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Abstract

On May 23, 1996, Galileo successfully switched to a new telecommunication mode with upgraded software on the spacecraft and comprehensively revised ground equipment. The new link offers multiple techniques (arraying, error-correcting coding, data compression, etc) to maximize the data return, while applying automation to minimize the complexity and cosf of operations. The design methodology and some of the equipment are especially suitable for the era of Discovery and New Millennium missions where there is sevens pressure to reduce both the spacecraft cost (e.g. antenna size and transmitter power) and operations cost.

After the Galileo High Gain Antenna (HGA) failed to deploy in April 7991, JPL completely redesigned the telemetry downlink to provide a viable mission, based on Galileo's S-band, Low-Gain Antenna. The redesign required 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 70 m antenna, the Tidbinbilla 70 m and 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.

Two key DGT features that would benefit the Discovery and New Millennium missions are the recovery of pre-acquisition data and the availability of digitally-recorded full-spectrum replicas of the signal for later processing. The former is especially important to short missions (balloons, penetrators) - it eliminates the telemetry loss during the acquisition/locking of the receiving equipment. The latter enables a "second chance" at recovering the data, if any equipment failures prevent the first attempt.

1. INTRODUCTION

Since the early *90's,* space exploration efforts of NASA and JPL must meet the challenge of flying future spacecraft at about 10% of the cost of the large, sophisticated flagships such as Galileo and Cassini. To meet this challenge, as formulated by the Discovery and New Millennium programs, drastic changes are required in all aspects of the spacecraft, in particular telecom. In the past it was expected, often required, that newer spacecraft operate at higher and higher data rates, returning large volumes o! minimally-processed data for viewing and further processing by both the scientists and the engineering staff. These higher downlink rates required the utilization of large spacecraft antennas, investment in sophisticated attitude and pointing subsystems, and enhancements of the power systems. For the Discovery and New Millennium era, as these spacecraft entrancements could lead to unacceptable expenditures, missions are destined to depend on lower-rate communications and different solutions are needed. In this paper we discuss the successful recovery of the Galileo mission and how some principles, and actual new operational equipment, from this recovery can be applied in the design and implementing of low-rate communications for Discovery and New Millennium spacecraft.

Galileo was launched in October 1989, planning on communicating via an X-band, 4.8-m high-gain antenna (HGA), with backup from two S-band, low-gain antennas (LGA) [1]. In this configuration, Galileo could communicate from Jupiter to Earth at rates 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 that were 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). Starting May 23, 1996, Galileo has switched to its Phase II software and has been communicating with the upgraded DSN ever since in this mode, returning fascinating data from 10, Ganymede, Europa, and Jupiter itself [3].

In Section 2 of this paper we describe the generic problem faced by a low-rate mission. In Section 3 we outline the improvements established for Galileo support, primarily **in the ground equipment.** Then in Section 4 we discuss some lessons learnt and conclusions.

2. THE GENERIC LOW-RATE CASE

What is a "low-rate" mission? In this paper we focus on missions where the data rate is below 1 Kbits/s. Typical examples are Galileo (32-160 bits/s) or Cassini during cruise (less than 200 bits/s). Missions fall into this category either by choice, e.g. restrictions on the antenna or transmitter for part or all of the mission, or by unforeseen technical problems, such as those facing Galileo. To maximize the utility of the telecom link, the approach to the design of low-rate communications needs to be fundamentally different from that applied to high-rate communications : while in the latter case, the telecom design is largely decoupled from the instrument design, in the former case the two are closely coupled. Simply stated, for low-rate missions there is in increased emphasis on providing more value for each downlinked bit via compression, editing, or other pre-processing. As a corollary, when any downlinked bits are lost due to link outage, many more bits (that were received correctly on the ground) can be rendered useless. This magnification-of-loss effect, that can be devastating for a low-rate mission, is caused by the interplay between three factors: data framing and error correcting coding, editing and compression, and acquisition time, Let us expand on this magnification-of-loss effect and the interdependency between frames.

2.1 Data framing and error-correcting coding. As defined by the CCSDS standard, transport frames are encoded with a Reed-Solomon (R/S) code, then with a convolutional code. The concatenation of the two codes converts channel symbols that are contaminated with noise, with symbol error rates of 0.1-0.2, to reliable information bits, with bit error rates of 10-3 or less. If a frame fails the R/S decoder then all the bits in the frame are suspect, so the basic unit of data reception is a full transport frame. Note that a typical frame has **4096** to **16,384** bits, Galileo uses a 16,384 bit frame, thus at 40 bits/s a lost frame is almost 7 minutes of data. **For** Galileo coding (and CCSDS coding) signal loss **for** 3% or **4%** of the frame will render the frame unrecoverable.

