

Optimizing the Galileo Space Communication Link

J. I. Statman

Communications Systems Research Section

The Galileo mission was originally designed to investigate Jupiter and its moons utilizing a high-rate, X-band (8415 MHz) communication downlink with a maximum rate of 134.4 kb/sec. However, following the failure of the high-gain antenna (HGA) to fully deploy, a completely new communication link design was established that is based on Galileo's S-band (2295 MHz), low-gain antenna (LGA). The new link relies on data compression, local and intercontinental arraying of antennas, a (14,1/4) convolutional code, a (255,M) variable-redundancy Reed-Solomon code, decoding feedback, and techniques to reprocess recorded data to greatly reduce data losses during signal acquisition. The combination of these techniques will enable return of significant science data from the mission.

I. Introduction

The Galileo spacecraft was launched in October 1989 for a 6-year cruise toward Jupiter [1]. Its Venus-Earth-Earth Gravity Assist (VEEGA) trajectory, shown in Fig. 1, includes encounters with Earth and two key asteroids, leading to its prime objective—long-term investigation of the Jovian system. During the investigation, Galileo will release a probe into the Jovian atmosphere, encounter Jupiter and its moon Io at close range, and conduct an 18-month, 10-encounter orbital tour of Europa, Ganymede, and Calisto. Throughout its travel, a variety of sensors will collect scientific data such as images, magnetic fields, and chemical composition for transmission to NASA's Deep Space Network (DSN) tracking stations.

The Galileo downlink was originally designed to utilize a 15-ft-diam (4.572 m) parabola-shaped HGA on the spacecraft. This antenna was folded during the launch and early flight awaiting an unfurling sequence that was scheduled for April 1991. However, the HGA did not open properly, resulting in a nonsymmetrical antenna pattern

with wide gain fluctuations, rendering it ineffective for reliable communications. After repeated attempts to solve this anomaly, the mission was reoriented in March 1993 to use the S-band LGA.

Because of the great reduction of the power received at the ground stations, the Galileo project has teamed with TDA and the appropriate technical organizations to develop a communications plan that maximizes the data return for the LGA-based S-band link.¹ The remainder of this article describes in some detail the techniques utilized in this design and their applications to future space missions.

II. Link Design

In redesigning the link, the team searched for methods that maximize the "bang for the buck," i.e., those that

¹ L. Deutsch and J. Marr, *Low Gain Antenna S-Band Contingency Mission*, 1625-501 (internal document), Jet Propulsion Laboratory, Pasadena, California, April 10, 1992.

provide the most cost-effective increases in science return. This proved to be a delicate task—unlike measures like transmitter power or data rate that are objective and lend themselves to easy quantifying and comparison, “science return” is a subjective measure and depends on the end-user’s preferences. The resulting design relies heavily on data compression, augmented by channel coding, arraying, and antenna improvement, to both increase the rate of the downlink and the “value” of each downlinked bit.

As shown in Fig. 2, when implementing this new design, JPL will be loading new software on the Galileo spacecraft, enhancing the Deep Space Communications Complexes (DSCCs) at Goldstone, California; Canberra, Australia; and Madrid, Spain, and upgrading other processing facilities. The DSCC improvements consist of a new subsystem, denoted DSCC Galileo Telemetry (DGT), that will be installed at the DSCCs in late 1995 and improvements to the Canberra antennas.

A. Data Compression

Galileo generates three types of data: images, low-rate science, and engineering. With a large number of algorithms available in the published literature, the overriding issue was to identify those algorithms that meet the spacecraft constraints and can be implemented in software in the spacecraft computers. Galileo, of a late 1970’s design, uses what, at the time, was modern technology: 8-bit and 16-bit microprocessors with total memory of less than 1 MByte, well below what would be considered acceptable for a modern desktop workstation.

The design team has elected to compress the image data primarily with an integer cosine transform (ICT) [2,3], a derivative of the conventional discrete cosine transform (DCT) method. The ICT is an especially economical implementation for fixed point processors. In the past, lossy algorithms such as the DCT or ICT have been rejected from use in deep space probes due to the uniqueness of the data. With the Galileo predicament, a team of developers and scientists determined that with compression ratios as high as 10:1, the resulting images, though not ideal, are of acceptable quality.

