in the array-combined signal for transmission data rates ranging up to 200 kbps for S-Band RF and 1 Mbps for X-Band RF. As the data rate gets higher, then the effect of a given frequency offset is reduced and it becomes less of a concern.

In summary, the maximum time accuracy before correlation will limit the maximum data rate the array can handle, and the maximum frequency accuracy will limit the minimum data rate of the array. At the Space Flight Laboratory, techniques have been developed to overcome both limitations to the current FSC array design. The first solution, to solve the frequency offset problem, is to employ a *frequency correlation* stage in the array.

FREQUENCY CORRELATION FOR MORE EFFECTIVE ARRAY DESIGN

To perform frequency domain correlation, a Fourier transform is performed on the signals over the correlation window time (Δt_c). Theoretically, the frequency spectra could then be cross-correlated and any frequency offsets could then be determined from the peak of the cross-correlation function. However, major issues are present that will prevent this process from working effectively in the presence of white noise.

The first issue is that the signal is not a pure sine wave carrier, but a modulated data transmission. If the original digital data stream being transmitted has a data rate of R bits per second (bps), then the carrier will be altered (i.e. modulated) every 1/R seconds (i.e. the data symbol time) in order to encode the digital data in the signal carrier. If Δt_c is large enough to contain multiple modulation symbol changes, then the different modulation levels will destructively interfere with each other in the frequency domain. In the presence of white noise, the correlation of the second spectra will produce a cross-correlation function with no well-defined peak, making it impossible to determine any frequency offsets. Frequency correlation is most effective when Δt_c is equal to the data symbol time, which for higher data rates, will limit the minimum SNR that can be frequency correlated.

The second issue with frequency correlation is that the minimum frequency offset that can be detected is equal to the data bandwidth. As previously stated, an offset error of 10% is enough to cause a bit-error increase in the array-combined signal. Frequency correlation as applied to typical signals will only detect offset equal to integer multiples of the data bandwidth. Therefore, a means must be developed that can be used to perform high-resolution frequency correlation. The solution that the Space Flight Laboratory applied to this problem is Orthogonal Frequency Division Multiplexing (OFDM)[13], a technique developed in the 1960s and is currently being used in wireless LANs[10] and is under consideration for cellular networks[11] and digital radio broadcasts[12].

Orthogonal Frequency Division Multiplexing

The idea behind OFDM is to provide spectrally efficient form of frequency division multiplexing. In typical frequency division multiplexing systems, the several narrow bandwidth (i.e. low data rate) PSK-modulated channels are separated by large guard bands (see Figure 3). If each channel is transmitted simultaneously, then the overall data rate will be the sum of all the low data rate channels. With OFDM, the separation between each channel is equal to the bandwidth of each channel, which is the minimum distance by which the channels can be separated (see Figure 4)[13]. Therefore, the channels occupy a similar bandwidth as the equivalent single-channel transmission, giving high spectral efficiency.
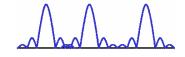

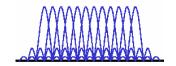**Figure 3: Frequency Division Multiplexing.**

Figure 4: Orthogonal Frequency Division Multiplexing.

Instead of sending data modulated on a single carrier with a given bandwidth, the usable spectrum is divided into multiple carriers, each modulated using phase-shift keying (PSK)[*] with a portion of the data at a lower data rate. The multiple channels in the wide-bandwidth OFDM signal make it possible to perform accurate, high resolution, frequency domain correlation of the signal, allowing the correlator to correct for local oscillator frequency drift between the antennas in the array. This removes the need to maintain frequency coherence between the local oscillators of each individual antenna because frequency correlation of an OFDM signal can detect frequency offset at a resolution finer than 10% of the data bandwidth, assuming more than 10 OFDM channels are used (typically, the number of OFDM channels used in other applications is 64 or greater).

By using OFDM, time correlation also becomes more effective as data rate limitations due to constraints on the initial time offsets between each antenna before correlation can also be relaxed. As previously

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[*] FSK cannot be used because the frequency channels cannot be moved. Amplitude Shift Keying (ASK) could be used on its own, or in concert with PSK when employing OFDM (known as QAM), but PSK on its own will only be studied for now.

described, if the clocks between two antennas can only be synchronized to within 1 us, the maximum data rate the array can handle will be 100 kbps. However, if the 100 kbps signal is instead divided into 100 OFDM channels, each at 1000 bps, then the initial 1 us accuracy previously required before correlation is now only 0.1% of the symbol period. Theoretically, the data rate can now be increased to 10 Mbps using a 100-channel OFDM signal, and adding more OFDM channels can further increase the maximum data rate. However, if concurrent frequency offsets are also present in a signal, then the required synchronization accuracy will be reduced, again limiting the maximum possible data rate. The required accuracy for this case is unknown and will be determined via experimentation. Still, the long symbol time and wide bandwidth of an OFDM will make it possible to perform frequency correlation between signals with a concurrent time offset greater than 10% of the data time. Attempting to correlate a single-channel signal with both frequency and time offset will be very difficult unless the time offset is very small, under 10% of the data time.

The practical limit to the number of OFDM channels into which the available bandwidth can be divided depends upon the clock frequency of, and amount of memory available to the processors performing the modulation and demodulation of the OFDM signal. Further, increasing the number of channels results in a greater peak-to-average power (PAP) ratio in the transmitted signal. A high PAP ratio imposes more stringent design requirements (e.g., greater linearity) upon the power amplifier of the transmitter. Therefore, the maximum number of channels considered in this work is 4096, which corresponds to the maximum number currently investigated by researchers in the field of OFDM communications. Many commercial applications tend to use OFDM channel sizes ranging from 256[17] (WOFDM), to 2048[18] as used in some digital radio services.