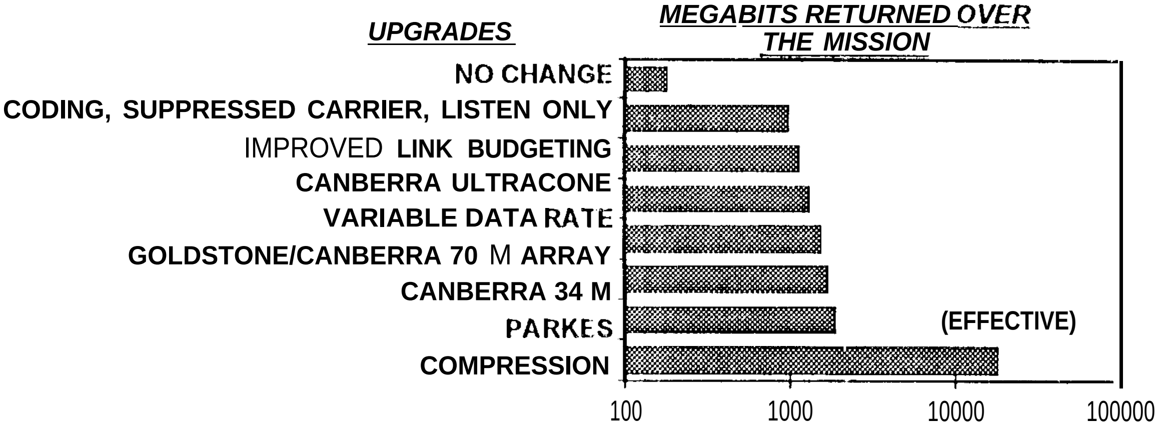

Figure 1- Galileo Data Volume - With and Without the Changes in the Link

2.2 Compression, editing an~ pre-processing. Compounding the impact of lost frames is the fact that the data is compressed or edited at the instrument and then packetized. Thus, when a frame is lost, the damage can easily propagate well beyond the frame boundary and prohibit the recovery of much larger amount of data.

2.3 Acquisition times. Finally, at low rates the acquisition/lock times for the demodulator and the decoder can get extremely long. Decoder acquisition/verification usually requires three frames, which at Galileo's 40 bits/s is 20 minutes of lost data.

The accumulated effects of these three factors can cause even short signal outages to result in disproportionately long science/engineering outages. Traditionally, telecom designers address the requirement of decoded bit availability - this paradigm must change for low-rate missions. As a reference, the DSN is committed to return **95%** of the telemetry (returned telemetry is defined as bits that were successfully Viterbi decoded) for Galileo. One can envision a case where the telecom link operates correctly and 95% of the downlink bits are recovered, but the missing **5%** are placed in the worst-case positions causing many frames not to be decodable or decompressable. To avoid this, the designers of telecom for low-rate missions, together with the instruments teams, must find a way to maximize not the number of returned bits but the number of bits from which valid science and engineering data can be recovered.

3. JPL'S UPGRADE PROGRAM

Starting in June 1992, JPL has embarked on an aggressive program to support a viable Galileo mission based on the LGA. Central to this program is the integration of the design, development, and test efforts of the Spacecraft team, the DSN development team and Operations organizations. As shown in Figure 1, the most dramatic gains were accomplished through on-board compression [4] and editing. In this section we'll focus on the changes made in the link and at the DSN to increase the data rate and prevent the magnification-of-loss discussed earlier. Figure 2 represents the DSN configuration for Galileo support. Note that Galileo is supported by antennas at JPL's three DSCC'S (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.**

