Array Signal Processing in the NASA Deep Space Network

Timothy T. Pham and Andre P. Jongeling
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109
Timothy.Pham@jpl.nasa.gov
Andre.Jongeling@jpl.nasa.gov

Abstract—The NASA Deep Space Network (DSN) has recently been augmented with an array capability. This is a third-generation system employing the full spectrum combining technique. The first deployment at Canberra, Australia in 1996 was made specifically to support Galileo mission; the second deployment at Goldstone, California, U.S., followed four years later in 2000 and was of multi-mission capability. The third installation extended the Goldstone capability to the other two DSN sites, namely Canberra, Australia and Madrid, Spain.

The new array capability offers many benefits to deep space missions whose signal reception is often constrained by the vast interplanetary distance. With an increase in signal level obtained from combining the inputs of several smaller antennas, the new capability helps to extend the mission lifetime for those whose received signal falls below the tracking threshold. For other missions not constrained by this problem, arraying can help to increase telemetry data return relative to that received from a single antenna. Aside from benefiting telemetry data, for the first time in the DSN history, arraying via full spectrum combining technique also enhance navigation performance.

In this paper, we will describe the benefits of arraying and past as well as expected future use of this application. The signal processing aspects of array system are described. Field measurements via actual tracking spacecraft are also presented.

TABLE OF CONTENTS
1. INTRODUCTION
2. PAST AND FUTURE USE OF ARRAYS
3. MERITORS FREESSPEC TRUMAR RAY
4. EQUIPMENT DESCRIPTION
5. SIGNAL PROCESSING
6. RESULTS
7. CONCLUSIONS

1. INTRODUCTION

Arraying is a common technique used to improve reception of weak signals [1]. It is symbolically represented in Figure 1. The signals received simultaneously from different antennas are combined, creating an enlarged aperture. This approach can be used to enhance deep space communication where the spacecraft transmitted signals are received at interplanetary distances.

This paper first provides an historical context for the development and application of arrays. It then follows with a system description and highlights of different aspects of signal processing. Also presented are results obtained from field data measurements and key performance parameters.

Figure 1B enefito far raying

2. PAST AND FUTURE USE OF ARRAYS

In the past, the Voyager mission relied on arraying to increase its data return during Uranus encounter in 1986 and Neptune encounter in 1989 [2, 3]. The Galileo mission was another recent example where arraying was used to significantly increase the science return. The spacecraft transmitted telemetry data was received at interplanetary distances.

Table 1 shows the improvement in data return.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Before Array</th>
<th>After Array</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Rate</td>
<td>10 Mbps</td>
<td>20 Mbps</td>
</tr>
<tr>
<td>Coverage</td>
<td>100 km</td>
<td>500 km</td>
</tr>
<tr>
<td>SNR</td>
<td>10 dB</td>
<td>20 dB</td>
</tr>
</tbody>
</table>

Table 1: Improvement in DSN Performance

Table 2: Predicted Array Performance

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Gain</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna 1</td>
<td>10 dB</td>
<td>80%</td>
</tr>
<tr>
<td>Antenna 2</td>
<td>15 dB</td>
<td>85%</td>
</tr>
<tr>
<td>Antenna 3</td>
<td>20 dB</td>
<td>90%</td>
</tr>
</tbody>
</table>

Table 2: Antenna Performance

Figure 2A: Array configuration

Figure 2B: Array performance

Figure 2C: Array efficiency

Figure 2D: Array gain
Future missions can also benefit from arraying. These include the class of missions where certain operational phases may require more performance than a single 34-meter antenna can provide. For example, the Cassini mission requires only single 34-meter antenna support during cruise period, but upon entering Saturn's orbit, in order to return 4 Gbits/day mapping data (averaging 4.6 kbits/s), it requires an array of up to 70-meter and 34-meter antennas. Another class of potential missions is those that need to relay critical science data back to Earth in the shortest amount of time possible. Stardust belongs to this group of customers. Upon entering the Wild 2 comet in 2004 and having analyzed the properties of cometary samples, the mission plans to reduce single-event risk by sending data back as fast as possible. An array of two 34-meter antennas will enable the Stardust mission to cut the transmission time in half compared to a single antenna.