LOW-COST, FLEXIBLE SOLUTION: ARTEMIS

The Arraying Technique for Enhanced Multiplexing of Interferometric Signals (ARTEMIS) system expands on the concept of the large array made up of small antennas by removing the need for strict frequency oscillator stability and strict clock synchronization. Such an array can be created based on the new research presented in this thesis on frequency correlation and its application to OFDM signals. By developing frequency correlation techniques and adding them to currently existing FSC techniques, it is possible to reduce hardware requirements by replacing them with software algorithms. This means that any antenna ground station, from a low-cost 1 m amateur radio station, to a

large antenna in the DSN, can be included in the array. This allows the user to easily establish an array at low-cost either through the construction of new stations and/or the inclusion of existing stations, allowing the user to customize a low-cost array to their specific needs. As examples, ARTEMIS can be used to array six 1 m antennas to communicate at 1 Mbps with a microsatellite in Low-Earth Orbit (LEO), or to link a cluster of just over 30 6.1 m antennas to communicate with the Mars Global Surveyor at its full data bandwidth.

The general approach used by ARTEMIS for dowlink communications is summarized here:

Downlink
At Each Antenna (each array element):
- Use an open-loop receiver to downconvert the incoming signal spectrum to baseband.
- Perform an analog-to-digital conversion – digitally oversample the signal (ie sample the signal at a frequency greater than two times its baseband frequency) to reduce quantization noise and provide greater time correlation resolution.
- Send digitized, baseband signal to central processing site with timing information determined by commercial GPS.

At VLBI Array Correlator/Combiner (central processing site):
- Perform Fast Fourier Transform to convert to frequency-domain.
- Correct for delays due to array geometry to bring signals into alignment (this stage could be performed at each antenna element).
- Correct for frequency shifts due to Doppler (this stage could be performed at each antenna element).
- Perform baseband correlation in the frequency and time domain on signals received from all array elements to obtain frequency, time, and phase alignment. For an OFDM signal, this is done over several data channels.
- Combine the baseband carriers to form an enhanced baseband carrier.
- Demodulate OFDM carriers into a collection of soft symbol streams.
- Feed soft symbol streams into decoders.
- Re-integrate resulting data streams into single data stream.

ARTEMIS HARDWARE EXPERIMENT

An experimental plan was developed for validation of the ARTEMIS downlink correlation principle in application for a range of individual receiver signal-to-noise characteristics. This plan involved the development of laboratory hardware experimental apparatus that could eventually form the core of flight payload hardware and ground support equipment. The other reason for developing the prototype hardware is that there are many aspects of ARTEMIS that cannot be tested effectively in simulation, such as quantization noise. Also, many aspects of the simulation are difficult to model accurately, thus it is important to get a secondary confirmation of the results. Though some differences are expected between the simulation results and the results obtained using the hardware prototype, they are expected to be minor.

Experimental Apparatus Configuration

A connectivity diagram of the experimental hardware apparatus is shown in Figure 5. Available commercial digital signal processor (DSP) hardware was researched and two were selected for inclusion in the experimental apparatus, one to run the microspacecraft transmitter software and one for the array correlator software. The DSPs have high processing speeds and are specialized for applications using Fast Fourier Transforms (FFTs), which, as will be shown, are the most prevalent functions present in all the software modules. The development environment and user provides a high-quality system in which C code can be developed on a PC console interfaced with the DSP. The code can then be uploaded from the interface PC to the DSP and compiled into cycle efficient assembler code for execution on the DSP. Finally, the DSPs are available on experimental prototyping boards that could be easily interfaced with data converter modules (both an analog-to-digital converter (ADC) connected to the ground correlator DSP and a digital-to-analog converter (DAC) connected to the microspacecraft DSP).
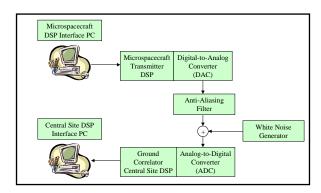

Figure 5: ARTEMIS Hardware Experimental Apparatus Setup.

Both data converters are also available on evaluation boards that can be interfaced with the DSP evaluation boards. One of the most important characteristics of a data converter when it comes to selecting one for the ARTEMIS hardware experiment is the sampling

bandwidth of each converter. The effect of quantization noise was of paramount concern when developing the apparatus, so it was decided to use a sampling frequency with an oversampling ratio of eight, which will mitigate the effect of quantization noise. The term oversampling refers to the practice of digitally sampling an analog signal at a greater frequency then is necessary to avoid signal aliasing. The minimum digital sampling frequency for any signal is two times the maximum frequency content that needs to be captured. This is referred to as the Nyquist frequency. Oversampling by a factor of eight means that the signal will be digitally sampled at a frequency 16 times greater than the data rate of the transmission. Beyond reducing quantization noise, oversampling also provides a wider bandwidth in which array frequency offsets can be tested. However, the chosen oversampling ratio does limit the maximum data rate that can be chosen, as the sampling bandwidth cannot exceed the bandwidth of the data converters. With a oversampling ratio of eight, it was decided to use a data rate of 9600 bps. This signal has a Nyquist frequency of 19200 Hz and an eight-times oversampled bandwidth of 153.6 kHz, which is under the 250 kHz sampling bandwidth of the ADC used in the experiment. If a higher data rate were to be used, either the oversampling ratio would have to be reduced, reducing the decteable frequency offset range and increasing the effect of quantization noise, or a filter with a wider bandwidth would have to be used.

