AUTOMATED OPERATIONS FOR GALILEO COMMUNICATIONS

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Abstract

After the Galileo High *Gain Antenna (HGA) failed to deploy in 1991, the Jet Propulsion Laboratory (JPL) faced the challenge of implementing a science-rich mission with* a *Low-Gain Antenna (LGA), at data rates that were almost four orders of magnitude less than origins//y p/anneal. To accomplish this, JPL completely redesigned the downlink to* maximize *the* dafa *return and increase its reliability, requiring the implementation of dramatic* changes both *in the Galileo on-board software and in the Deep Space Network (DSN). Key features* of *the new link include data compression, antenna arraying, recording and reprocessing* of *telemetry, suppressed carrier tracking, and highly efficient error-correcting* coding, resulting in an *effective* data *return that is approximately two orders of magnitude* above *that that* would have *been feasible with the LGA had the changes not been implemented (see Figure 1 below). In particular, JPL* has *developed and deployed* a new *DSN* Galileo *Telemetry (DGT) subsystem at the three DSN sites: Goldstone, USA, Tidbinbilla, Australia,* and *Madrid, Spain. To maximize the data return, the DGT parameters (data rate, tracking loop bandwidths, array configuration) are continuously adjusted and the link operates on* a *very-narrow margin. Because the operation will continue for almost two years, 24-hours-per-day, the DGT is designed as an automated system that continuously monitors and adjusts its operational parameters and environment in response to either pre-loaded sequences or* changes *in internal state, with minimal operator intervention. The single-an tenna DGTs* have *been deployed at the DSN sites and the follow-on* array *DGTs will be deployed shortly. /*n addition *to the Galileo support, these automated DG Ts are suitable to provide ground support for ofher low rafe missions.*

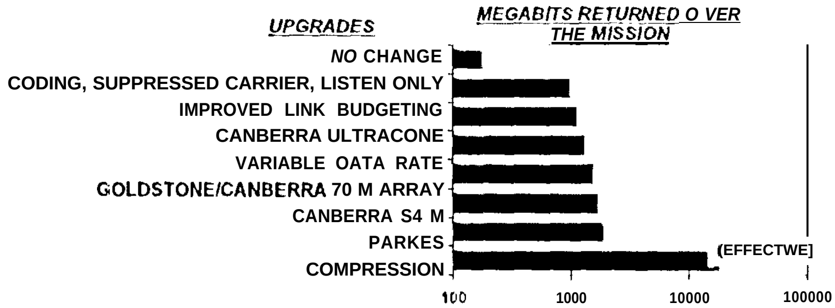

Figure 1- Galileo *Data Volume - With and Without the Changes in the Link*

[1] The work reported in this article was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration,

1. INTRODUCTION

The Galileo Spacecraft was launched in October 1989 on a difficult VEEGA (Venus- Earth-Earth-Gravity-Assist) trajectory shown in Figure 2. The mission's communications were based on the use of an X-band, 4.8-m high-gain antenna (HGA), with backup from two S-band, low-gain antennas (LGA). In April 1991 Galileo was commanded to deploy the HGA but the deployment failed due to mechanical problems. The Jet Propulsion Laboratory (JPL) faced then the challenge of implementing a science-rich mission with a LGA at data rates that were almost four orders of magnitude (!) less than originally planned for the HGA-supported mission. To accomplish this, JPL completely redesigned the downlink to maximize the data return and increase its reliability, requiring the implementation of dramatic changes both in the Galileo on-board software and in the Deep Space Network (DSN). Key features of the new link include data compression, antenna arraying, recording and reprocessing of telemetry, suppressed carrier tracking, and highly efficient error-correcting coding, resulting in an effective data return that is approximately two orders of magnitude above that that would have been feasible with the LGA had the changes not been implemented. In Section 2, we present the new DSN Galileo Telemetry (DGT) subsystem that JPL has developed and deployed to address this challenge. In Section 3 we discuss the operational challenges and how automation was introduced to overcome them. in Section 4, we highlight a key lesson learned from the DGT development. T-he DGT has been routinely supporting Galileo since May 23, 1996, with extremely high reliability and minimal operator intervention.

