GAI.ILEO SYSTEM DESIGN FOR ORBITAL OI'1H{ATIONS

Julia George, Gary Kunstmann, Samuel Southard, and Edwin Upchurch

Jet Propulsion laboratory, California Institute of Technology, Pasadena,CA91109

ABSTRACT

In April ***1991,*** *Galileo's X-band high gain antenna failed to deploy. An alternate approach which utilizes the spacecraft's S-band low gain antenna was conceived and is in development. This approach will enable the accomplis - ment of at least 70 percent of Galileo's original scientific objectives. The short development period dictates that the spacecraft system design, the ground data system design, and the operational system scenarios and procedures necessary to conduct the mission be developed concu rrently, and places a premium on validating the system designs as early as possible. This paper presents an overview of the Galileo mission, briefly describes the changes required to implement the orbital phase of the Galileo mission, and describes the Junctional model of the end to end system which was developed to support the systems design effort.*

1. BACKGROUND AND MISS1ON I)1CSCRIPTION

Following the failure of Galileo's X-band high gain antenna (H GA) to deploy in April 1991, an approach which utilizes the spacecraft's S-band low gain antenna (1 .GA) was conceived and is in development. The alternate approach was first described in Reference [1] and later in [2] and [3]. Reference [4] provides an overview of the entire Galileo mission and provides details about the science instruments. This paper describes a process used to aid in the validation of the system design by discussing a number of the issues that introduced uncertainty into the system performance and tbc usc of an end to end system functional model that qualitatively characterized that performance.

As the spacecraft (S/C) to Earth range increases, tbc achievable data rate with tbc existing S/C and ground capabilities will fall to less than 10 bits pcr second (bps) during much of tbc remaining mission. After all attempts to deploy the HGA were exhausted, the Galileo Systems Development organization was established in March 1993 with the objective of fully implementing tbc alternative approach.

Because of the extent of tbc software changes required to perform the mission using the LGA and the limited size of tbc on board memories, the remaining Galileo mission using the LGA must bc accomplished with three distinct software loads.

The existing spacecraft software, referred to here as Phase O, will bc used until about March 1995.

The software in tbc spacecraft Command and Data Subsystem (CDS) will then bc modified to Phase 1 software which will bc active on the spacecraft from March 1995 through March 1996, during which time tbc Jupiter approach, 10 encounter, Jupiter probe relay, and Jupiter orbit insertion (JOI) portions of the mission will bc performed. Reference [3] describes tbc design of the Phase 1 soft ware in detail.

Lastly, Phase 2 changes will include a ncw flight software load for tbc CDS and software changes to eight out of eleven of the S/C science instruments, Phase 2 changes will bc transmitted to the S/C in March and April 1996 and will remain active throughout the remainder of the mission.

A total of ten encounters with three of tbc Jovian satellites (Call isto, Europa, and Ganymede) will occur during tbc orbital operat ions portion of the mission. As shown in Figure 1, each of these encounters will consist of an approximately

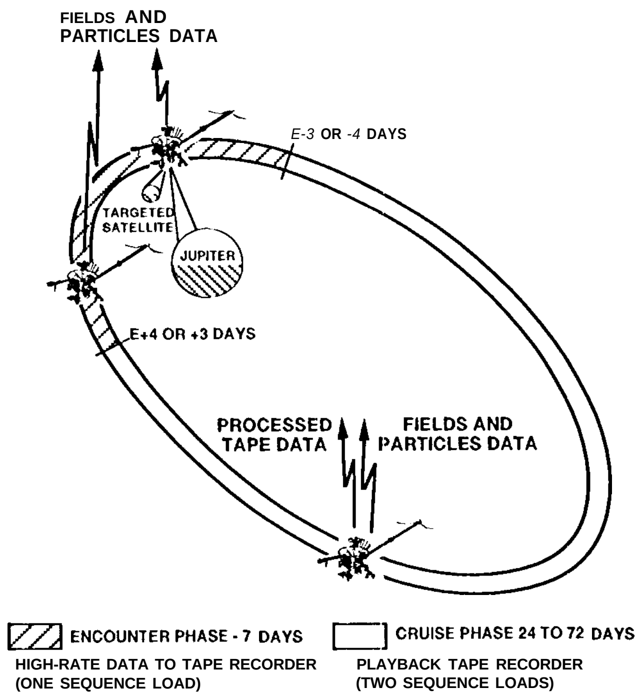

Figure 1. Orbital operat ions scenario.

scvcn day cncountcr with Jupiter and the satellite, followed by orbital cruise during which the data collcctcd during tbc cncountcr will bc returned to Earth. Fields and particles (F&P) data will bc collcctcd and returned in real time during most of each orbit as well as a fcw short duration remote sensing scicncc observations which may bc rccordcd during the orbital cruise period for later return during the same or subsequent orbit. Each of the tcn cncountcr orbits is of different duration and each occurs at a different Earth to spacecraft range, rcsulting in unequal amounts of data being returned from the tcn orbits.