In the DSN, the 70-meter antenna, being the largest tracking station, is often relied on for tracking spacecraft in the outermost region of deep space. This antenna, however, was built in the late 1960s. As the antenna structure ages and requires more maintenance service, there is a growing concern regarding its availability. An array of several smaller 34-meter antennas can serve as a backup for the 70-meter during extended maintenance outages.

Another way of looking at the issue is that arraying increases the flexibility of DSN scheduling and allows for better utilization of available resources. In the absence of an arraying capability, a shortfall in 34-meter link performance would be noted that the 70-meter antenna, or other array usage discussed in this paper, refers only to downlink processing. The capability, as built, does not support an arrayed uplink.

3. MER ITSELF ULLSPEC TRUMAR RAYING

Themain objective of arraying is to coherently combine signals from different antennas; however, because the antennas are geographically separated, the signal received at each site has different delays and Doppler which are dependent on the antenna's position and motion relative to the spacecraft. The differential delay and Doppler must be removed so that data streams can be coherently combined. In the arraying techniques described below, these quantities are modeled, and the residuals between them are used to estimate the actual alu wasa eto y cros and the whole spectrum [9,10,11,12]. Figure 3 illustrates these differences. For implementation described in this section, the ploysh eul is spectrum eth. Int he followinp aragraphs, we highlight the differences between this technique and others commonly used.

Among the six antennas capable of receiving X-band at Goldstone, the largest being the single 70-meter antenna and the rest 34-meter's. The 34-meter group is further categorized into high efficiency (HEF) and beam waveguide (BWG) due to differences in their commonly used

![Figure 2](image-url)
Symbol combining

Symbol combining, demodulated symbols from different antennas are delay compensated, cross-correlated, and finally combined. Combining can be done with complex symbols. The resulting signal has a higher energy per bit to noise spectral density ratio (Eb/No), thus realizing a lower bit error rate performance. Thus, the combined signal allows for proper decoding of telemetry information where individual symbols streams wouldn’t. The technique was successfully used in the Voyager mission. The symbol combining technique offers an advantage of doing signal processing at relatively low symbol rates, typically in the range of tens of hundreds of kHz. Requirements on the accuracy of data alignment are therefore less constrained. Transporting of symbols streams to be combined over long distance is also easier, allowing individual antennas at large distances to participate in the array.

A drawback, however, is that it requires the signal level at individual antennas to be well above the threshold of the receiver. Otherwise, valid symbols can’t be derived.

Carrier arraying and symbol combining

In carrier arraying, the information derived from the carrier signal is used to achieve acquisition at the supporting antennas. Once both receivers lock up, symbol streams can be combined, and the resulting signal is virtually identical to the signal as it moves at the reference antenna. Downstream processing further reduces the required threshold, enabling proper demodulation of the combined signal, but such processing cannot be done on the individual signals.

In summary, symbol combining is achievable as long as individual antennas in the array can acquire and demodulate the signal. Its benefit, thus, applies mostly to the decoding process. Carrier arraying helps to overcome the shortfall in the receiver carrier-tracking loop at the supporting antennas. Full spectrum arraying further reduces the required threshold, enabling proper demodulation of the combined signal, but such processing cannot be done on the individual signals.

4. EQUIPMENT DESCRIPTION

Signal processing for arraying ing a signal on two main assemblies: the IF uplink spectrum receiver (FSR) and the full spectrum combiner (FSC), see Figure 4. The FSR receives a demodulated 00 MHz Hz IFs are derived from the carrier signal of the IF detector, amplified by the microwave combining network. The FSR is a narrowband receiver that has a high output level of the signal, which is then downconverted to a low frequency by the downconverter. The FSR is a digital, high-resolution receiver that uses digital processing to increase the signal-to-noise ratio. In conclusion, the results of the experiment confirm the feasibility of using arraying in such a system.
processing (such as demodulation, decoding, and range detection) cannot be accomplished on the combined output in order to yield final science and engineering data products.