The ICT implementation for Galileo is augmented with an error-containment capability. This is important because the deep space link often operates with reduced margins and is sensitive to data gaps. The ICT error containment is applied to minimize the impact of the gaps that could not be avoided.

For the low-rate science and engineering data, the design team considered lossless algorithms focusing on the

Rice [4], Lempel–Ziv–Welsh (LZW) [5], and Huffman code [6] approaches. These approaches are still being evaluated, with emphasis on minimizing the additional loading on the restricted spacecraft computer resources.

B. Data Rate Averaging

Figure 3 shows qualitatively how the “science capture” and “downlink capacity” vary for a typical deep space mission. The downlink capacity varies primarily with the distance of the spacecraft from Earth. In contrast, science capture is often massive during short events (e.g., planetary encounters) with long “cruise” periods in between, when a much lower volume of science data is captured. Missions communications systems are designed to handle the peak science capture, resulting in excess link capacity during the “cruise” phases. Prior to the Galileo HGA anomaly, this was the planned Galileo strategy. However, with the anomaly, it became desirable to buffer data during peak science capture periods to reduce the variation in downlink rate.

Galileo has two such buffering areas: an onboard tape recorder and the resident memory. The tape recorder, with a total capacity of approximately 100 MBytes, is used to record images and other data at encounter periods and then replay the data at a much slower rate during cruise periods. The resident memory is used to store and replay the probe data and to add a further buffer between the tape recorder replay and the downlink transmitter.

This buffering allows for spreading of the data return to optimize the link utilization and minimize unused link capacity, in line with the low achievable data rates and the high goals of the Galileo mission. However, it also imposes a heavy burden on the ground receiving stations. As currently stated, Galileo requires continuous support (24 hours per day for almost 2 years) from the DSN 70-m network, plus augmentation from some 34-m antennas.

C. Improved Channel Coding

Galileo planned on utilizing a channel coding scheme similar to the standard Consultative Committee for Space Data Standards (CCSDS) channel coding: concatenated (7,1/2) convolutional code and (255,223) Reed–Solomon (R/S) code. To improve performance, a modified coding scheme [7], shown in Fig. 4, is implemented. Its key features are listed below:

- (1) A (14,1/4) convolutional code that provides an approximate 1.2-dB coding gain over the (7,1/2) code. The selection of the (14,1/4) code is forced by the hardware configuration of Galileo—it is impossible

to bypass the hardware (7,1/2) encoder, hence the higher-constraint code is constructed by cascading an (11,1/2) software encoder to the (7,1/2) hardware encoder. Though not optimal among (14,1/4) convolutional codes, it provides remarkable coding gain.

- (2) A variable redundancy R/S code. The particular implementation utilizes a four-redundancy code.
- (3) A redecoding path, where data that have been decoded by the Viterbi decoder and R/S decoder are then passed a second time (and, if needed, additional times) through the Viterbi and R/S decoders. During each pass, the Viterbi decoder operation is "aided" by the knowledge that some bits were determined "true" in previous pass(es).
- (4) An improved synchronization scheme [8] that accomplishes frame synchronization and Viterbi decoder node synchronization jointly.

Overall, the decoder provides a coding gain of approximately 1.8 dB as compared with the standard published by the CCSDS. Note that the decoder performance is measured at a bit error rate of 5×10^{-3} .

D. Minimization of Gaps

As described earlier, the downlink will operate continuously and transmit compressed data. Because of the compression and coding, even minute interruptions pose the risk of data being undecodable, with resulting severe damage to the decompression process. Such gaps occur in the deep space communications link due to receiver and decoder acquisition periods, pointing errors, and momentary equipment failures. Though it is impossible to fully prevent these gaps, the DGT incorporates two capabilities that greatly reduce their impact:

- (1) The DGT's recording and buffering, as shown in Fig. 5, provides extensive recording of the signals, including those prior to any synchronization. This protects against data losses during acquisition.
- (2) The DGT uses adaptive gap-closure algorithms consisting of software that attempts to recover data by reprocessing recorded data while adjusting the process parameters (e.g., tracking loop bandwidth) to recover data that were lost due to mismatches between the actual signal and the processing parameters.