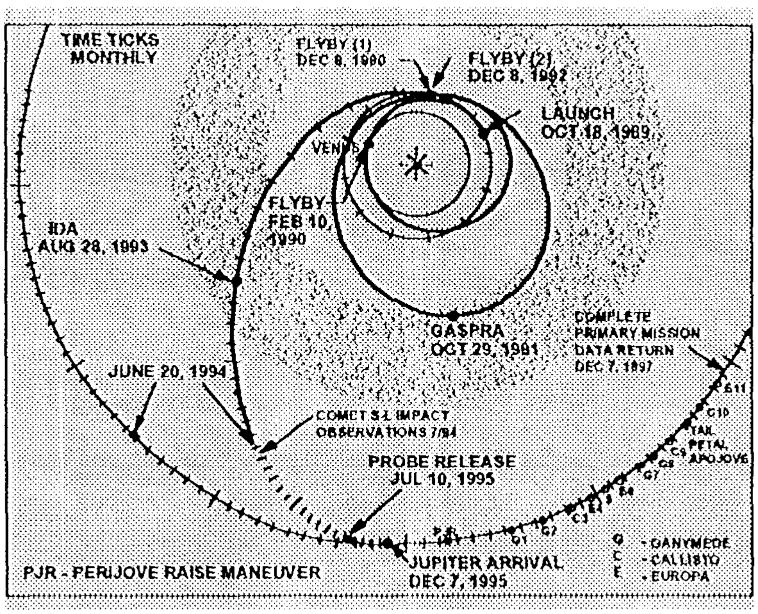

Figure 2- The Galileo VEEGA Trajectory

2. THE DSCC GALILEO TELEMETRY (DGT) SUBSYSTEM

To address the Galileo challenge, JPL developed and installed DGT equipment [1] at the three DSN sites: Goldstone, USA, 1 idbinbilla, Australia, and Madrid, Spain. The DSN configuration with the DGT is shown in Figure 3. Key features of the DGT are:

1. The DGT is a self-contained telemetry recovery unit. It receives an IF signal and produces decoded data frames - all signal processing is internal to the DGT

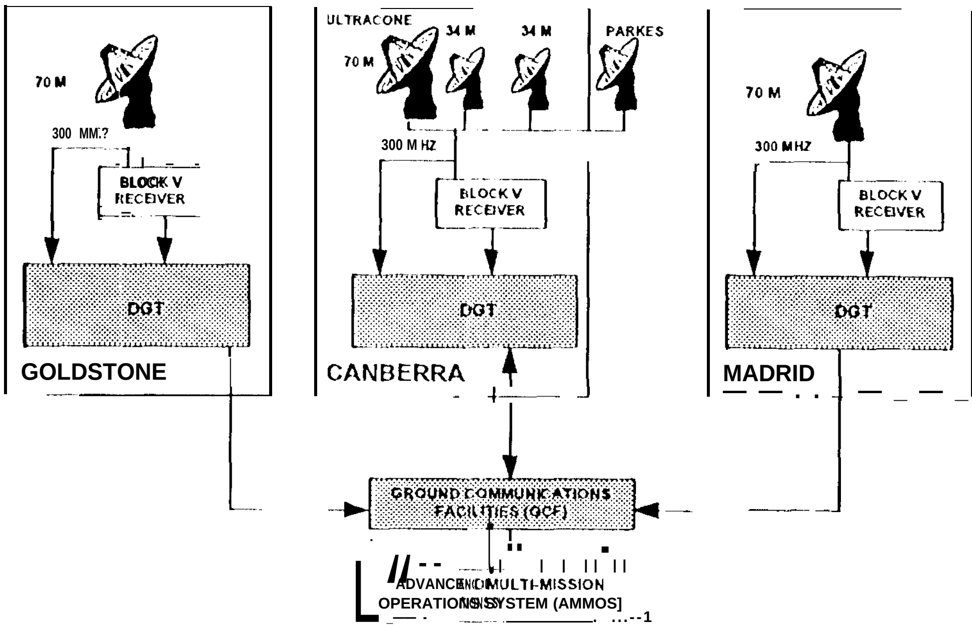

Figure 3- DSN Configuration with DGT

2. An IF arraying capability is provided, This allows the DGT to combine the IF signal from multiple antennas, effectively adding the G/T (the ratio of antenna gain to system noise temperature) of the individual antennas with minimal loss in the combining process. For Galileo, the DGT combines the signal from two 70-m antenna at Goldstone and Canberra, two 34-m antennas at Canberra, and a 64-m radio-telescope at Parkes Australia.

3. An IF recording capability is incorporated, enabling recovery of telemetry at a later time, if the initial recovery is unsuccessful due to equipment failures or sub-optimal setup. Note that IF recording requires no "locking" thus it provides a full record of the received signals for the full duration that the antenna points to the spacecraft.

4. Superior error-correcting coding is included. The decoding uses frame detection in the symbol domain, a (14,1/4) convolutional decoder, and a 4-redundancy Reed Solomon decoder, all implemented in software. The decoder is fully programmable and can be easily adopted to other missions.