Figure 4: Array signal processing equipment

Major components of the FSR are illustrated in Figure 5. The analog/digital converter and digital downconverter capture relevant portions of the 300 MHz IF analog signal in a 6 MHz, 8-bits sampled, in-phase and quadrature-phase digital data stream. The delay line and diphasic corrector boards correct signal delay using information from predictst together with feedback from the FSC derived residuals. These alues are provided to the operators for monitoring. The array controller relayed to the FSC corrects the delay using the delay error feedback together with feed back from the FSC.

Figure 5: Processing in the full spectrum receiver.

Figure 6 presents major components in the FSC. The cross correlations of upper and lower sideband of different antennas are used to derive differential phase and delay values for feedback to the FSRs. At the same time, the Weight and Sum combine the weighted FSRs input, to produce optimal output. The D/A and Upconverter transforms the digital baseband stream to an analog 300 MHz IF. The Signal Monitor as well as the Realtime and Data processors carry out functions similar to those in the FSR.

5. SIGNAL PROCESSING

This section highlights the processing of the signal received by the array. The main focus is on correlation, delay compensation and combining.

Correlation

The success of combining depends on good correlation results. Correlation is an essential process without which proper combining cannot be done.

Figure 7 shows the detailed processing of correlation. With the aid of Doppler predictions, the upper and lower sidebands of the received signal from each antenna are captured. The upper sideband from one antenna is correlated with the same component of the array reference, from which the phase difference at the upper sideband is measured. The same process is simultaneously performed on the lower sideband component. An array geodesy of the two phasemeter measurementsthen yields the phase difference between the upper and lower sidebands measured. The same process is simultaneously performed on the lower sideband frequency providing the in the delay.

Figure 6: Processing in the full spectrum combiner

Figure 7: Correlation processing
There are different ways to implement the correlation process. The useful spectrum arraying equipment supports two approaches, both successfully tested. The simpler scheme ("simple") involves choosing the antenna signal of largest SNR to be the reference, against which all other antenna signals are correlated. This scheme works well when only one element of the array has a significantly higher SNR than others, as in the case of fararray's 70-man d 34-meter antenna. The second method, referred to as "simple", treats the array reference as a rotating sum of all antennas except one under consideration. In other words, one antenna will be cross-correlated against the sum of the others. Simulation results indicate that the rotating sum method performs better than the fixed reference, and that the final solution emerges within a few iterations, see Figure 8[13]. Note that the simulation includes a third approach using eigenvector methods[14] however, this algorithm is not implemented in the FSC.

Consideration needs to be given to the setting of integration time for the correlation process. From thermal noise considerations, a long integration period is preferred since it would yield an estimate of small error. Obviously, the lower the signal level, the more integration time required. The problem is that the signals received at different antennas travel through the Earth's troposphere and therefore are subjected to different delay. These tropospheric delays vary on a relatively short timescale, resulting in less correlation for long integrations. An illustration is provided in Figure 9 for a fixed combined symbol SNR at -5 dB, with equal aperture antennas separated by a baseline of 1 - 10 km[15, 16]. At X-band, the tropospheric limit for a 20-degree correlation error is about 20 seconds. The operating region is the triangular area in the lower right corner of Figure 9. It is upper-bounded by the tropospheric noise and lower bounded by thermal noise. Note also that the graph is expressed in terms of symbol rate, rather than in received signal to noise ratio. Given a fixed symbol SNR, these two quantities are equivalent.

Care must also be given to the use of correlation measurements. Invalid cross correlation arises when one or both signals encounter problems. For example, one antenna could be mis-pointed, or the spacecraft could go behind a planet. As in any control feedback system, care must be given to the design so that bad estimation of the error signal does not drive the system away from a stable condition. This prevention is achieved with a filter on the FSC correlation estimates.

Delay compensation

The delay compensation process is done in two steps. First, each FSC Ris provided with two sets of delay predictions, one for the reference antenna, the other for the antenna under processing. Using a predictive model, the FSC removes a large portion of the delays so that its signal can be aligned with the reference. These predictions are computed based on the spacecraft trajectory and the locations of the tracking antennas. The second step involves minor correction based on residual errors being measured from the correlation in the FSC and fed back to the FSC.

