IAF-97-Q.2.03

INTER-CONTINENTAL, INTER-AGENCY ARRAYING - THE GALILEO EXPERIENCE

J. Statman
K. Simpson
P. Beyer
Jet Propulsion Laboratory, California Institute of Technology

48th International Astronautical Congress
October 6-10, 1997 I Turin, Italy

INTER-CONTINENTAL, INTER-AGENCY ARRAYING - THE GALlLEO EXPERIENCE

Joseph I. Statman
Kimberly A. Simpson
Patrick E. Beyer
Jet Propulsion Laboratory, California Institute of Technology'
4800 Oak Grove Drive, Pasadena, California 91109, USA

Abstract

Since ***November 7, 1996,*** *the Galileo orbital tour of Jupiter and its moons (Ganymede, Callisto, and Europa) is routinely supported by a massive array of large antennas: two 70-meter antennas in GDSCC[2] (California) and CDSCC[3] (Australia), a 64-meter antenna at Parkes (Australia), and additional 34-reefer antennas at CDSCC. The scope of this array is unprecedented - it operates daily in a routine fashion, inter-continentally, and employs antennas of several agencies, namely two complexes of JPL's Deep Space Network (DSN) and CSIRO's[4] Parkes facility. The success of this routine arraying operation is the basis for the DSN'S new array of 34-meter antennas that is being implemented at GDSCC.*

Arraying offers a *flexible method to applying resources* to a communications *link. By* ***varying*** *the number of the antennas* ***in the*** *array,* ***enough*** *G/T[5]* ***can be constructed to*** *address a particular mission's downlink requirements. A specific use is for beacon-mode, or on-demand communications.' some (or all) of the antennas in the array monitor many spacecraft for* a *low-rate request- for-downlink. When such a request is detected, the full array is deployed to provide the requested service.*

In this paper we discuss the processes associated with making the operationally-complex arraying feasible - lessons learned from the Galileo support. ***The architecture of arraying large numbers of smaller antennas results in a more efficient, and cost-effective, method of supporting deep-space missions.***

1. INTRODUCTION

Ever since the beginning of Deep Space Communications, designers faced the challenge of overcoming the physical limitation inherent in long-distance communications: that the received power is reduced in proportion to the square of the distance between receiver and transmitter. As probes were sent farther away into space, the vast distance drove the designers to employ larger and larger antennas, receivers with added sensitivity, and better modulation and error-correcting techniques. Figure 1 captures the increase over the years in communication capability from a spacecraft to the ground, accomplished through a variety of investment and innovation.

One of the tools in the designer's arsenal is arraying - electronically combining the signals from multiple antennas to create a single, larger effective antenna. Though arraying can

1 The work reported in this paper was **performed at the Jet** Propulsion **Laboratory, California Institute of Technology, under** contract **with the National Aeronautics and Space Administration.**

2 GDSCC **- the Goldstone Deep Space Communications Complex**
3 CDSCC - **the Canberra** Deep Space Communications Complex
4 CSIRO **- Commonwealth Scientific Industrial Research Organization**
5 G/T **- Ratio** of **Antenna Gain to System Noise** temperature

be applied to both receiving and transmitting of signals, in this paper we limit the discussion to arraying of received signals. In this context, the effective antenna created by arraying has a G/T that is the sum of the G/T of the member antennas, less some processing losses[6]. Thus, if two identical antennas are arrayed, the G/I is doubled and hence the down-link data rate can be doubled. This tool has been used by JPL in several forms: baseband combining[1], symbol stream combining[2], and full-spectrum combining[3], to support primarily the Voyager and Galileo missions. As powerful as arraying is, there are several drawbacks:

a. It requires the allocation of many scarce resources (i.e. antennas) to support a single mission, whereas the same resources could be allocated to support multiple competing missions.

b. The likelihood of loss-of-data increases since the failure of any antenna in the array causes failure of the array. In the simplest model, if the availability of an antenna is p, then the availability of an array of N antennas is p^N

c. The likelihood of loss-of-data due to operational or procedural error increases as arraying requires coordination of multiple operations teams, often not co-located.