Clearly, gaps caused by complete signal loss (e.g., large antenna pointing errors) are likely to be not recoverable. But, by and large, these techniques are expected to provide the decompressor with a minimal-gap bit stream.

E. Arraying

A popular technique for increasing the data rate is to array the signals from multiple antennas. For the weak Galileo signals, only large DSN antennas with diameters of 34 m and 70 m are used. Two arraying techniques are applied: full-spectrum combining [9,10] and complex-symbol combining [11].

Unfortunately, while arraying increases the overall ratio of antenna gain to system noise temperature (G/T), it also tends to reduce the overall reliability: the link, marginal as it is, becomes dependent on the correct operation of a number of antennas. In addition, the operational complexity of such a configuration, and the associated probability of human error, must be considered. Nevertheless, judicious application of arraying is expected to improve the overall science return.

F. Improved Antennas

Finally, the G/T of the individual antennas involved in the Galileo support was examined. It was observed that the DSN antennas were designed for multifrequency support, primarily at the S- and X-bands. The multifrequency support, as well as the extensive test capability, resulted in receiving systems with less-than-optimal S-band G/T. Since Galileo is visible primarily from the southern hemisphere, the DSN embarked on modifying the S-band receiving system in the Canberra 70-m antenna to improve its G/T by 0.97 dB. This is achieved, primarily, by reducing the system noise temperature from 15.6 to 12.5 K.

III. Future Uses

Is the approach taken in the improvement of the downlink suitable for Galileo only, or does it have a long-term payoff? The answer depends on the direction that the space program takes.

The DGT design is especially appropriate for the space program that NASA envisions, focusing on a large number of low-cost missions. For such missions, highly-directional antennas (mechanical or steered-beam) are costly; broad-beam antennas may be the norm. With these antennas, and the limited power offered by nonnuclear-based power supplies, the communications engineer must contend with lower data rates and tighter utilization of any communication link excess. The DGT approach provides an avenue to optimize the science return for a relatively low data rate.

Three classes of missions are of special interest:

- (1) Multiple objects-in-a-beam missions. For missions that use several vehicles to land and/or orbit a

planet, a single antenna can be used for tracking. With the DGT approach, a single recorded stream can be processed sequentially to extract the data for the individual vehicles in near-real time. Transmissions for individual vehicles can be separated using any of the multiple-access techniques currently in use.

- (2) Large uncertainty-in-predict missions. At times, spacecraft experience events where the characteristics of the downlink signal pose large uncertainties. Often these are associated with high dynamic events—change of trajectory, release of a probe, etc. The DGT, not requiring synchronization prior to the first recorder, allows capturing of the signal and postevent recovery.
- (3) Short, intense, science-capture missions. For some missions, all the science data are captured during a short encounter period. The DGT enables the space-

craft to buffer the data on board and slowly downlink it, assuring the ability to close gaps and recover an uninterrupted science stream.

Overall, the DGT approach seems highly applicable to future missions. In fact, the only part of the DSCC augmentation that will find minor usage after this mission is the enhancement for the 70-m antenna. It will likely be dismantled after the end of Galileo support.

IV. Conclusions

A science-rich Galileo mission is being enabled through a concentrated effort to optimize the communications downlink with modifications both on Galileo and in NASA's ground tracking system. Much of the techniques, approach, and equipment can be applied to support other deep space missions.

Acknowledgments

The author is indebted to Dr. Sami Hinedi and Mr. Pat Beyer for reviewing this article and providing insightful comments. The author also thanks the many people on the design and implementation team whose hard work is reflected here.