2. SPACECRAFT DIMKXIP11ON

Rcfcrcncc [5] provides an overview of the Galileo spacccraft and Rcfcrcncc [6] describes the CDS. Although a very brief description of parts of tbc spacecraft relevant to the modifications being made to support the LGA based mission will bc givcn here, more detailed information should bc obtained from the rcfcrcnccs.

3. SPACECRAFT SOFTWARE DESIGN FOR ORBITAL OPERATIONS

3.1 Overview

The objectives of tbc Phasc 2 modifications arc to:

(1) Incrcasc scicncc information density of the downlink using compression and othcr onboard processing,

(2) Incrcasc thc number of downlink data rates and modes in order to utilizc link capability cfficicntly,

(3) incorporate advanced coding techniques to incrcasc tclcmctry return, and

(4) Incrcasc the actual or cffcctivc Deep Space Network (DSN) aperture for Galileo.

Phase 2 involvcs more cxtcnsivc changes to both spacccraft and ground systems than Phase 1. These changcs allow editing and compression of the scicncc and cnginccring data streams, and provide a buffering mcchanism to manage tbc flow of data from real time sources and tbc Data Management Subsystcm (DMS) rccordcr playback into the downlink channcl. A fundamental changc from time division multiplcxcd (TDM) downlink to packet tclcmctry is also being made to make cfficicnt usc of the downlink channel given variable packet sizes which result from data compression and toprovidc flexibility in selecting which data is tobc included in tbc downlink.

A large number of special processing features arc provided which allow flexibility in controlling the data collcction, processing, and downlink. They include individual and/ or group instrument dcsclcction from the realtime, record, or playback data streams, editing algorithms, compression algorithms, and a number of features used to provide data continuity.

Eight out of clcvcn scicncc instruments arc being modificd to change their functionality to bc compatible with tbc ncw spacecraft capabilities; Dust Dctcctor Subsystcm (DDS), Energetic Particle Detector (EPD), Extreme Ultraviolet (EUV), Magnctomctcr (MAG), Near-InfrarcdMapping Spcctromctcr (NIMS), Plasma Subsystcm (1'1.S), Solid-State imaging (SS1), and Ultraviolet Spcctromctcr (UVS). The Heavy Ion Counter (H IC), Photo Polarimctcr Radiometer (PPR), and Plasma Wave Subsystcm (PWS) arc not rcprogrammablc in flight,

3.2 Real Time Processing

Figure 2 shows the processing flow for real t imc scicncc and cnginccring data. In tbc ccntcr of tbc figure arc two buffers, a 4 Kbytc priority buffer, and a 70 Kbytc multiusc buffer. Each of thcsc buffers arc first in first out buffers. When any data arc in the priority buffer, they arc sent to the ground before any data in tbc multiusc buffer arc sent.

The priority buffer rcccivcs data from CDS cnginccring telemetry at onc of three commandablc rates; 2 bps, 10 bps, or 40 bps. It also rcccivcs edited optical navigat ion (OPNAV) images from SS1.

F&P instrument data (MAG, EPD, PLS, PWS, DDS, HIC) and EUV, UVS, and NIMS arc collcctcd using onc of nine real time scicncc (RTS) formats.

The capability is provided to dcsclcct any source or sources from inclusion in tbc RTS data stream. This dcsclcct capability allows flexibility in control of the downlink data content, but contributes to tbc variability of tbc RTS stream.

Record rate changc covcragc (RRCC) is used to provide data cent inuit y during DMS record rate changes. The RRCC collects data during this change period and inserts it into the multiusc buffer for downlink with the real time data. Thus, this data might arrive weeks ahead of related data that was stored on the DMS tape rccordcr.

