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GALILEO'S TELECOM USING THE LOW-GAIN SPACECRAFT ANTENNA[1]

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Galileo's accomplishment of a *science-rich mission through* a *low-gain antenna* was *made possible by* a *coordinated efforts of the Deep Space Network Support team, the spacecraft designers, and the science principal investigators. This team has worked together since late 1991, its efforts resulting in the flawless transition of Galileo, on May 23, 1996, to a completely new telecommunications link.*

The efforts included extensive changes in the DSN facilities in Goldstone (USA), Canberra (Australia) and Madrid (Spain) and at the Parkes Observatory in Australia, as well as *new uploads of Galileo's on-board software. The DSN/Parkes upgrades include increasing the antenna sensitivity, adding wide-area arraying between the Goldstone and Canberra 70-m antennas, the Canberra 34-m antennas and the Parkes 64-m antenna, installing new error-correcting coding, and providing the infrastructure to ensure gap-free, guaranteed delivery, telemetry processing. At the same time, Galileo has developed extensive on-board data editing and compression capabilities. Together, The DSN/Parkes and Galileo upgrades increase the raw downlink volume by a factor of 10, and its value by another factor of 10, resulting in* Galileo *meeting 70% of the original science* goals.

1. INTRODUCTION

The Galileo spacecraft was launched in October 1989, to investigate Jupiter and its moons. The baseline plan for communication utilized a prime link via X-band, 4.8-m high-gain antenna (HGA), as well as two backup links through S-band, low-gain antennas (LGA) [1]. Galileo's data rate through the prime link, at Jupiter range, would have been as high as 134.4 Kbits/s. After the HGA deployment failed, JPL faced the challenge of implementing a science-rich mission with a LGA at data rates of 10-20 bits/s, almost four orders of magnitude less than originally planned for the HGA-supported mission. A JPL study [2] in late 1991 led to a successful integrated program that included reprogramming of the spacecraft, development of new ground equipment, and some radical changes in the operational concepts. The cumulative effect of all the changes was to recover almost 2 orders of magnitude (see Figure 1). Additional re-ordering of science priorities led to recovery of almost 70% of the science objectives. On May 23, 1996, Galileo has switched to its new onboard software and has been communicating with the upgraded DSN ever since in this mode, returning fascinating data from 10, Ganymede, Europa, Callisto, and Jupiter itself [3].

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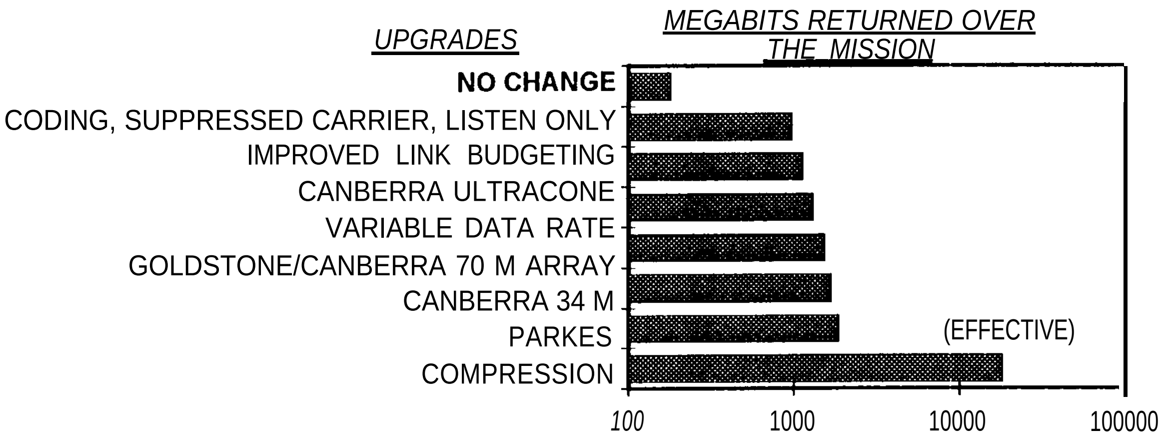

Figure 1- Galileo Data Volume - With and Without the Changes in the Link

2. PROGRAM OUTLINE

As shown in Figure 1, the most dramatic gains were accomplished through on-board compression *[4,5]* and editing. In this paper we'll focus on the changes made in the link and at the DSN to increase the data rate and prevent the additional losses associated with transmission of compressed data.