References

- [1] C. T. Russell, ed., *The Galileo Mission*, Boston: Kluwer Academic Press, 1992 (reprinted from *Space Science Review*, vol. 60, nos. 1–4, pp. 1–616, 1992).
- [2] K. M. Cheung and K. Tong, "Proposed Data Compression Schemes for the Galileo S-Band Contingency Mission," in *Proceedings of the 1993 Space and Earth Science Data Compression Workshop*, Snowbird, Utah, April 2, 1993.
- [3] W. Cham, "Development of Integer Cosine Transform by the Principles of Dyadic Symmetry," in *IEE Proceedings*, part 1, vol. 136, no. 4, pp. 276–282, August 1989.
- [4] R. Rice, *Some Practical Universal Noiseless Coding Techniques*, JPL Publication 79-22, Jet Propulsion Laboratory, Pasadena, California, March 1979, and JPL Publication 83-17, Jet Propulsion Laboratory, Pasadena, California, March 1983.
- [5] T. A. Welsh, "A Technique for High Performance Data Compression," *Computer*, vol. 17, no. 6, pp. 18–19, June 1984.
- [6] D. A. Huffman, "A Method for the Construction of Minimum Redundancy Codes," in *Proceedings of the IRE*, vol. 40, pp. 1098–1101, 1952.

- [7] T. Chauvin and K. M. Cheung, "A Parallel Viterbi Decoder for Shared Memory Multiprocessor Architecture," presented at the 3rd SIAM Conference on Linear Algebra in Signals, Systems, and Control, Seattle, Washington, August 1993.
- [8] J. Statman, K. M. Cheung, T. Chauvin, J. Rabkin, and M. Belongie, "Decoder Synchronization for Deep Space Missions," *The Telecommunications and Data Acquisition Progress Report 42-116*, vol. October-December 1993, Jet Propulsion Laboratory, Pasadena, California, pp. 121-127, February 15, 1994.
- [9] A. Mileant and S. Hinedi, "Overview of Arraying Techniques in the Deep Space Network," *The Telecommunications and Data Acquisition Progress Report 42-74*, vol. April-June 1983, Jet Propulsion Laboratory, Pasadena, California, pp. 13-28, August 15, 1983.
- [10] D. H. Rogstad, "Suppressed Carrier Full-Spectrum Combining," *The Telecommunications and Data Acquisition Progress Report 42-107*, vol. July-September 1991, Jet Propulsion Laboratory, Pasadena, California, pp. 12-20, November 15, 1991.
- [11] D. Divsalar, "Symbol Stream Combining Versus Baseband Combining for Telemetry Arraying," *The Telecommunications and Data Acquisition Progress Report 42-104*, vol. October-December 1990, Jet Propulsion Laboratory, Pasadena, California, pp. 109-115, February 15, 1991.