An analog channel interface was implemented in hardware to provide anti-alias filtering at the input to the ADC, and to facilitate adjustment of the SNR of the received analog signal. The anti-aliasing filter took the form of a low-pass filter with a 3 dB cutoff frequency of 80 kHz, so that any frequency offset within the non-aliased bandwidth of 76.2 kHz (153.6 kHz divided by two) can be detected and corrected without any data from being lost. Signal SNR adjustment is accomplished by combining the filter output with an additive white Gaussian noise (AWGN) signal provided by a signal generator connected to the circuit. This type of noise is representative of the thermal noise that dominates in the reception signal of a typical satellite receiver. Potentiometers on the combiner circuit allow the user to adjust the voltage of the noise line and signal lines so that bit energy-to-noise density (E_b/N_o) characteristics ranging down to a minimum of -13 dB can be tested. The E_b/N_o characteristic is the equivalent of SNR for a digital signal. The hardware experiment could work with signal E_b/N_o characteristics lower than -13 dB if more sensitive equipment were used. For now, -13 dB is sufficient for the current set of experiments, at it is representative of the E_b/N_o of the received signal of a small antenna (3 to 6.1 m) picking up a low-power (4 W), low data rate (1 to 50 bps)

microsatellite transmission being sent from Mars orbit or a medium to high data rate (35 kbps to 125 kbps) microsatellite transmission sent from the Moon. These are the type of interplanetary communications scenarios that need to be investigated using the AETEMIS hardware apparatus. This minimum E_b/N_o value is much lower than is typically obtained using DSN arraying communicating with such spacecraft as Galileo and Voyager, which typically handles E_b/N_o values of 0 to -3 dB[14,15].

In order to maintain controlled experimental conditions and to remove the complexities associated with the development of an RF communications link in the initial stages of the experiment, a hardware test setup was devised in which the DSPs implementing the microspacecraft transmitter and ground station correlator communicate via a wired, low-IF analog channel. In the absence of an actual antenna array, a software routine was developed to simulate the multiple signals received by an array and introduce representative frequency and phase offsets in each signal. Details about this array simulator will be discussed in the next section, along with the other software that runs on the DSPs.

ARTEMIS Software Modules

The software modules integral to the execution of the experiment include:
- *Transmit Data Generation;*
- Microspacecraft transmitter, i.e., modulator and OFDM signal generator with digital frequency upconversion;
- DAC controller;
- Antenna array impairment emulator;
- ADC controller;
- Central site correlator, i.e., frequency & time/phase correction and demodulation;
- *Experimental telemetry collection (correlation accuracy, BER, etc.).*

(note: the modules in italics run on the interface computers). A block diagram of these modules is illustrated in Figure 6, indicating the hardware on which each software module is located. All of the code except for the array simulation code could be used for flight if similar hardware were used in an actual microspacecraft and ARTEMIS array. During software development, the amount of test code written that would not be used in the final hardware setup was kept to a minimum.
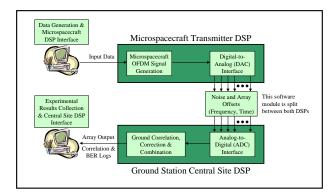
Figure 6: Software Modules for the ARTEMIS Experimental Apparatus.

Transmit Data Generation

The Microspacecraft DSP Interface Computer is primarily used to upload the microspacecraft DSP code to the microspacecraft DSP as well as to control the execution of this code. It is also used to generate a random digital data sequence for use in a Monte Carlo simulation analysis of the ARTEMIS hardware and software. The microspacecraft DSP software could be used to generate this sequence, however for post-experiment data analysis purposes, it is easier to have the original transmit sequence stored on the interface PC.

Microspacecraft Transmitter Software & Digital-to-Analog Conversion

The primary purpose of the microspacecraft software is to take the transmission data and convert it into an OFDM signal. It then upconverts the signal to a higher frequency and send it to the DAC for analog conversion.

Before the OFDM signal is generated, the digital data stream is converted into a series of modulation data symbols according to any one of many phase modulation techniques, e.g., PSK, or quadrature-amplitude modulation (QAM). Though higher order modulation techniques provide improved bandwidth efficiency, the required combined array output SNR for a given bit-error rate (BER) increases commensurately; hence, BPSK and QPSK are most commonly employed in microspacecraft communications systems. The modulation data symbols come from the I-Q complex plane based on the phase angles used in PSK. For example, BPSK uses two phase angles, 0° and 180°, which are equivalent to +1 and –1 on the I-Q plane, to represent single bits (0 or 1). QPSK uses four phase angles, 0°, 90°, 180°, and 270°, which are represented by +1, +i, -1, and –i in the I-Q plane, to represent a pair of bits (00, 01, 10 or 11).

To create an OFDM symbol with N channels, an N-point IFFT applied to N data symbols. The IFFT is applied contiguously for every N data symbols, in each instance generating an OFDM symbol for transmission. This process of dividing the data symbol stream into groups of N symbols is similar to frequency division multiplexing, where a group of the N data symbols is used to modulate N different IF carriers, with the frequencies of the carriers selected such that the guard bandwidth between each signal is sufficient to prevent interference. The signals are then summed to create the transmitted signal. In this case of OFDM, the various frequencies are selected such that no guard space is present, meaning that the data channels are separated by the minimum bandwidth possible (see, previously, Figure 4 vs. Figure 3). This means that all the frequency channels are orthogonal to each other, making the entire process equivalent to an inverse Fourier transform process. A block diagram demonstrating this fact is illustrated in Figure 7. A simplified block diagram showing the generation of an OFDM symbol in the transmitter software is shown in Figure 8. The multiple frequency channels present inside the data bandwidth provide a means for high-resolution frequency correlation. Also, since the data symbol time has now been increased by a factor of N, time correlation becomes more effective and data rate limitations caused by initial time offsets between signals in an array being a significant fraction of the original data symbol time can be relaxed by a factor of N without a loss in overall data rate.
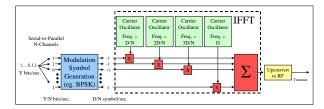

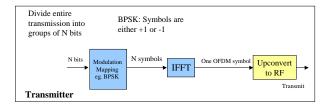**Figure 7: Orthogonal Frequency Division Multiplexing Functional Block Diagram**

Figure 8: OFDM Transmitter Block Diagram

With regard to the digital frequency upconversion algorithm located on the microspacecraft DSP, this employs a Hilbert transform to upconvert the signal to any desired IF before it is sent to the DAC[16]. In

application, following digital upconversion, the output signal from the DAC would then be mixed with an oscillator to bring the signal up to the desired RF.