5. Data delivery from the DGT to the project is provided using commercial "guaranteed delivery" protocol, including TCP/IP for block transfers and FTP for file transfer.

The DGT implementation relies heavily on the use of high-speed SUN workstations, performing the function of demodulation, decoding, and arraying. Only the front-end portions of the DGT, and its test signal generator, use custom hardware.

3. OPERATIONS CHALLENGES - HOW THEY WERE ADDRESSED

Even with the link improvements described above, the maximum data rate from Galileo is no more than 160 BPS. To maximize the data return, the Galileo telecommunications link was set to operate on a very-narrow margin and the DGT parameters (data rate, tracking loop bandwidths, array configuration) need to be continuously adjusted. Because the mission operations will continue for almost two years, 24-hours-per-day, the DGT had to be designed as an automated system that continuously monitors and adjusts its operational parameters and environment in response to either pre-loaded sequences or changes in internal state, with minimal operator intervention. This resulted in radical departures from routine mission operations.

Let us highlight a specific example of the difference between Galileo operations and routine spacecraft operations. During a tracking pass, as a spacecraft ascends from the horizon to maximum elevation and then descends back to the horizon, the received Signal-to-Noise-Ratio (SNR) varies as shown in Figure 4 (squares and triangle symbols), primarily due to changes in the System Noise Temperature (SNT). The variation can be as much as 2 dB, a significant G/T gain for deep space missions, and a mission could vary the data rate during the pass to take advantage of the higher mid-pass SNR. In practice, most missions forego this potential benefit either to avoid the loss-of-lock associated with a data rate change or to maintain simple planning and operations. For the Galileo mission we have selected to adjust the downlink data rate to maximize the data return, as shown in Figure 4, resulting in an increase of approximately 1.0 dB (26%) in the data return for the mission.

And the data rate adjustment is accomplished without any operator intervention! - the process is fully automated. At the planning stage, the data rate is increased almost as soon as the link margin permits it, and decreased as soon as required. The DGT then automatically adjusts its tracking parameters to “cruise” through the data rate change without any loss of telemetry. The data rate transitions and their timing were selected so that the whole process is automated.

Another example for the innovative operations approach employed in the DGT implementation is the concept of “post-pass processing”. Telemetry equipment is designed to process data in real-time, with minimal or no buffering. How does such equipment respond to unforeseen changes in the signal level, stability, or timing? The designers of the telecommunications link usually provide a “statistically-acceptable” solution. At JPL, the practice is to compute or derive the standard deviations of the “losses” in the link, convert them to dB loss, sum them and define the result as the standard deviation of the link, σ_L, expressed in dB. I-hen a link margin, typically $2\sigma_L$, is added to the link, reducing the downlink data rate. Factors such as limited signal stability are accommodated through wider tracking loops, further reducing the achievable data rate. The only practical way to pare down some of these data losses is to continuously adjust the downlink data rate based on residuals from real-time tracking, a process that is operationally cumbersome. The result is a link design that is very robust and very conservative - its driving philosophy is "there is no second-chance to recover the telemetry".

In contrast, the DGT allows a second -chance (and a third, and a fourth...) to recover the telemetry. The DGT operates in two stages: "real-time processing (RTP)" and "post-pass processing (PPP)", as shown in Figure 5. During the pass, the DGT operates in the RTP mode: the tracking parameters are set at moderately-conservative values with a goal of recovering at least 90% of the telemetry. This "real-time" data is useful in determining the latest state of the spacecraft but is not comprehensive enough to recover science data. After the pass is complete, the DGT switches to the PPP mode and attempts to recover the remaining 10% of telemetry. During this fully-automatic stage, the DGT zeroes in on the missing data and adjust the processing parameters (e.g. loop bandwidths) repeatedly to recover the missing data. The algorithms are quite sophisticated, including processing forward and backward in time, and are selected automatically from a tool-box, according to their probability of success. PPP ends when the pre-determined time-limit has arrived, with a default of 4 hours.

Actual Data Rate With and Without Parkes

Achievable And Actual Telecom Performance -- C1O Orbit

Date	Diplexer	Ranging	Range (AU)	JEP (degrees)	Jupiter Temp (K)	SEP (degrees)	Scin Degradation (dB)	Achiev Data Return in 24 Hours (Mbits)	Step Data Return in 24 Hours (Mbits)	% of Achieve	Data Return with 15 Minute Minimum Restrict	% Loss due to 15 Minute Minimum	Cone Angle
0/7/97	Off	Off	4.56	0.11	2.68	118.43	0.00	6.66	5.68	85.4%	5.68	0.0%	4.0°

