Chapter 2
Background of Arraying in the Deep Space Network

The Jet Propulsion Laboratory (JPL) operates the Deep Space Network (DSN) for the National Aeronautics and Space Administration (NASA) in order to communicate with spacecraft that are sent out to explore the solar system. The distances over which this communication takes place are extraordinarily large by Earth-based standards, and the power available for transmitting from the spacecraft is very low (typically 20 W or less). As a result, the communications links are invariably operated with very low margin, and there is a premium placed on improving all aspects of the ground system (i.e., antennas, low-noise amplifiers, receivers, coding, etc.).

An early system analysis of both the ground and flight aspects of deep-space communications by Potter et al. [1] concluded that the optimum ground configuration should be centered around large (i.e., at that time, 64-meter-diameter-class) antennas rather than arraying smaller antennas to create the equivalent capture area. This analysis was based on the concept of a dedicated link between a single ground antenna, a spacecraft that was continuously monitored from rise to set, and the highest possible data rate that technology would allow when the spacecraft encountered a distant planet.

In the more than 30 years since the Potter et al. study, a number of assumptions have changed. First, it was realized that spacecraft have emergencies, and no matter how much collecting area an agency had on the ground, that agency always wanted more in an emergency. One alternative was to "borrow" aperture from other agencies, but this implied arraying capability. Second, during an encounter with a distant planet, the scientists always wanted the maximum possible data return. Since it was not always politically or economically feasible to put up new 64-m antennas, again the pressure grew to borrow other apertures to increase the data return. This culminated in the concept of interagency arraying when the 27 antennas of the radio astronomy community's Very Large Array were borrowed during the Voyager 2 encounter with Neptune in the mid-1980s and arrayed with the 70-m and two 34-m antennas at the Goldstone Deep Space Communications Complex to provide a data return that was not considered possible when the mission was launched. Third, it was realized that, during the long cruise phase of an interplanetary mission, the communications requirements were rather modest and could easily be satisfied by a much smaller antenna than one of 64 or 70 m in diameter. In this way, the DSN developed the concept of a collection of 34-m antennas that could be individually targeted for the increasing number of missions being envisioned, but that could also be arrayed for "special" events.

A more recent study by Resch et al. [2] examined the cost and performance ratio of a single 70-m aperture versus an array of paraboloids with the diameter of the paraboloid as a parameter. They concluded there was no obvious cost saving with an array configuration, but it did offer scheduling flexibility not possible with a single aperture.

2.1 Early Development

During the late 1960s and 1970s, interest in arraying within the DSN grew slowly, and two very different approaches to the problem were developed. The first approach capitalized on the fact that most deep-space missions modulate the carrier signal from the spacecraft with a subcarrier and then modulate the subcarrier with data. Since typically about 20 percent of the power radiated by the spacecraft is in the carrier, this carrier can serve as a beacon. If two or more antennas on Earth can lock onto this beacon, then the radio frequency (RF) spectrum at each antenna can be heterodyned to a much lower intermediate frequency (IF) range, the difference in time of arrival (i.e., the delay) compensated, and the IF spectrum from each antenna added in phase.

The second approach to arraying developed synergistically with a program that was intended to pursue scientific investigations of geodesy, Earth rotation, and radio astronomy. This program involved the observation of natural radio sources whose spectrum was pure noise, and the array was a collection of antennas functioning as a compound interferometer. The intent of the scientific investigations was to use the radio interferometer, whose elements commonly were separated by nearly an Earth diameter, as a device to measure parameters like the baseline length, the position of radio sources, and small changes in the rotation rate of the Earth. The quantity measured was the difference in time of arrival of the signal at the various antennas. However, as equipment and techniques were perfected, it was realized that, if the measurements could be done with enough accuracy, then the delay could be compensated, either in real time or after the fact if the data were recorded, and the resulting outputs from all elements of the compound interferometer added in phase (rather than multiplied, as in interferometry) to yield an enhanced signal.

In 1977, JPL launched two Voyager spacecraft ostensibly with the purpose of exploring Jupiter but with the option of continuing on into the far solar system to fly by the outer planets. In fact, when these spacecraft were launched, it was not clear how much data could be returned from distances greater than that of Jupiter, and this question motivated a more intense study of arraying.

Voyager 2 obtained a gravitational assist from Jupiter and went on to fly by Saturn, Uranus, and Neptune. Saturn is almost twice as far from the Sun as Jupiter, Uranus almost four times as far, and Neptune six times as far. If nothing had been done to improve the link, then we would have expected about one-quarter of the data from Saturn as compared to that received from Jupiter; Uranus would have provided only one-sixteenth; and Neptune a mere one-thirty-sixth.

The data rate at Saturn was improved by upgrading the DSN 64-m antennas to a diameter of 70 m and lowering their system noise temperatures. At Uranus, the 70-m antenna in Australia was arrayed with a 64-m antenna belonging to the Commonwealth Scientific and Industrial Research Organization (CSIRO) and located approximated 180 km distant from the DSN 70-m antenna. At Neptune, arraying was accomplished using the 70-m and two 34-m antennas at Goldstone together with the 27 antennas of the Very Large Array (each 25 m in diameter) located in the middle of New Mexico. All of these efforts were successful in improving the data-rate return from the Voyager Mission. An important result was that the improvement obtained was very close to what the engineers predicted based on theoretical studies of the techniques used.

2.2 Current Status of Development

In this section, we discuss the systems that are in use in the DSN. It covers three systems whose deployments span a period of 8 years, from 1996 to 2003. All three employ the full-spectrum arraying technique.