Antenna Array Impairment Emulator
In the absence of an actual antenna array, a software routine was developed simulate an array. This software routine takes the microspacecraft signal generated on the microspacecraft transmitter DSP and duplicates multiple times, once for each element in the simulated array. The software can then add frequency, time, and phase offset to each individual signal, simulating an array where no element is in-phase or frequency-aligned with any of the other elements. These offsets are user controlled. Though these offsets are currently fixed over the simulation period, it is very simple to modify the code to allow for changing offsets throughout the entire simulation.

Part of the simulated array software runs on the microspacecraft DSP and part runs on the ground correlator DSP so that no single DSP is burdened in running this extraneous code. At this stage, the array size is fixed at three, which is the smallest non-trivial array, so that more DSP memory could be allocated to testing the correlation algorithms. This memory is needed so that large OFDM channels sizes can be tested for their effectiveness in the correlation of noisy array signals. This small array size is acceptable for now because the purpose of the hardware apparatus is to test the functionality of the ARTEMIS correlation algorithm at different receiver E_b/N_o levels, not confirm that combining the signals of an array that have been aligned in time and frequency via correlation leads to a higher signals E_b/N_o and lower BER, something that is already well known. Later, as more memory is added, a larger array can be simulated concurrently with the correlation algorithms. Also, if a third DSP becomes available, it alone can be used to simulate the array to reduce processor loading on the other two DSPs.

Analog-to-Digital Conversion & Ground Station Correlator Software
The primary purpose of the ground correlator software is to receive the analog signal created by the simulated array, convert it to a digital signal, separate the individual signals received by each "element" in the simulated array, and correlate them. After correlation, any frequency, time and phase offsets identified by the correlation functions can be corrected, the signals can be aligned and added together to increase the E_b/N_o of the aggregate signal. The OFDM signal can then be de-channelized, extracting the modulation data symbols, which can then be converted into the digital data stream transmitted from the microspacecraft.

A block diagram of the overall correlation process performed by the ground correlator DSP software is shown in Figure 9. Unlike current arrays, which only correlate the signals in the time domain to detect any time offsets between the array signal, ARTEMIS precedes this stage with an additional *frequency* correlation stage. This makes the ARTEMIS correlator design more flexible because it does not rely on frequency alignment between the individual array signals. A breakdown of each correlation function, both frequency and time, is shown in Figure 10 and Figure 11. The most prevalent function in correlation is the Fourier transform (including the inverse transform). Like in the transmitter software the processor efficient FFT/IFFT digital functions are used. Also note that since the signals being fed into the time correlation process shown in Figure 11 are already in the frequency domain, having just gone through the frequency correlation routine, the FFT in the cross-correlation algorithm is not needed.
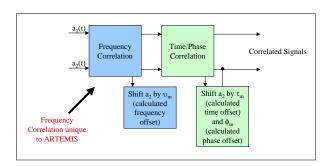

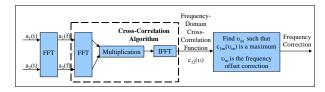**Figure 9: Block Diagram of the Entire ARTEMIS Correlation Process**

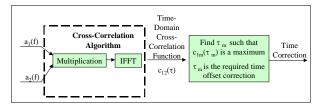**Figure 10: Frequency-Domain Correlation Block Diagram**

Figure 11: Time-Domain Correlation Block Diagram.

In both diagrams, two signals in the array are correlated at a time. One method of array correlation is to pick

one signal to which all the other array signals are correlated. The number of required correlations is just (n_a-1) every correlation period (Δt_c), where n_a is the number of antennas in the array. Though this method of "pair-wise" correlation can be used on any array, it works best on one where one antenna in the array is more powerful than the other ones. All the other signals in the array are correlated with respect to this signal. A second correlation option, one developed for ARTEMIS, is to periodically correlate every array signal with a known, noiseless training sequence stored in memory at the central site. The microspacecraft transmission would repeatedly transmit this known sequence. The training sequence must be repeated in order to keep up with any changes in υ_{off}, τ_{off} and ϕ_{off}. The addition of a training sequence in the transmission comes at a cost of a slightly reduced data throughput. However, this would allow ARTEMIS to correlate extremely noisy signals, with E_b/N_o characteristics even lower than what is possible with "pair-wise" correlation and keep the number of required correlations down to n_a per correlation period (ie. one correlation per antenna). It is this method of "training sequence" correlation, along with simple "pair-wise" correlation that have been studied in application to ARTEMIS, since they are the two extremes in terms of functionality for a given signal E_b/N_o characteristic.

After correlation is complete and all the offsets between the signals are corrected, they can be added together and the OFDM symbol can be de-channelized. In the case of the OFDM receiver, the software contiguously performs an N-point FFT to the received signal (the inverse of the OFDM transmitter), retrieving the data symbols for each of the N streams. A block diagram demonstrating this process is shown in Figure 12. The reconstituted modulation data symbols are then assembled into a single stream and demodulated to recover the transmitted data.
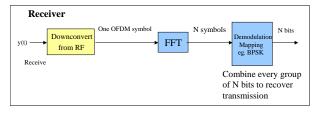

Figure 12: OFDM Receiver Block Diagram

The received data stream is then sent to the PC interfaced with the ground correlator DSP for post-experiment analysis. When compared to the original data transmission, the bit-error rate (BER) can be calculated. The frequency and time offsets calculated by the correlation algorithm are also sent to the interface PC and compared to the actual offsets used in the simulated array. The correlation-error rate (CER) can also be calculated for the experiment.