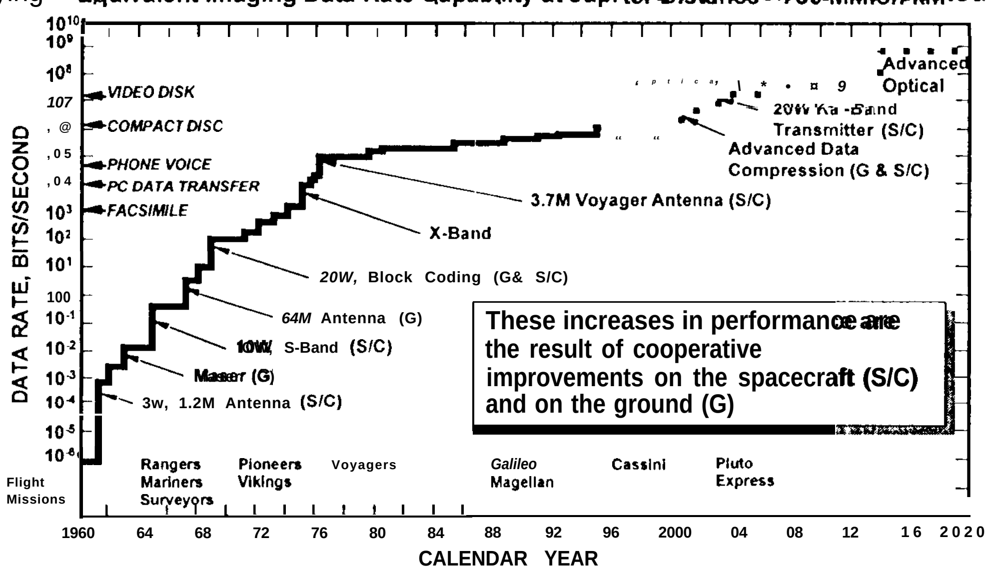

Figure 1- Equivalent Imaging Data Rate Capability at Jupiter Distance -750 Million Km

With these serious drawbacks, arraying has been used sparingly. JPL has conducted long-distance arrays to enhance the Voyager encounters with Uranus (CDSCC-Parkes array) and Neptune (GDSCC-VLA[7] and CDSCC-Parkes arrays). With the array difficulties listed earlier, these long-distance arrays were limited to short events (i.e. spacecraft flyby of a planet) and the operations staff was heavily supplemented with engineering staff. In addition, JPL is routinely arraying two antennas locally (within either CDSCC or GDSCC) to support Voyager, once every several months.

Arraying for Galileo necessitated a completely new operation paradigm. It was part of the JPL-developed mission operations strategy to retrieve meaningful science from the Galileo spacecraft in face of the failure of the high-gain antenna [4]. (The success of this strategy is

[6] In the remainder of this paper we assume that combining losses are negligible

[7] VLA - the NRAO Very Large Array (27 antennas) at Socorro, New Mexico)

now common knowledge with the fascinating images and science from Jupiter and its *moons.)* Key to the strategy was that Galileo had a series of encounters with Jovian moons, separated by *60-90* days, over *2* years. Data was recorded during each encounter and then relayed slowly to earth in-between the encounters. So arraying for Galileo required operation on a daily basis for almost two years, with an unprecedented number of Deep Space antennas (up to 7) and over large distances (GDSCC, CDSCC, and Parkes). In this article we describe how the array was constructed, operated, and succeeded. In spite of the challenging environment, the array performance for Galileo has been almost flawless, comparable to the-performance of a single antenna, thanks to the endless efforts of the engineers and the operators involved and the close cooperation between the agencies involved, NASA's DSN and Australia's CSIRO.

2. ARRAY CONSTRUCTION

As described in *[4],* after exploring utilization of antennas from NASA and other agencies, JPL selected to deploy a large array that consisted of a 70-meter antenna at GDSCC, a 70-meter antenna at CDSCC, several 34-meter antennas at CDSCC and a 64-m radio-telescope at Parkes.[8] The array was designed to accept inputs from up to seven antennas, though the array combined signals from only five antennas on a routine basis.