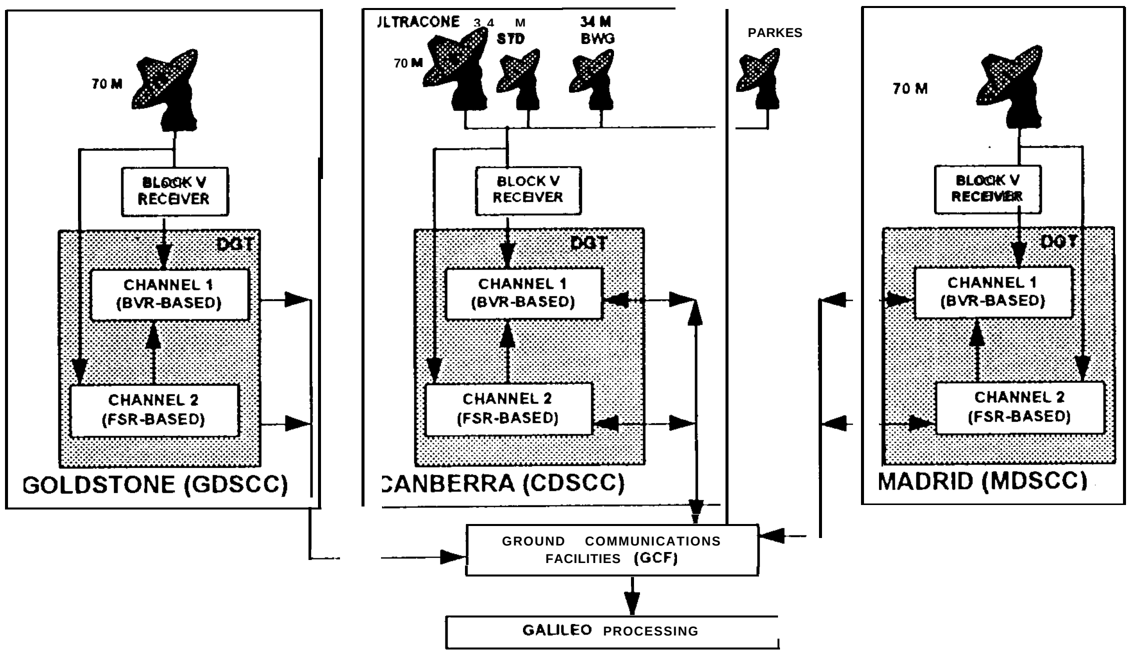

Figure 2- The DSN support configuration for Galileo

Figure 2 is the DSN configuration for Galileo support. Note that Galileo is supported by antennas at the DSN'S three DSCCs (Deep Space Communications Complex): GDSCC in Goldstone, California, MDSCC near Madrid, Spain, and CDSCC near Canberra, Australia. The three DSCCs together provide Galileo with 24 hour continuous coverage. In addition, the 64-meter Parkes radio-telescope is available to augment the support configuration.

In each DSCC, a new subsystem, DSCC Galileo Telemetry (DGT) was installed. The DGT is a fully-redundant two-channel system, Both channels receive IF signal(s) and produce decoded frames. Channel 1 uses the DSN Block V Receiver (BVR) [6] as the demodulator while Channel 2 uses a Full-Spectrum Recorder (FSR) to capture the signal and a Buffered Telemetry Demodulator (BTD) to demodulate it. We'll discuss the elements of the DGT in more detail below.

From the start it was recognized that the DSN upgrades had to provide a seamless, uninterrupted stream of decoded frames to the project scientists and engineers. Any interruption in the flow of frames could be magnified into a major loss due to compression and re-acquisition effects. Thus, the first five features we introduced are:

3.1 Pre-detection recording / buffering. Conventional telemetry is recovered in real-time, with no buffering. The combination of the low rates and the criticality of seamless telemetry led to the introduction of a pre-detection recorder that retains a permanent record of the spectrum of the received signal. In the DGT this is implemented by an FSR which converts the signal to baseband and then samples it (in-phase and quadrature) onto computer disk and tape backup. From that point on, none of the processing (in Channel 2) is truly in real-time - they are conducted from the digitized spectrum stored on disk. This pre-detection recording is crucial to restoring any breaks in the telemetry stream, either at the DSCC's with the built-in post-pass processing (3.2) capability or later at JPL.

3.2 Post-pass processing. The DGT operates in two stages: Real-time Processing (RTP) and Post-pass Processing (PPP). 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 may not be 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.

3.3 Lossless data-rate change. Given that tracking continues for 24 hours a day, what happens as the spacecraft changes its data rate to accommodate the changing signal-to-noise ratio (SNR)? The DGT has provisions to allow Galileo to adjust the data rate during the pass without any loss-of-lock. In fact, the data rate can be adjusted as often as once per frame. Note that for Galileo the continuous adjustment of the data rate increases the data return by approximately 1.0 dB (26%).

3.4 <u>"Guaranteed Delivery" data transfers</u>. To assure that the seamless data flow is not affected by breaks in communications between the DSCC's and JPL, the DSN has chosen to use commercial TCP/IP and FTP protocols, with all their associated acknowledgment and accountability features. To accomplish this, the DSN's Ground Communications Facility (GCF) was outfitted with commercial routers.