ARTEMIS HARDWARE INITIAL EXPERIMENTAL RESULTS

Several experiments were performed, using the experimental apparatus, to confirm the validity of the ARTEMIS correlation concept for downlink communications and the conclusions drawn based on the simulation results. The following sections detail each experiment and the results gathered.

Frequency Correlation

A series of frequency correlation experiments were performed to determine the relationship between the number of OFDM channels in the signals and the minimum signal E_b/N_o that could be correlated in the frequency domain with a minimum of errors (correlation error rates (CERs) of 10^{-3} was chosen to be the requirement). No concurrent time offsets were present in the signal for these experiments, so the results given here represent the minimum number of OFDM channels that are required for the receiver E_b/N_o in order to successfully perform either frequency or time correlation. The frequency offsets were approximately 0 kHz for the first antenna, 10 kHz for the second, and 20 kHz for the third.

The first set of experiments involved "pair-wise" frequency correlation and used a range of OFDM channels of 16 to 512 (with the number of OFDM channels always being a power of two). The correlation time was equal to the data symbol time, which gets longer as the number of OFDM channels is increased. As the number of OFDM channels in the signal is increased, both frequency correlation and time correlation can be done on lower signal E_b/N_o values because more orthogonal frequency channels are present and the OFDM symbol time is much longer, providing a longer correlation window. A typical single-channel signal was also used in the experiment for comparison. The single-channel signal, having the shortest symbol time, will have the shortest correlation window and only one frequency channel, making it the most difficult signal to frequency and time correlate when the signal is noisy. Even if a longer correlation time was used for the single-channel signal, with multiple data symbols within the correlation window, it would still require a much higher receiver E_b/N_o in order to achieve the same performance as using an equivalent OFDM signal (approximately 3 to 6 dB depending on the noise level). This is because the different modulation levels in each data symbol will interfere with each other in the correlation window, and

this interference will reduce the effectiveness of the algorithm when used on a signal already buried deep in noise.

The experimental results were compared to simulation results previously generated (Figure 13 for "pair-wise" correlation and Figure 14 for "training sequence" correlation). The first fact to note is that for the simulations, the maximum number of OFDM channels used was extended to 4096 since they were performed on PCs with enough memory to handle the larger channel size. With 4096 channels, frequency correlation is functional down to an E_b/N_o of -8 dB for "pair-wise" correlation and -21 dB for "training sequence" correlation. With the hardware experiment going up to 512 OFDM channels, frequency correlation is functional down to and E_b/N_o of -1 dB for "pair-wise" correlation and -13 dB for "training sequence" correlation. The latter value is the minimum E_b/N_o that can be modeled using the hardware. However, it does demonstrate that a small antenna array using commercial oscillators, ones with lower frequency stability, and employing ARTEMIS will be able to communicate with the low data rate Mars microspacecraft mission and medium to high data rate Moon microspacecraft missions previously described.
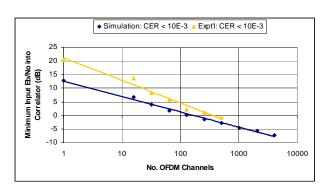

Figure 13: Performance of Pair-Wise Frequency Correlation – Experimental Results vs. Simulation
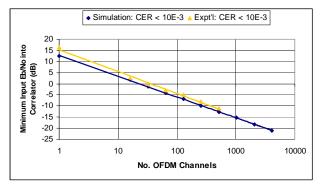

Figure 14: Performance of Training Sequence Frequency Correlation – Experimental Results vs. Simulation

A second fact to note from these experiments is that in all cases, the experimental results performed worse as compared to the simulation. Even in the best case at 512 OFDM channels, a difference of 3 dB was present for the "pair-wise" correlation results. Similar results were obtained from the experiments using "training-sequence" correlation, through the difference between the experimental results and the simulation was consistently 2 dB. At first, it was thought that something was wrong with the simulation results. However, on further consideration, it was found that the anti-aliasing filter was causing the difference between the experimental and simulation results. The filter is not flat across the oversampled bandwidth, leading to some phase rotations at certain frequencies, causing an apparent decrease to the signal SNR. Therefore, when the SNR is set on the multiplexed signal, if each signal is at a different frequency, then the SNR of each individual signal might be lower than the "average" SNR value of the multiplexed signal. This will lead to apparent degraded performance in frequency correlation. To determine if this was the issue, the experiments were repeated with a shorter range of OFDM channels – 64 to 512. This time, the frequency offset was kept the same for all of the signals, to remove any effect of the anti-aliasing filter bandwidth. For pair-wise correlation, the new experimental results essentially matched the simulation results (see Figure 15).
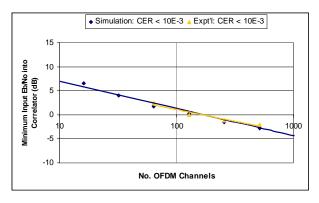

Figure 15: Performance of Pair-Wise Frequency Correlation when Frequency Offset is the Same in All the Signals.

For training-sequence correlation, the experimental results matched the simulation for the 64-channel OFDM signal. However, there was still a divergence about 1 dB between the experimental and simulation results for the 512-channel OFDM signal. The cause for this is still unknown, however, a possible hypothesis is that when the noise generator is at a very high enough setting, which was true for the training-sequence 512-channel OFDM experiment, the noise is no longer purely white and has some frequency

dependencies. Though these irregularities are very small, it might be enough to cause the 1 dB performance degradation.
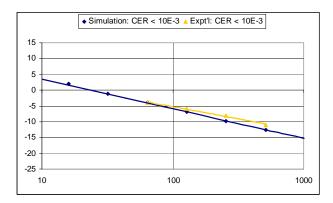

Figure 16: Performance of Training Sequence Frequency Correlation when Frequency Offset is the Same in All the Signals.