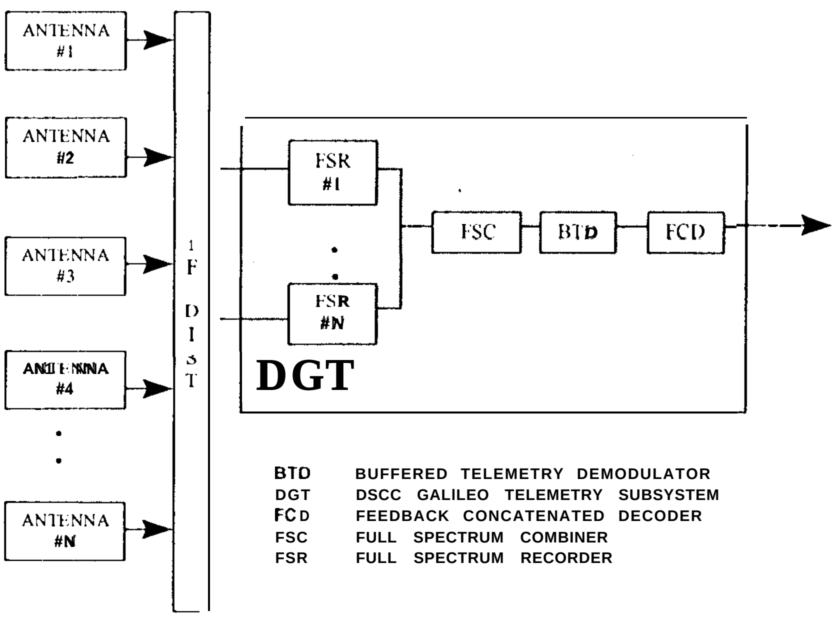

Figure 2- Components of the Array System

Array mechanization is shown in Figure 2. The implementation focused on the signal processing and maintained the antenna control (pointing and configuration) to the existing subsystems. Specifically, JPL implemented a new subsystem, designated DGT (DSCC Galileo Telemetry) to perform the unique features of the signal processing, including arraying. In the DGT, an FSR (Full Spectrum Recorder) was assigned to each antenna. The FSR received the Intermediate Frequency (IF) signal from the antenna, at approximately 300 MHz, down-converted it to near base-band, creating both in-phase and quadrature (I/Q) components. Because the Galileo signal is modulated on a square-wave subcarrier, there are actually nine

[8] In addition to the arraying, the Parkes radio-telescope was upgraded to be frequency agile, thus easily shared between Galileo support and the specific radio-astronomy assignments it must carry.

I/Q components created: one for the carrier, and two each for the 1st, 3rd, 5th and 7th harmonics. Each of these signals is sampled, time-stamped, and forwarded to a Full-Spectrum Combiner (FSC). At the FSC the delay and phase differences between the signals received by the different antennas are measured and compensated, continuously, because the delay and phase differences vary (primarily with the geometry but also with the weather and other factors). Note that the measurement and compensation need be accurate to within a small fraction of a S-band wavelength - the design is based on measuring and correcting differences to 0.3 mm in total path length! The output of the FSC is effectively the sampled baseband signal at the combined antenna which is then demodulated and decoded in a more straightforward way.

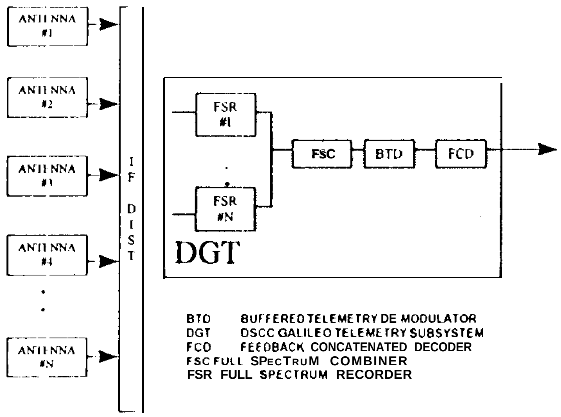

Figure 3- Typical Array Timeline

The array timeline is shown in Figure 3 illustrates the typical evolving of such an inter-continental, inter-agency array (times are only approximations). As earth rotates, different antennas “see” Galileo at different times and the array composition changes. First the GDSCC **70-meter antenna tracks Galileo by itself.** Then the CDSCC 70-meter antenna and 34-meter antennas join in, then the Parkes antenna joins in, then the GDSCC antenna drops out, then Parkes drops out, then finally the array is terminated. Let us highlight **a few issues that** contribute to this sequence (physical as well as operational):

Different antennas have different minimal elevation angles. In particular the Parkes antenna has a minimal elevation angle of 30 degrees, thus it joins the array late and drops out early. (DSN antennas operate at elevation angles below 10 degrees).

Even when antennas are at the same complex, and have same minimal elevation angles, they may not join the array (or drop out of the array) at different times due to either individual elevation masking, or due to the requirements of preceding or succeeding antenna commitments to missions.

When an antenna joins the array, there is a process of acquisition that, for Galileo’s weak signal, may take several minutes. ‘The spacecraft cannot take full advantage of the added SNR[9] (e.g. to raise the data rate) until this acquisition is complete otherwise there is potential for loss of data.