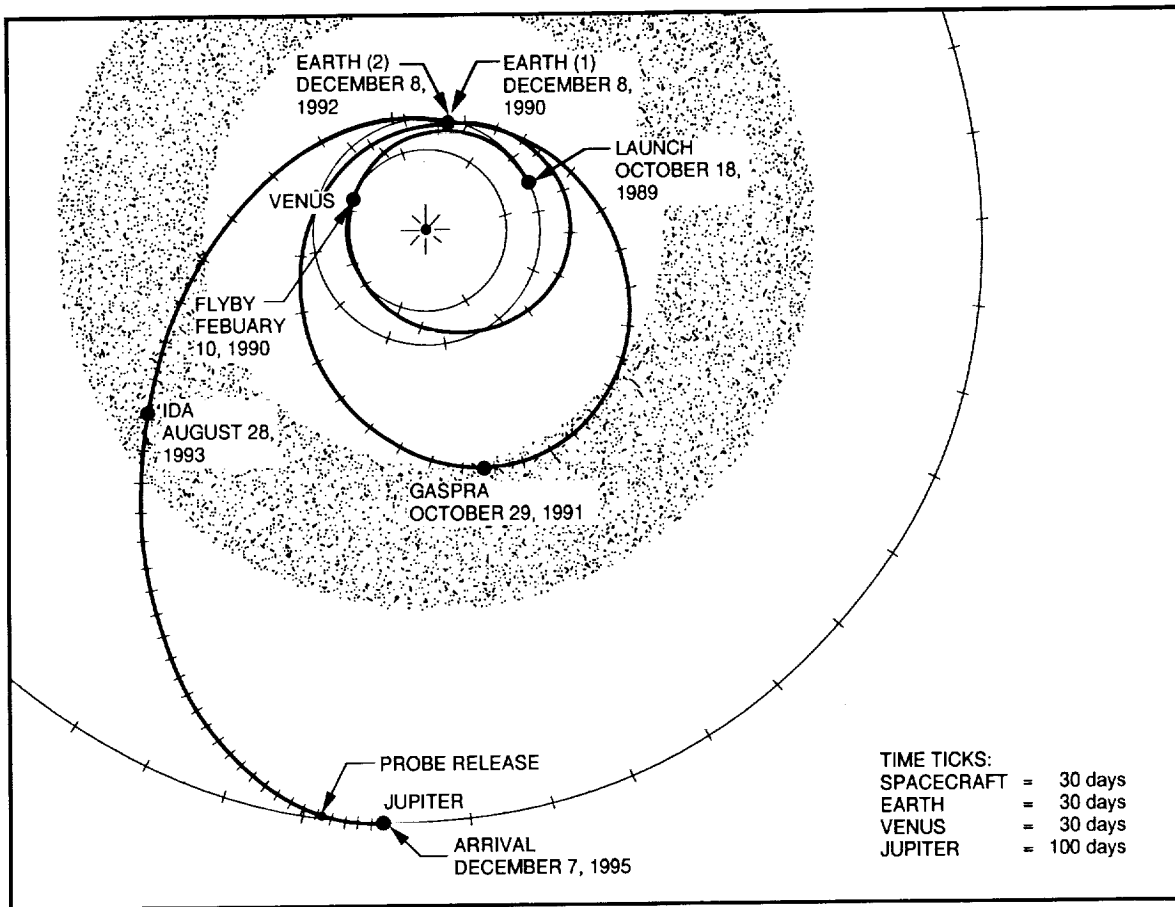


Fig. 1. The Galileo VEEGA trajectory.

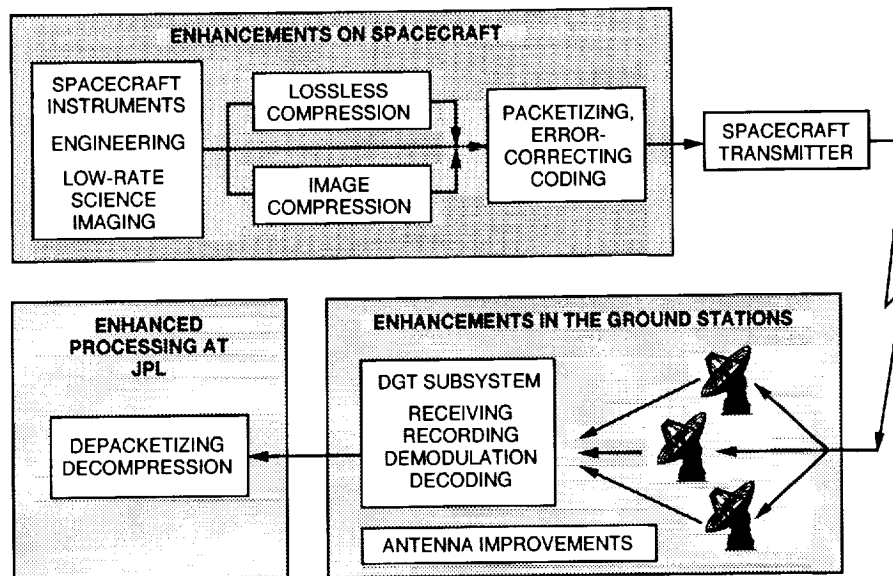


Fig. 2. End-to-end downlink flow.