EFFECT OF TIME OFFSETS ON FREQUENCY CORRELATION

The previous experiments on the functionality of the ARTEMIS frequency correlation algorithm assumed no significant time offsets were also present between the antenna signals along with the unknown frequency offset. Any time offsets will induce different phase shifts in each OFDM channel because the FFT window performed on the data symbols for use in both frequency correlation and data demodulation will no longer be aligned with the OFDM symbol boundaries. Examples of the effect of such a phase shift due to a time offset on an OFDM symbol are illustrated in Figure 17. In this example, a 128-channel OFDM symbol oversampled by a factor of 8, expressed in the frequency domain (hence the presence of the 128 BPSK data symbols in the frequency spectrum) is shifted in the time domain by a time offset equal to 6 digital samples. Given the oversampling ratio, this is a time shift equal to $6/(2*8)*100\%$, or 37.5% of the overall data rate time. This time offset causes the individual OFDM channels to shift in phase at differing degrees. The higher frequency channels have actually been phase shifted past 90° and are reversed as compared to the original symbol. Note that the low-frequency channels are relatively unaffected. A larger time offset will lead to even more channels undergoing a large phase shift. Frequency correlation attempted between frequency spectra with different phase shifts due to time offsets will eventually fail once the phase shifts get large enough.
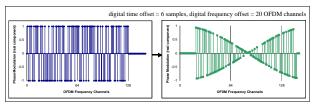

Figure 17: Phase Shifts Introduced by a Time-Shifted FFT Window on OFDM Frequency Spectrum (signal is oversampled 8 times above Nyquist).

OFDM Channel Filtering for Functional Frequency Correlation with Concurrent Time Offsets

A solution for to this problem was developed for ARTEMIS, based on the nature of the OFDM frequency spectrum. Looking at the first OFDM spectrum in Figure 17, if the OFDM channels with worst phase shifts at the high end of the frequency bandwidth could be removed (ie. digitally filtered), then it would be possible to perform frequency correlation even if some of the remaining OFDM channels still have phase distortions. This process is illustrated in Figure 18. The spectrum that is going to be correlated is multiplied by a rectangular window half the bandwidth of the OFDM data spectrum, where every digital data point outside the window is multiplied by zero and every point inside the window is multiplied by one. If this rectangular window, or filter, is placed at the start the of OFDM spectrum, it can be used to remove the higher frequency OFDM channels adversely phase shifted by the time offset, it would make frequency correlation possible. If the filter were made even smaller, say one quarter of the OFDM data bandwidth, then even more OFDM channels with slight phase shifts would be removed, keeping only those at the low end of the bandwidth which have only minor distortions.
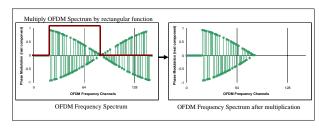

Figure 18: OFDM Spectrum after Adversely Phase Shifted Channels are Removed via Multiplication with a Simple Rectangular Function (filter)

However this introduces two problems. The first is that as more OFDM channels are removed, then frequency correlation will cease to function at the E_b/N_o levels determined in the previous experiment. The solution to

this is to add more OFDM channels than are strictly necessary given the signal E_b/N_o, as shown previously in Figure 13 and Figure 14, to compensate. The second problem, which is more serious, is that if the filter is to be placed at the beginning of the OFDM spectrum before frequency correlation, then an efficient way must be determined to estimate the frequency offset in order to place the filter properly. Otherwise, some of the badly distorted OFDM channels will still be present in the signal during frequency correlation. If the filter is placed with a slight error, frequency correlation will still work as long as the error is minor. Therefore, this estimate of the frequency offset need not be exact, but it must be reasonably accurate.

Coarse Frequency Offset Estimation

The solution that was determined for this problem is to correlate the *magnitudes* of the frequency spectra before normal frequency correlation. Figure 19 illustrates the magnitude of the OFDM frequency spectrum illustrated previously in Figure 17. Since taking the magnitude of an OFDM frequency spectrum will also remove the phase modulation, it will always look like a rectangular signal. Since the magnitude of the OFDM spectrum will always be a rectangular signal, the received spectrum magnitude can simply be correlated with a computer generated noise-free rectangular signal.
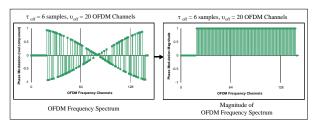

Figure 19: Magnitude of an OFDM Frequency Spectrum (this example uses a 128-Channel OFDM Symbol).

Since the two functions being correlated are simple rectangular functions, it will be impossible to determine the exact frequency offset in the presence of noise as the correlation function will not have a sharply defined peak as shown previously in the second diagram in Figure 2 (this was determined via simulation). It will usually be incorrect by many frequency sample points even in the presence of a small amount of noise. However, even in the presence of this error, the correlation of the frequency magnitudes can still be employed to calculate a *coarse* estimate of the frequency offset. This estimate can then be used to place the rectangular filter at the beginning of the data bandwidth.

ARTEMIS HARDWARE FOLLOW-UP EXPERIMENTAL RESULTS

Frequency Correlation with Concurrent Time Offsets

The next set of experiments using the hardware apparatus were performed to validate the coarse frequency correlation and filtering algorithm and to determine if it made it possible to perform regular frequency correlation between two signals functional in the presence of a concurrent time offset. Pair-wise and training sequence correlation experiments were performed using both a 128- and 512-channel OFDM signal. The frequency offsets were the same as in the first experiment (0 kHz for the first antenna, 10 kHz for the second, and 20 kHz for the third.) and a CER of 10^{-3} is desired. Three OFDM channel filter configurations were used:

- No filter;
- Filter with a bandwidth equal to the data bandwidth (ie. it keeps all the OFDM channels, but removes the out-of-band noise);
- Filter with a bandwidth equal to half the data bandwidth (ie. half of the OFDM channels are removed from the higher frequency side of the data bandwidth).