Over the track, the relative position of different antennas in the array changes with respect to the spacecraft. The delay of the non-reference signal varies relative to that of the reference. The relative delay is corrected by adjusting the physical delay line in the non-reference FSC. Since such adjustment is only possible with positive values, a delay bias is introduced into all antennas. The bias is typically set at a value equal to the maximum delay among all antennas. This later correction is achieved in the following sequence.

Another consideration is the determination of different antennas in the array changes with respect to the spacecraft. The delay of the non-reference signal varies relative to that of the reference. The relative delay is corrected by adjusting the physical delay line in the non-reference FSC. Since such adjustment is only possible with positive values, a delay bias is introduced into all antennas. The bias is typically set at a value equal to the maximum delay among all antennas. This later correction is achieved in the following sequence.
Combining

Combining is done relatively straightforward. The 16-MHz samples from different FSRs are weighted according to their relative SNRs. The system allows disabling of certain inputs where the signal is not detected, so that the non-contributing elements will not affect the gain performance.

6. RESULTS

Results of field demonstrations at Goldstone with missions currently in flight are discussed below. Emphasis will be placed on the array gain for telemetry and radiometric data.

Telemetry array gain

Figure 10 shows the new antenna array at Goldstone with two 34-m antennas at different FSRs allowing a combined signal using one of the Mars Climate Orbiters. The profile varies as a function of time because of the changing elevation. An average array gain of 2.9 +/- 0.2 dB was observed, compared to a theoretical gain of 3.0 dB. The 0.1 dB difference is attributed to errors in the presence of noise as well as signal processing issues with the hardware.

Laboratory measurements with calibrated test signals showed that the SNR degradation caused by sideband noise is within 0.2 dB.

Radiometric array gain

Ranging measurements with Cassini with an array of two 34-meter antennas. The realized gain for ranging is less than that of telemetry. A 1.6 +/- 0.3 dB gain was measured, relative to a 2.4 dB theoretical improvement which was confirmed by a measured 2.3 dB on telemetry. The less favorable performance is caused by the fact that the ranging signal lies much further away from the carrier, compared to the telemetry subcarrier. In the presence of noise and ever-changing Doppler frequency, the error in the phase and delay estimation of the 22 kHz sideband gets magnified when extrapolated to the 1 MHz ranging signal.

7. CONCLUSIONS

In summary, this paper discusses the recently deployed array capability within the NASA Deep Space Network. It provides a brief history of arraying and how this particular method of full spectrum arraying is beneficial to missions, compared to other array techniques. A general description of equipment and special considerations on signal processing are presented. Performance improvement observed with spacecraft in flight is consistent with expectation.

This new product enables the NASA Deep Space Network to provide better support to missions. It is now possible to provide extra performance in radiometric data as well as telemetry. Also, with advances in digital signal processing, the delay within the new system is no longer subjected to the phase drift of analog electronic components. This in turn eliminates the need for pre-track calibration that was often required with past equipment, resulting in an easy-to-operate and more schedule-efficient system.
ACKNOWLEDGMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

This work is a result of dedication from members of the 34-meter Array Implementation team. The authors wish to acknowledge the technical contributions of Charles Goodhart, Elliott Sigman, Susan Finley, Robert Navarro, Stephen Rogstad, David Fort, Roland Holden, Christine Chang, Leslie White, Robert Proctor, Nat Chavira, Kumar Chandra, Hossein Hosseini and Kenneth Clark.

REFERENCES


BIOGRAPHY

Timothy Pham is a member of the technical staff at the Jet Propulsion Laboratory. He led the development of several systems, ranging from demonstration of carrier arraying, radio science, Galileo telemetry support and more recently, 34-meter antenna arraying. He received a BSEE from the California Institute of Technology and a MSEE from the University of Southern California.

Andre Jongeling is a member of the technical staff at the Jet Propulsion Laboratory. He participated in the development of the arraying system for the Galileo mission, and has led the software team in the development of the 34m arraying system. He received a BSEE from the California State Polytechnic University in Los Angeles.