This is some of the complexity that Galileo and the DSN faced (and overcame!) in planning for the arraying operations. A largely-automated system was developed to schedule

---

[9] Signal to **Noise Ratio**

the **array join/drop-out structure** and the corresponding data rate changes. It was driven by a set of simple rules, and resulted in a crisp definition of the array and efficient generation of plans, sequences-of-events, and the other products required for successful routine operations.

3. INTERCOMPLEX AND INTERAGENCY COOPERATION - LESSONS LEARNED

Though the Galileo array support was exceptionally successful, this section will linger on some of the problems encountered, and solved, with the hopes that these learned lessons will help in making future arrays be even more successful.

Early in the implementation, it was decided that all array operations would be managed from a single site - CDSCC, being the site of the largest number of arrayed antennas. Thus, CDSCC was designated as the center of operations where the FSC resided and where the demodulated and decoded data were generated. The staff of CDSCC was made part of the development effort, including the development of a detailed operational concept. As a result, the staff at CDSCC had full visibility and control over the equipment in their complex. The challenge became establishing the equipment, procedures and contracts to assure that the interfaces from CDSCC to GDSCC and Parkes *were* seamlessly incorporated.

In addition to its role supporting the array, GDSCC also served as an independent center of operations, supporting Galileo in a single-antenna mode for hours prior to joining the array. Thus GDSCC was equipped and fully staffed to run and monitor the local equipment that was part of the array - at GDSCC the same equipment supported single-antenna and array operations. Only two operational concerns emerged (and were addressed):

> During the 4-6 hours of single antenna operations, operators routinely relied on indications from the demodulator and decoder status to know that antenna was on-point, and operating properly. Unfortunately, shortly after the array commenced, the data rate was increased enough to make it impossible for GDSCC to demodulate or decode the signal. **The GDSCC operators had to rely on spectrum-analyzer-like signals to assure that the signal was received, e.g. that** the antenna remained on point.
>
> One resource that was shared with other missions was the NASA-leased lines between GDSCC and CDSCC. Though the data transfers (mostly from GDSCC to CDSCC) employed a TCP/I P protocol, at times the lines were quite busy resulting in increasing (and unacceptable to the project) backlogs. The solution was to add at the application layer (in the DGT) a traffic-reducer, allowed for the dynamic reduction in data volume via a corresponding reduction in the fidelity of the transmitted data as the backlog increased. The full-fidelity data at GDSCC was recorded and preserved as backup.

With these concerns addressed, GDSCC's inter-continental arraying with CDSCC proceeded smoothly.

The Parkes operational interface was quite different. Unlike the DSN sites, the Parkes facility usually provided only “antenna drivers” who oversaw pointing the antenna and related safety issues. Operations of the other equipment was the responsibility of the investigators. (Under this interface, JPL/CDSCC provided a resident staff at Parkes for the previous Voyager support). Given the expected length of the Galileo supped, the operations at Parkes were fully remoted, that is - all the DGT equipment installed at Parkes was operated from CDSCC via the communications link. When the remote operations concept was initially established, there were concerns about the potential loss of Parkes - several hours away. In practice, very little data loss occurred due to hardware failures attesting to the quality of the DGT equipment and to the strong cooperation (and phone consultations) between the CDSCC staff and the Parkes staff. Few concerns worth mentioning are:

The leased direct line between Parkes and CDSCC was supplied by a commercial vendor and was routed in ways that were not always visible. As it turned out, the dedicated line between Parkes and CDSCC required even more application-layer traffic-reducing capability of the DGT. Overall, it did not result in any appreciable loss of data.

The Parkes radio-telescope was more susceptible to wind, compared to the DSN antennas. Combined with an unusually-windy season, this caused a significant loss of data during array final testing and initial operations.

Though the DGT was designed for largely remote operations, it still contained tape **drives, requiring insertion and removal of tapes between passes. This limited operation was conducted** by the CSIRO-supplied "antenna drivers". Due to DGT limitations, the CSIRO personnel had to be present at the antenna several hours before Parkes joined the array because tape insertion/removal had to occur before the array checkout at CDSCC.