The maximum tolerable concurrent time offset for functional frequency correlation was determined for all cases at different signal E_b/N_o levels. The first set of results for pair-wise frequency correlation is referenced in Figure 20 and Figure 21 – 128 and 512 OFDM channels respectively. The vertical line indicates the nominal correlation operating point for the given OFDM channel size. At the respective operating points of both figures, if no coarse frequency correlation is performed, then a concurrent time offset of about 10% to 20% of the data period can be tolerated before frequency correlation fails. However, by placing a filter equal to the data bandwidth using coarse frequency correlation, this can be improved to 40% to 60% of the data period. In fact, by using the filter to remove the noise that is outside the bandwidth of the OFDM spectrum, frequency correlation will function down to an E_b/N_o level 2 dB lower than if no filter is used, assuming that no time offsets are present. Beyond this point, the signal is too noisy for frequency correlation to function at the desired CER of 10^{-3}.

By using the smaller filter, the maximum tolerable concurrent time offset can be further increased to 60% to 110% of the data period, a significant improvement. However, frequency correlation will not function at the desired CER for an Eb/No much less than the nominal

operating point, even assuming no time offsets are present. This occurs due to two reasons. The first is that too many OFDM channels are being removed for the frequency correlation algorithm to function at that level. The second is that the channel filter is not being placed accurately due to the noise level leading to frequency offset estimates with very larger errors. Thus many OFDM channels with large phase distortions are interfering with the correlation algorithm.
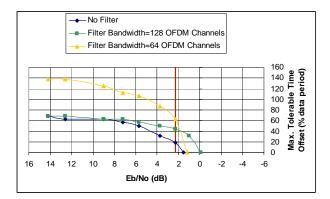

Figure 20: Maximum Tolerable Concurrent Time Offset for Functional Pair-Wise Frequency Correlation vs. Signal E_b/N_o (the vertical line indicates the nominal correlation operating point of a 128-channel OFDM signal).

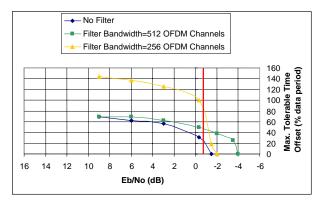**Figure 21: Maximum Tolerable Concurrent Time Offset for Functional Pair-Wise Frequency Correlation vs. Signal E_b/N_o (the vertical line indicates the nominal correlation operating points of a 512-channel OFDM signal).**

By including additional, redundant OFDM channels (ie. more that are strictly necessary given the E_b/N_o operating point of the signal) in the transmission, every case can be improved to tolerate a time offset on the order of 100% of the data period. For example, if the receiver E_b/N_o of a given scenario dictates the use of 128 OFDM channels for pair-wise correlation, if 512 OFDM channels are used instead, then the maximum tolerable time offset between any two signals will be improved from 60% to 125% of the unchannelized data period.

The results for the training sequence frequency correlation experiments are somewhat worse than those gathered from the pair-wise correlation experiments (see Figure 22 and Figure 23). For both OFDM channel sizes, the maximum tolerable time offset was reduced to 10% of the data period when no coarse frequency correlation and filtering is performed. And, when these functions are used, the accuracy of coarse frequency estimation at these E_b/N_o levels is so poor, that frequency correlation of the filtered OFDM bandwidth fails at the E_b/N_o operating point of the OFDM signal, even when the filter is at its largest size of the full data bandwidth. The 10% concurrent time offset tolerance is better than what can be achieved using a single-channel signal, since frequency correlation of that type of signal will fail at the same E_b/N_o level even when no offset is present due to the different modulation levels present in the correlation window interfering with each other. However, if a better tolerance to time offsets is required due to a higher data rate being used, then redundant OFDM channels must be used for training-sequence frequency correlation. As an example of this, if 512 OFDM channels are used in a scenario where 128 OFDM channels are mandated by the receiver E_b/N_o, then the tolerance of frequency correlation to concurrent time offsets can be improved to 50% of the data period using a filter equal in size to the data bandwidth. If 64 OFDM channels are required for the given receiver E_b/N_o, then by increasing the number of OFDM channels to 512, a time offset equal to 120% of the data period can be tolerated if a filter size of half the data bandwidth is used after coarse frequency correlation.
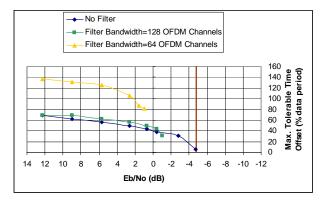

Figure 22: Maximum Tolerable Concurrent Time Offset for Functional Training Sequence Frequency Correlation vs. Signal E_b/N_o (the vertical line indicates the nominal correlation operating points of a 128-channel OFDM signal).
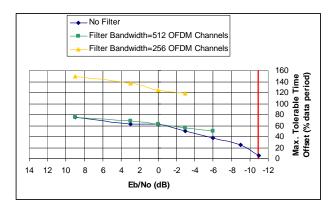
Figure 23: Maximum Tolerable Concurrent Time Offset for Functional Training Sequence Frequency Correlation vs. Signal E_b/N_o (the vertical line indicates the nominal correlation operating points of a 512-channel OFDM signal).

A summary of the timing offset tolerance limits when coarse frequency offset estimation is and is not used is references in Table 1. Without coarse frequency estimation and OFDM channel filtering, ARTEMIS can handle initial time offsets equal to our 2 times the size of the 10% data period limitation found in most existing arrays. With coarse estimation and OFDM channel filtering, ARTEMIS can handle initial times offsets ten to twelve times larger than current systems. Redundant OFDM channels will be required to achieve this, but this comes at a small cost and allows an ARTEMIS array to outperform currently exiting standards. This increase in time offset tolerance allows the ARTEMIS array to work for signals with higher data rates than can be handled on currently existing arrays, while at the same time performing frequency correlation, something that is also not done on those arrays.