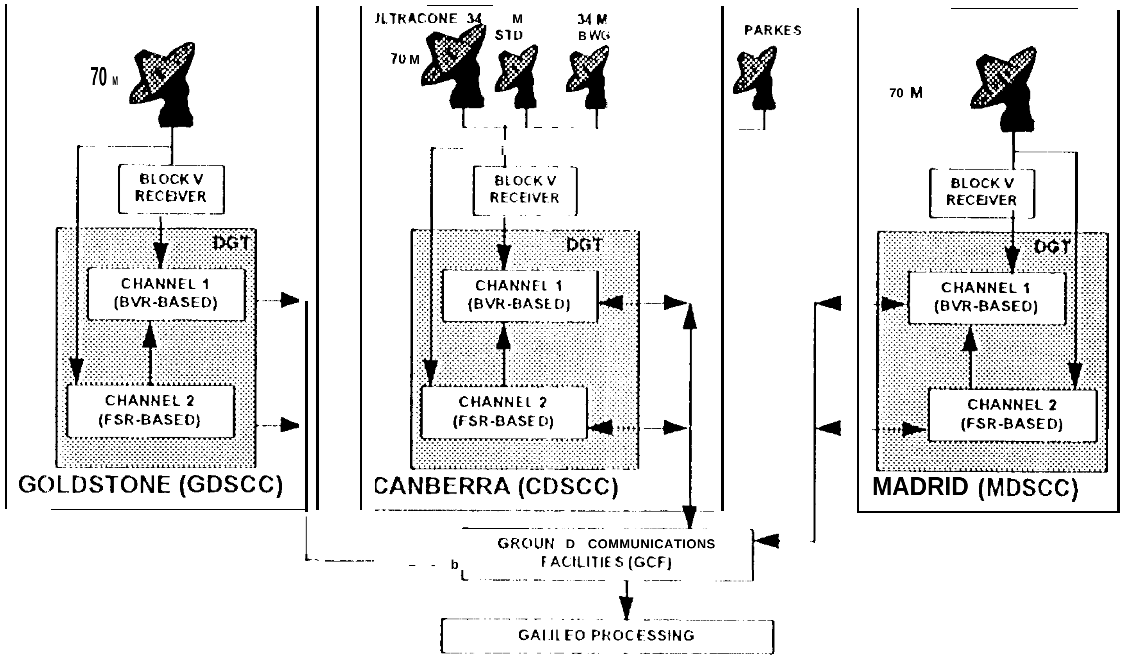

Figure 2- 7-he DSN support configuration for Galileo

In each DSCC, a new subsystem , DSCC Galileo Telemetry (DGT) was installed. The DGT, shown in 'Figure 3, is implemented as a fully-redundant two-channel system. Both channels receive IF signal(s) and produce decoded frames. Channel 1 uses the existing DSN Block V Receiver (BVR) [5] 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. T bus, 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 processirrg (3.2) capability or later at JPL.

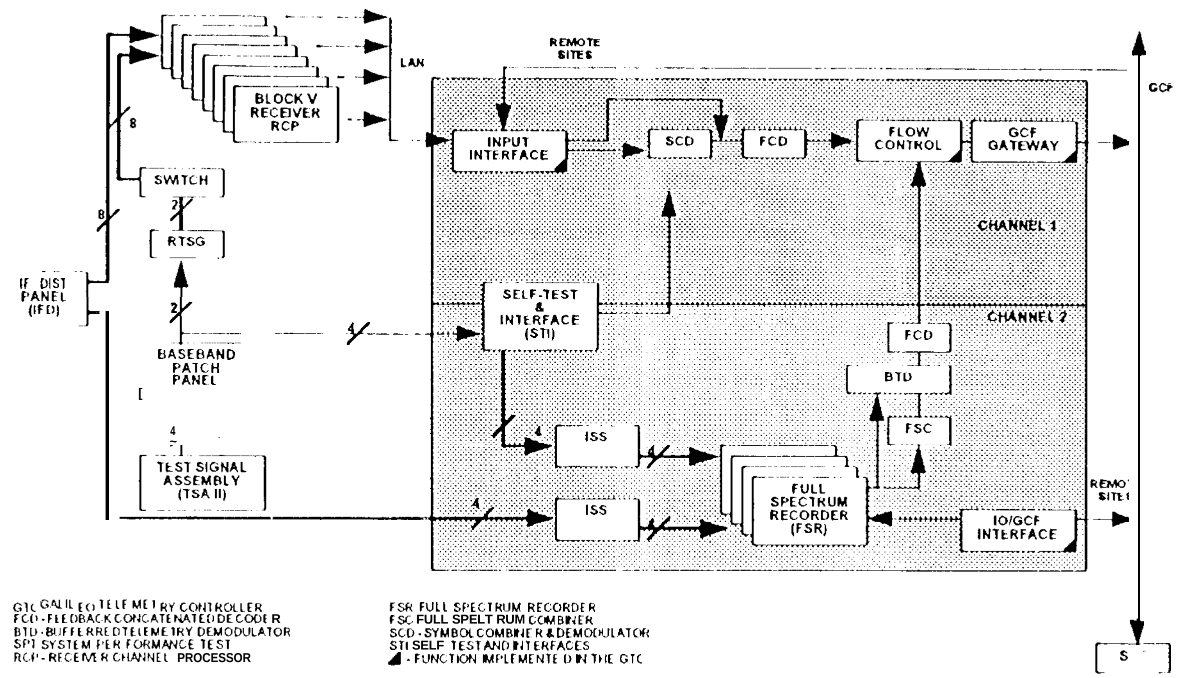

Figure 3- Signal Processing Block Diagram

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?"0 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 all of the missing data is recovered or when a pre-determined time-limit (with a default of 4 hours) was reached,

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 "Guaranteed Delivery" data transfers. 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. 1-0 accomplish this, the DSN's Ground

Communications Facility (GCF) was outfitted with commercial routers.