In 1996, the first full-spectrum arraying system was developed and deployed to support the Galileo Mission [3]. The signal processing is done in near-real time, with a latency of a few minutes. A specially designed front-end processing captures the appropriate signal spectrum that contains telemetry information from each antenna participating in the array. The data then are turned into data records and stored on commercial computing workstations. The follow-on functions of correlating and combining, as well as the demodulating and decoding of the combined signal, are all done in software. Since the correlation and combining are implemented in software, the array can be applied to configurations that span over large baselines, e.g., thousand of kilometers in the case of the Galileo Mission, using a standard Internet-type connection. A drawback, however, is the bandwidth constraint of this connection. In order to meet a reasonable latency performance (i.e., a few minutes), this system tends to be more useful to missions of low data rates, which is the case with the Galileo Mission because of the limited equivalent isotropic radiative power (EIRP) from the spacecraft's low-gain antenna. The Galileo system as designed is constrained by a maximum data rate of 1 ksym/s. This ceiling is a result of three factors:

1) The technology and cost constraints associated with that particular implementation. The objective was to deliver a system within given cost and schedule constraints, as dictated by Galileo Mission events.
2) A design that is specifically created for the Galileo Mission but can be extended for multimission support. For example, only certain output data rates most likely used by Galileo are built, tested, and delivered to operations. The current capability works within performance specifications for a data rate up to 1 ksym/s; however, with small software modifications, it can be extended to about 10 ksym/s. This upper limit is due to a constraint set by the bus bandwidth used in the electronics of the system.
3) In post-combining processing, the demodulation and decoding functions being done in the software. A software decoder allows for implementation of a new design of concatenated (14,1/4) convolutional and variable-redundancy Reed–Solomon codes that can offer a much higher coding gain. The software receiver allows reprocessing of data gaps, thus increasing the return of usable data. The drawback, however, is that software processing is throughput limited, making the system less adaptable to a large set of high-data-rate missions.

In 2001, a second full-spectrum arraying system became operational at the Goldstone Complex. It is a follow-on to the Galileo system and is called the Full Spectrum Processing Array (FSPA) system. The correlation and combining functions are done in real time, using hardware of field programmable gate array (FPGA) technology. In addition, the post-processing functions of demodulation and decoding are accomplished by the standard hardware that supports multimissions, rather than special-built equipment as in the Galileo system. In so doing, the real-time array system at Goldstone can support data rates in the range of Msym/s, and it allows for up to six-antenna arraying within a DSN complex. Note that, due to the hardware nature of the processing and its larger bandwidth, this system is limited to arraying within a single DSN site. The capability to array between two DSN complexes is not supported. The array is capable of operating at X-band frequency (8.4 GHz), which is the most common frequency used for deep-space communications; however, because the arraying is actually done at IF frequency after the first RF/IF downconversion, the corresponding IF frequency for S-band (2.3-GHz) and Ka-band (32-GHz) signals is also within the range of captured bandwidth. As a result, existing missions that operate at S-band and future missions using Ka-band also can be arrayed, if desired.

In 2003, a third array system, which is functionally equivalent to the FSPA system described above, will be ready for deployment at the two overseas DSN facilities: Madrid and Canberra. Since these sites have fewer antennas, the deployed system has been downscaled to support four-antenna arraying. In this system, the design is further consolidated with more advanced FPGA technology. Functions that previously were done on application-specific boards, such as digital downconversion, delay, phase rotation, correlation, and combining, now reside on one board of a common design. Differences in functionality are handled by the FPGA programming. With a more powerful processor from recent technology advances, more functions can be packed onto the board. As a result, the system becomes much more compact. While the old design requires four fully populated racks, the new system can fit in two racks.

2.3 Anticipated Applications with Current Capabilities

An anticipated near-term use of DSN arraying is support for the return of high-value science data for the Cassini Mission. This mission has a commitment to return 4 Gb of data per day during its orbital phase. A single 70-m antenna does not provide adequate margin to support this required data rate. However, an array of one 70-m and one 34-m antenna is sufficient. This configuration increases the data return by 25 percent relative to that of the 70-m antenna. The arraying is being planned over the Goldstone and Madrid Complexes. It occurs in late 2004 and continues periodically until 2008.

Arraying is also likely to be used during the asteroid encounter of the Deep Impact Mission. In July 2005, the Deep Impact spacecraft will be releasing an impactor into the nucleus of the comet Tempel 1. With the data collected from the impact, scientists will be able to better understand the chemical and physical property of comets. Since this is a single-event observation most critical to the mission and it is occurring in a potentially hazardous environment, it is desirable to return the data as quickly as possible. An array of the 70-m and several 34-m antennas will help to increase the data rate.

Aside from increasing the mission data return, the array also is used as a tool to provide the backup support to the 70-m antenna during critical periods or during long maintenance periods. The backup support, however, is limited, not a full replacement of the 70-m antenna functionality. The backup capability applies to downlink telemetry and radio metric functions, but not to uplink commanding. Also, at the overseas complexes, there are not sufficient 34-m antennas to provide the equivalent aperture of a 70-m antenna. In Madrid, with a new 34-m BWG antenna scheduled for completion in 2003, there will be three 34-m antennas available. They can make up 75 percent of the reception capability of the 70-m antenna. In Canberra, the 34-m subnet consists of only two antennas; thus, about 50 percent of a 70-m antenna's capacity can be realized via array. Goldstone, on the other hand, has four 34-m antennas and thus can closely match the 70-m capability.

References

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[3] T. T. Pham, S. Shambayati, D. E. Hardi, and S. G. Finley, "Tracking the Galileo Spacecraft with the DSCC Galileo Telemetry Prototype," *The Telecommunications and Data Acquisition Progress Report 42-119, July–September 1994*, Jet Propulsion Laboratory, Pasadena, California, pp. 221–235, November 15, 1994. http://ipnpr.jpl.nasa.gov/progress_report/