3.5 <u>Use of "fill" data. At times.</u> At times, link analysis indicated that even with the DGT operating properly, a break in the data recovery is expected, e.g. due to high spacecraft dynamics. In these cases, Galileo inserts frames of uncompressed "fill" data with lower or no value, to assure that even if this secondary data is lost, the loss will not be magnified and hamper the recovery of the primary data.

Once the seamlessness of downlink data stream was assured, additional measures were taken to increase the physical data rate:

3.6 <u>Arraying of multiple ground antennas.</u> One of the known techniques to increase the receiving G/I (Antenna Gain divided by System Noise Temperature) is to array multiple antennas. At the inception of the Galileo support program, an extensive assessment of large antennas at the United States, Japan, Russia, Ukraine, India and Germany resulted in selection of a southern-hemisphere array configuration consisting of the two DSN 70-meters antennas at CDSCC and GDSCC and two 34-meters antennas at CDSCC. In 1994, the array was augmented by CSIRO's 64-meter radio-telescope at Parkes, Australia. Two separate arraying techniques are being used: Channel 1 arrays the telemetry at the complex symbol level while Channel 2 performs full spectrum combining. Either approach is relatively lossless - the effective G/T is virtually the sum of the G/T of the individual antennas.

3.7 <u>Improvement of antenna G/T.</u> Two of the antennas underwent significant modifications, both in Australia. At the CDSCC 70-meters antenna, a special S-band feed was added, that reduces SNT by 24%, corresponds to a 24% increase in the volume of data return relative to what the data return for this antenna alone would have been without the upgrade. At Parkes, the radio-telescope was upgraded to a frequency-agile prime-focus system, enabling sharing of the radio-telescope between the Radio-Astronomy user community and the Galileo support.

3.8 <u>Suppression of carrier power.</u> In traditional communications, part of the power is "wasted" by maintaining a residual carrier components The DGT was designed to operate in the suppressed-carrier mode, and Galileo has been in this mode since the transition to the new onboard software.

3.9 <u>Improved Error-correcting coding</u>. The error-correcting coding for the mission is a 4-redundancy (255, n) R/S code concatenated with a (14,1/4) convolutional code. The total coding gain is 1.3 dB compared to the CCSDS standard coding - (7,1/2) convolutional code concatenated with a (255,223) R/S code.

Finally, let us discuss four more aspects of the system used to recover the Galileo data.

3.10 Configurability. The DGT is implemented in software, wherever possible. In Channel 2, the Full-Spectrum Combiner (FSC), the Demodulator (BTD) and the Decoder (FCD) are implemented on SUN computers. In Channel 1, the Symbol Combiner/Demodulator (SCD) and the Decoder (FCD) are similarly implemented in software. They are designed with much flexibility allowing easy adaptation to many missions with data rates that are less than 640 symbols/s. Re-configuration is easily accomplished via loading of the appropriate set-up tables.

3.11 Automation. With all the added sophistication, is the DGT harder to operate than routine telemetry equipment? Recent experience has shown that the answer is a clear NO. From the onset, the DGT has been implemented with sufficient automation to be an effective "load- and-go" system. It requires minimal operator intervention.

3.12 Health indicators. One of the subtle effects of low-rate missions is the great reduction in telemetry health indicators. These are the parameters available to the operator, indicating that the loops are locked and tracking and data flow is proceeding well. The DGT incorporates additional health indicators, such as FFT displays derived from the signal sidebands, to assure constant feedback to the operators.

3.13 Operation with low link margin. At JPL, the link design practice is to compute or derive the standard deviations of the components of the link budget, convert them to dB loss, sum them and define the result as the standard deviation of the link, σ_L, expressed in dB. Then 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. With the availability of pre-detection recording and post-pass processing, Galileo could operate with a reduced link margin, relying on these tools for recovery of marginal data.

3. CONCLUSIONS

The program described here has resulted in the on-going successful recovery of significant science from Jupiter and its moons, and will be part of the recently-approved Galileo Europa Mission. In addition, the techniques and some of the operational equipment are directly applicable to support of other low-rate missions.

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ACRONYMS

BTD	Buffered Telemetry Demodulator
BVR	Block V Receiver
BWG	Beam Waveguide 34-meter antenna
CCSDS	Consultative Committee for Space Data Systems
CDSCC	Canberra DSCC
CSIRO	Commonwealth Scientific Industrial Research Organization
DGT	DSCC Galileo Telemetry (subsystem)
DSCC	Deep Space Communications Complex
DSN	Deep Space Network
FCD	Feedback Concatenated Decoder
FSC	Full-Spectrum Combiner
FSR	Full-Spectrum Recorder
GDSCC	Goldstone DSCC
HGA	High Gain Antenna
JPL	Jet Propulsion Laboratory
LGA	Low-gain antenna
MDSCC	Madrid DSCC
R/S	Reed-Solomon code
SCD	Symbol Combiner/Demodulator
SNR	Signal-to-Noise Ratio
SNT	System Noise Temperature
STD	Standard 34-meter antenna