Table 1: Summary of Maximum Tolerable Concurrent Time Offset for Functional Frequency Correlation (values expressed as percentage of data period).

	Pair-Wise	Training Sequence
Regular Frequency Correlation	20%	10%
Frequency Correlation with Coarse Correlation and Filtering	60%-110% Redundant OFDM channels possibly required for >100% tolerance	50%-120% Redundant OFDM channels always required

In all cases, different filter sizes other than one half the data bandwidth can be used to tune the performance of the system. If, given the array equipment, only values of τ_{off} are expected to occur, then a wider filter bandwidth can be applied. For larger offsets, a narrower filter might be required, along with the usage

of additional OFDM channels to compensate for the filtered channels. The filter size, which is, in essence, just a software parameter in the ARTEMIS ground correlator, can also be adjusted during operations to keep up with any significant changes in time offset.

Time Correlation

After frequency correlation, the signal can be filtered to remove out-of-band noise in the oversampled bandwidth and time correlation can be performed on the signals. Therefore, the performance of the time correlation algorithm will be better than the frequency correlation algorithm. Due to signal oversampling, the time correlation algorithm can be incorrect by a few samples and still allow for the signals to be aligned with enough accuracy so that the array-combined signal has a low BER.

An interesting fact is that if ARTEMIS is to be employed on arrays communicating with Earth orbiting microsatellites communicating at very high data rates, such as 1 Mbps or greater, any frequency offsets between array signals due to local oscillator drift will be a very small percentage of the data bandwidth, under 10% depending on the radio transmission frequency. Therefore frequency correlation will not be required. However, when using a traditional FSC array, a data rate of 1 Mbps or greater might not be achievable due to the requirement of an initial time offset less than 10% data period before time correlation is performed. This will be difficult to achieve since the high data rate signal will have a very short symbol time. However, when using ARTEMIS and an OFDM signal and employing time correlation without any frequency correlation, this data rate constraint can be relaxed by a factor of N, the number of OFDM channels. This can be done because the symbol time an OFDM signal with the same data rate as a single-channel signal is N times longer, which reduced the effect of inter-symbol interference (ISI) when using the time correlation function. Theoretically, by using accurate GPS equipment previously described, this would allow the array to time correlate signals with data rates much higher than 1 Mbps when a large number of OFDM channels are used. without worrying about the effect of ISI.

FUTURE EXPERIMENTS AND DEVELOPMENT OF ARTEMIS

Additional Memory for More OFDM Channels

More memory should be added to the correlator prototype to allow for more OFDM channels to be used.

If a fast enough DSP is used, it might even be possible to use more than 4096 OFDM channels in the signal.

Radio Frequency (RF) Link to Between Microspacecraft DSP and Correlator DSP

The next major stage for the development of ARTEMIS is to add RF links between the microspacecraft DSP and individual receiver elements connected to the ground correlator DSP. This will bring the prototype very close to the actual ARTEMIS system that would be employed in the field. The first step of this improvement is to have just one receiver connected to the correlator DSP. The array-multiplexed signal currently used with the prototype can then be transmitted. This will make it easier to perfect the design of the anti-aliasing filter and power-amplifier needed for each antenna. The power-amplifier design must be done correctly so that it can work properly with the OFDM signal. It must be able to deal with the high peak-to-average power ratio of OFDM signals with a large number of channels.

When multiple receivers are connected, the best way of simulating offset errors is yet to be determined (assuming they aren't simulated in software, like they are now). For frequency offsets, the use of voltage-controlled oscillators at each receiver should work in creating frequency and phase offsets between the array signals. Time offsets can be generated by differing the cable length linking the transmitter to each receiver (assuming a wired RF link is used), or by changing the position of the transmitter with respect to the receivers (assuming a wireless RF link is used). However, it is difficult to simulate specific time offsets using either of these methods. Voltage-controlled time-delay stages in the downvconverter stage of each receiver or software induced time offsets located in the correlator programming provide are methods of controlling the time offsets for a given experiment. It should be noted that the complexity of this setup is very high, requiring the use of equipment that will not be used in the final ARTEMIS configuration, and hence leading to additional costs. A better way to do this would be to first perform some preliminary steps to confirm the functionality of the antennas in the array and that they can communicate with the ground correlator. Then, the development of ARTEMIS can proceed to the next phase, the flight experiment.

Nanosatellite Flight Experiment

Once the previous development stagess are completed, an experiment using an ARTEMIS array on the ground communicating with an OFDM transceiver on-board a nanosatellite built at the Space Flight Laboratory (SFL) can be performed. The data rate used in the experiment will depend on the functionality of the S-Band radio on the upcoming CanX-2 nanosatellite flight. The array will most likely comprise of group of 1 m antennas, each with its own local oscillator and GPS receiver, connected to the central correlator site located at the SFL.

CONCLUSIONS

ARTEMIS combines the radio astronomy techniques of FSC and VLBI with OFDM to create a promising new technology for facilitating the construction of flexible, low-cost, ground station arrays for communicating with microspacecraft. A thorough development of the theoretical principles underlying the ARTEMIS concept has been accomplished and a proof-of-concept experiment has been developed to validate the ARTEMIS principle. Preliminary observations are promising, and concur with results derived from theoretical models and simulations. More advanced experiments have been devised to further demonstrate the benefits of ARTEMIS.

It is evident that ARTEMIS will be of particular use to future microspace missions, in that its application will facilitate higher data rate communications to and from microspacecraft in LEO, and help extend the microspace concept to interplanetary distances.

ACKNOWLEDGMENTS

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