With dedicated staffs at CDSCC and Parkes, with backing from JPL engineering, these minor problems were controlled to have only minor effect on overall data return

4. RESULTS

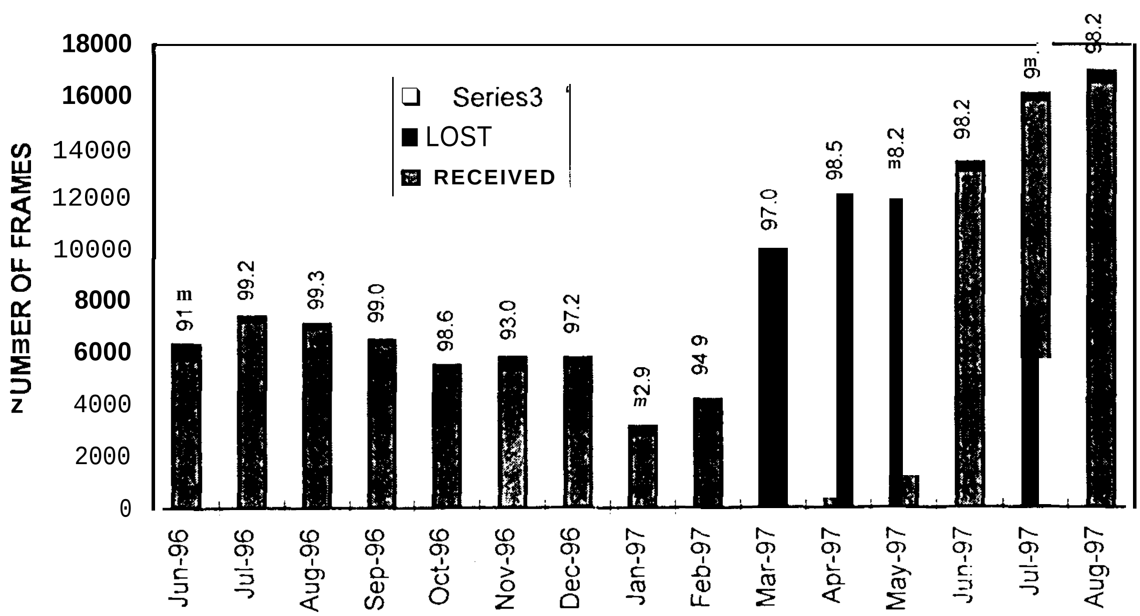

Figure 4- Galileo Data return in Frames and percentage

Elsewhere [5], the science results from Galileo are presented. Let us focus on the array performance metrics. The standard JPL metric for telemetry return is the percentage of returned telemetry (Viterbi-decoded) compared to total committed telemetry. Typically, this percentage hovers around 98°/0. When arraying was first planned, the simplistic model (assuming that all antennas are independent) indicated that data return may drop to 90.4% (0.985), while more statistical models, accounting for the specific antennas and the link margin predicted data returns of 94 %-96%. The measurements at present, Figure 4, show that the telemetry return since April 97 has been consistently over 98%. Very few of these outages are due to equipment failures - they are largely due to wind and procedural error. Given the complexity of the operation, these results are exceptional and indicate that arraying may be a viable method for future spacecraft support.

5. CONCLUSIONS

We are very pleased with the success if the inter-continental, inter-agency array support for Galileo. JPL is implementing a local array at each of the DSCCs. These arrays will provide a flexible capability to support spacecraft with between one and eight antennas at a complex, allocating resources as needed to support the upcoming surge in concurrently flying missions.

REFERENCES

[1] **Feria, Y.,** "A Closed-Loop Time-Alignment System for Baseband Combining," Jet Propulsion Laboratory TDA Progress Report 42-117, pp. 92-109, May 15, 1994. **Pasadena, California.**

[2] **Hurd,** W. J. et al, "Antenna Arraying of Voyager Telemetry Signals by Symbol Stream Combining," Jet Propulsion Laboratory TDA Progress Report 42-86, pp. 131-142, August 15,1986, Pasadena, California.

[3] Million, S., B. Shah, and S. Hinedi, "A Comparison of Full-Spectrum and Complex-Symbol Combining Tecniques for the Galileo S-Band Mission," Jet Propulsion Laboratory TDA Progress Report 42-116, pp. 128-162, February 15, 1994, Pasadena California.

[4] **Statman, J. et al, "Galileo Telecom Link and Its Application to Future Missions,"** 47th IAF Congress, IAF-96-Q.5.02, October 7-11, 1996, Beijing, China.

[5] O'Neill, W.J. et al, "Project Galileo: Completing its Primary Mission," 48th IAF Congress, IAF-97-Q-2.02