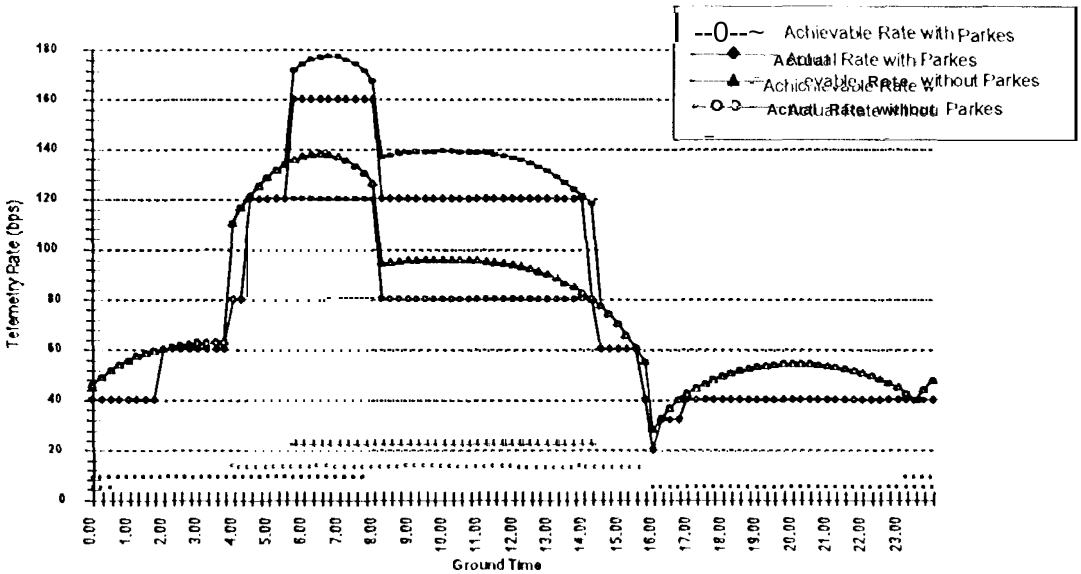

Figure 4- Effect of Changing the Data Rate During a Pass

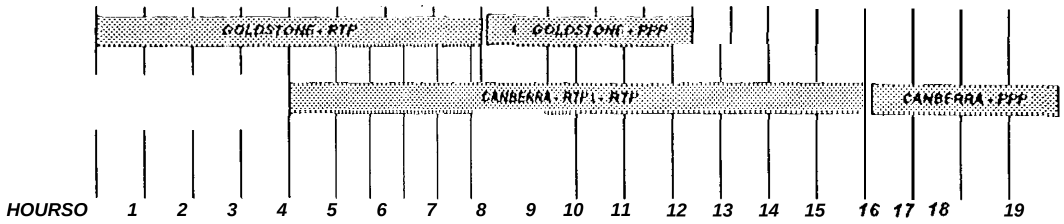

Figure 5-1 imeline of a Typical DGT Pass

These two examples highlight the fact that the DGT establishes a new balance between the sophistication of processing and automation. In a typical pass, the operators are required to conduct a minimal number of steps prior to the pass and perform no steps during the pass. Nevertheless, through automation the DGT is able to "tweak" its operations to maximize the data return for the mission.

4. LESSONS-LEARNED

The single largest factor in the successful emergence of the DGT as an operational system is the involvement of the Operations Organization and staff from the early stages of the development, Even though the DGT emerged from the confluence of the Galileo antenna anomaly and the maturation of a significant R&D program, it could not have turned into a successful operational system without the involvement of the operations teams at the three DSN sites as well as at JPL and Pasadena. To accomplish this, at the outset of the project, both an operational concept and an operational scenario were developed jointly by the implementation and operations staffs, well before the DGT configuration and design were solidified. Then, the operations staff participated in recommending, reviewing, and sometimes designing (e.g. man-machine interfaces). Levels of automation and maintenance were jointly established, Thus when the implementation was completed, the DGT reflected the operational experience developed over many years and missions. We see this successful transfer to operations in the surprisingly low number of phone calls and other requests for help from the operations staff.

5. CONCLUSIONS

As these words are written, the JPL approach to recovering from the Galileo HGA anomaly is proving its success by delivering spectacular pictures and discoveries from Ganymede, the first target of a 2-year tour of the Jupiter system. What was four years ago a risky conversion of R&D technology into an operational system, calculated risk as it may be, is paying off with handsome science return, and without an overdue loading on the operational infrastructure.

REFERENCES

[1] Statman, J., *"Optimizing the Galileo Space Communications Link"*, Telecommunications and Data Acquisition F'regress Report 42-116, Jet Propulsion Laboratory, February 15, 1994.