3.3 Record Processing

Figure 3 shows the processing flow for record data. NIMS and PPR data arc edited in CDS. PPR data, bccausc they arrive at a rate much slower than the minimum DMS rccordcr record rate, arc buffered in a burst buffer prior to recording. F&P instrument data, including PWS high rate data, EUV, UVS, and SSI arc rccordcd directly to tape.

Fiftccn record modcs provide fixed opt ions for select ing bow much of each instrument is rccordcd on tape and at what spccd the data arc rccordcd onto the DMS rccordcr. Onc of the ncw record modes provides the capability to dump the multiusc buffer to the DMS recorder. This buffer dump to

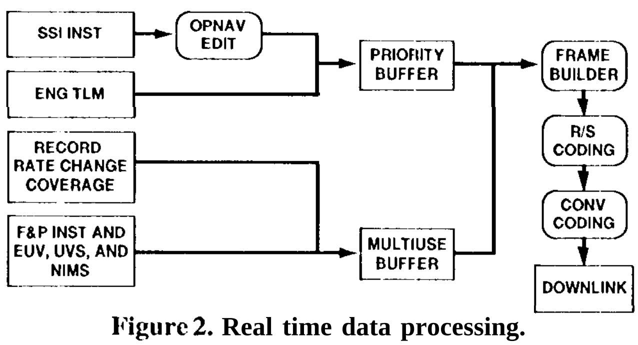

Figure 2. Real time data processing.

3.7 Telemetry Processing

Telemetry processing has been fundamentally changed from a fixed TDM structure to a packet telemetry structure, except for fault recovery conditions where the existing 10 and 40 bps TDM residual carrier modes of the existing design have been retained. The new processing steps consist of collecting the data into packets, assembling packets into virtual channel data units (VCDUs), collecting VCDUs into R-S encoded frames, convolutional encoding, modulation, and transmission.

Figures 5 and 6 describe the variable length packet structure and the fixed length VCDU structure. No further elaboration on these structures is planned in this paper.

VCDU processing is shown in Figure 7. As shown, all VCDUs eventually end up in the processed data portion of the multiuse buffer, except for VCDUs with ID = 0, which go through the priority buffer.

As downlink telemetry link allows, VCDUs are collected, four at a time, first from the priority buffer, then from the multiuse buffer, and finally from special PWS fill data VCDUs. These four VCDUs are assembled into a 2048 byte telemetry frame and R-S encoded as shown in Figure 8. A R-S interleave depth of eight is used along with four different lengths of R-S parity bits.

The CDS then software (11, ½) convolutionally encodes the frame and sends the data to the Telemetry Modulation Unit (TMU) in the Modulation Demodulation Subsystem at one of eight ground commandable downlink telemetry rates (8, 20, 32, 40, 60, 80, 120, or 160 bps). These downlink telemetry rates are determined by a combination of hardware constraints within CDS and the selected 2048 byte frame size.

The TMU hardware (7, ½) convolutionally encodes the data received from CDS, providing an effective (14, ¼) convolutional code on the downlink symbol stream. These coded data are modulated onto the downlink carrier using the low rate subcarrier and a modulation index of 90°, resulting in a fully suppressed carrier signal. This resulting signal is sent to the Radio Frequency Subsystem for transmission through the S-band transmitter, operated at its high power setting, and the S-band LGA.

Ninety telemetry modes are provided. These ninety modes represent combinations of the three engineering data rates, the nine RTS formats, and the eight downlink telemetry rates. When the effective collection rate of the RTS and engineering data is less than the downlink telemetry rate, the multiuse buffer is emptied, and vice versa. Emptying of the multiuse buffer is a required condition for being able to play back data from the DMS recorder.

4. FUNCTIONAL MODEL

As discussed, the disparate science data acquisition and telemetry downlink rates, which require extensive data buffering on the spacecraft, and the uncertainties introduced by data dependent compression, which result in data volume

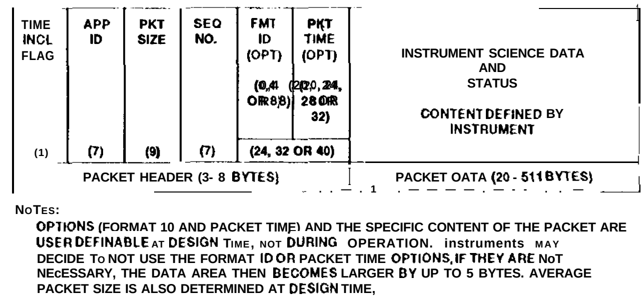

Figure 5. Packet structure.