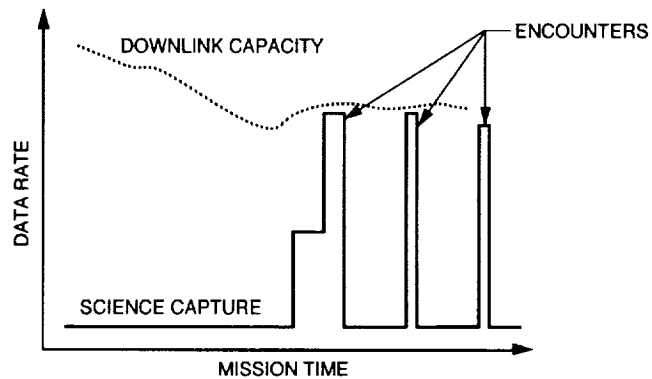


Fig. 3. "Science capture" versus "downlink capacity."

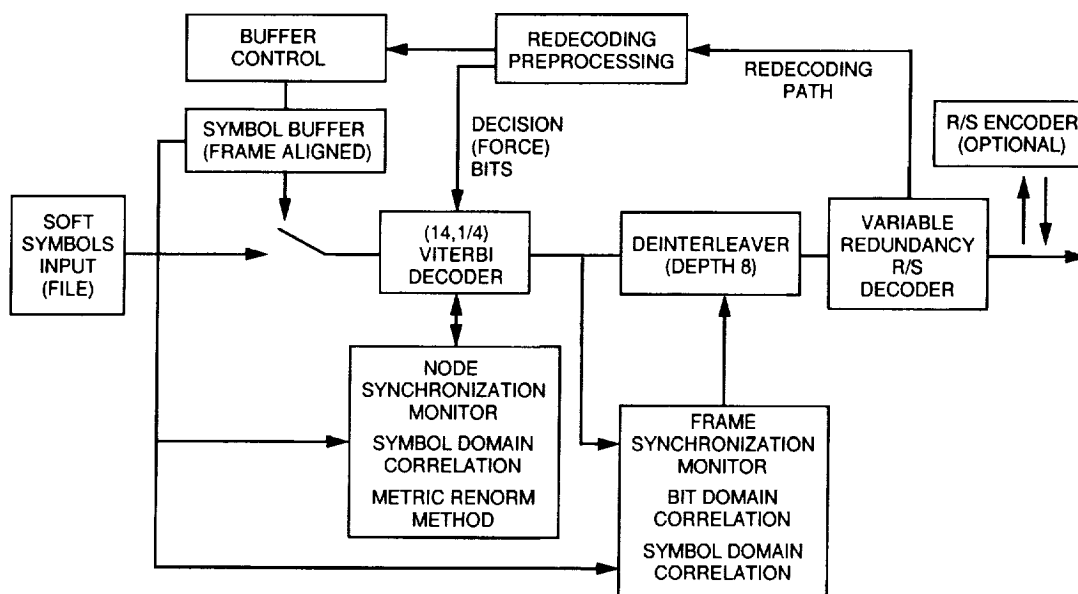


Fig. 4. The Galileo decoder.

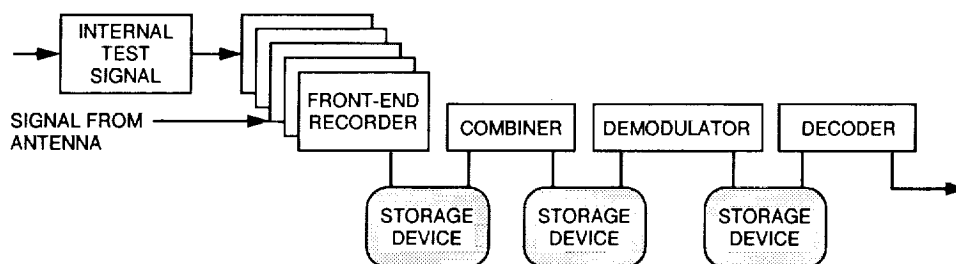


Fig. 5. DGT architecture.