3.5 Use of "fill" data. At times. 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 Arraying of multiple ground antennas. One of the known techniques to increase the receiving G/T (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, India and Germany resulted in selection of a southern-hemisphere array configuration consisting of the two DSN 70-meters antennas at CDSCC and GDSCC, two 34-meters antennas at CDSCC, and 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 Improvement of antenna G/T. Two of the antennas underwent significant modifications, both in Australia (not surprising since as a southern hemisphere spacecraft Galileo data return benefits the most from improvement in these antennas.

At the CDSCC 70-meters antenna, an Ultracone [6,7] was added. The Ultracone is an S-band receive-only system with a total system noise temperature of 11.8 degrees Kelvin, compared to 15.6 Kelvin for the multi-frequency receiving system. This represents a 24% increase in the volume of data return. The Ultracone Installation was completed in summer of 1995, and it was operational prior to the Galileo's Jupiter Orbit Insertion Maneuver (JOI).

At Parkes, the radio-telescope has a prime focus configuration, where the switching between feeds is manual and tedious. This was upgraded to a frequency-agile prime-focus system where a number of feeds, including a new HEMT-based S-based feed, are mounted on a transport mechanism that allows switching quickly between the various frequencies. The Parkes upgrades were completed in early 1996 and Parkes will be used in the operational array starting in November 1996.

3.8 Suppression of carrier power. In traditional communications, part of the power is "wasted" by maintaining a residual carrier components. As long as the carrier is stable, e.g. can be tracked by a sub-1-Hz tracking loop, eliminating the residual carrier, and shifting all the power to the data modulation can result in a significant increase in the data return. The actual benefit will depend on the mission design point but as a reference, if the mission design point has a modulation index **of 45 degrees,** than by changing to suppressed carrier modulation, the data rate can be doubled.

The demodulators used for Galileo support, both in Channel 1 (BVR) and in Channel 2 (BTD) are capable of processing suppressed carrier signals, and Galileo has been in this mode since the transition to Phase II software.

3,9 Improved Error-correcting coding. The error-correcting coding for the mission is a 4-redundancy (255, n) R/S code concatenated with a (14,1/4) convolutional code [8]. 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.

There is an interesting story of struggle and creativity behind the choice of the unusual (14,1/4) convolutional code. In the wake of the Galileo HGA anomaly, JPL engineers found out that there is no way to bypass the hardwired convolutional encoding. They have investigated and found a method by which a software (11,1/2) convolutional encoder, followed by the (7,1/2) hardware encoder, results in a good (though sub-optimal) (14,1/4) convolutional code that . This particular code is not likely to be used again but the decoder is very flexible and can process, for example, the Cassini, Mars Pathfinder, and Mars Global Surveyor codes.

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 20,,, 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.**

4. LESSONS AND CONCLUSIONS

As **of Fall 1996, the Galileo-driven implementation discussed above is either** complete or in the last stages of completion:

4.1 The Ultracone at DSS 43 and the upgrades to the Parkes Radio-telescope were completed and are supporting Galileo. These are unique to S-band missions, though the Parkes frequency agile set-up could also support X-band missions.

4.2 The DGT single-antenna version was fully installed and has been successfully supporting Galileo **since** May 23, 1996 [9]. A stand-alone FSR in Madrid will also support the Mars Pathfinder's entry, descent, and landing phase on July 4, 1997.

4.3 The DGT array (channel 2) was installed and is being prepared to start operational support by November 1, 1996. Arraying for Channel 1 is still undergoing testing and is expected to be operational starting in February 1997.

Overall, the techniques and some of the operational equipment, developed and demonstrated in the successful recovery of the Galileo mission 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
CDSCC	Canberra DSCC
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
JOI	Jupiter Orbit Insertion
JPL	Jet Propulsion Laboratory
LGA	Low-gain antenna
MDSCC	Madrid DSCC
PI	Principal Investigator
R/S	Reed-Solomon code
SCD	Symbol Combiner/Demodulator
ST D	Standard

34-meters antenna