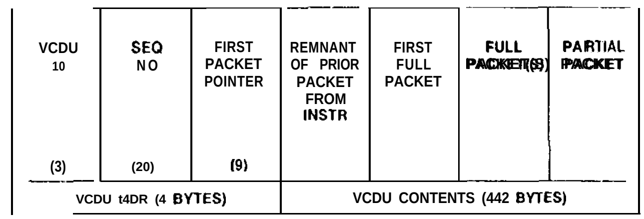

Figure 6. General VCDU structure.

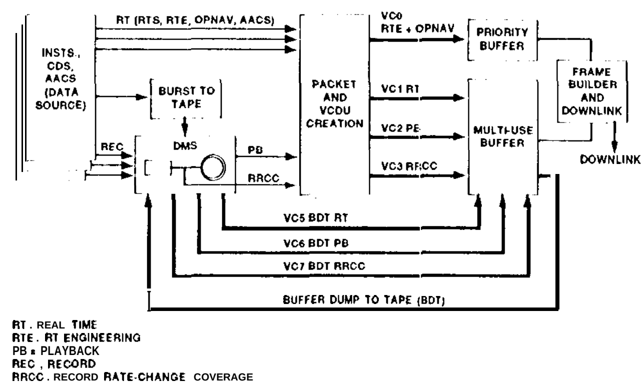

Figure 7. VCDU processing.

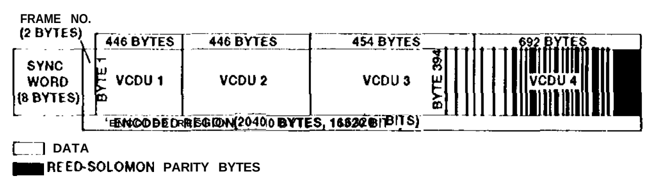

Figure 8. Telemetry frame structure.

uncertainties of approximately 2:1, make the performance of the system designs non deterministic. The additional complexity of one way light times approaching one hour requires much autonomous data handling on the spacecraft.

To fully appreciate the interaction of these factors, an end to end system functional model was developed using a commercial modeling tool. Using this tool to simulate the operation of the end to end system, from instrument data sources to the project database on the ground, for a representative orbit, designers have been able to make design tradeoffs and to look for surprises in the operation of the system.

4.1 Overview

The Galileo system was modeled for four primary reasons:

1. To ensure that a multiuse buffer overflow did not lead to uncontrolled loss of data,
2. To analyze the effect of tradeoffs in Phase 2 software design,
3. To visualize how the system responds to varying command sequences, and
4. To calculate statistically the time between data acquisition and ground data reception.

The multiuse and priority buffers, instruments, DMS recorder, and downlink arc included with varying levels of detail. Since concern over multiuse buffer overflows was utmost, the model tracks each datum entering and exiting the multiuse buffer. The instruments, however, simply produce data at a specified rate.

A commercial tool [10] provided the basic facilities needed to develop the Galileo model. Its hierarchical nature allows a model to be developed at a high level, specifying details only when necessary.

The model requires two input files:

1. A file containing the sequence of commands which occur during the orbit in question and
2. A file containing the status of each of the instruments (whether the data collected by each instrument is retained or discarded, and how compressible that data is estimated to bc) as a function of time.

When run, the model uses a Parallel Virtual Machine [11] to communicate with a graphical user interface. The graphical user interface displays various information about the system, such as the contents of the multiuse buffer or what types of VCDUs arc being downlinked.

4.2 Instruments

The model views instruments as a source of data packets, with no information about the data contents. The data from the instruments arc either queued into the molt iuse buffer, the priority buffer, or the recorder or arc discarded.

4.3 Data Management subsystem

The DMS keeps track of the record mode and selected instruments as a function of time. Data packets arc not produced until the tape is read.

When in playback mode, the DMS begins producing data packets based on the appropriate record mode when the multiuse buffer usage drops below the minimum fill level. The DMS stops producing data packets when the multiuse buffer rises above the maximum fill level. The minimum and maximum fill levels arc controlled via the command sequence data file.

4.4 Multiuse and Priority Buffers

The data buffers keep track of the data type (specific instrument, record data, or VCDU) for every byte in the buffer. If a packet would cause a buffer to overflow, the packet is discarded.

4.5 VCDU Production

Downlink VCDUs arc divided into five categories: priority, real time, recorded data, RRCC, and fill. Each of the categories of VCDU is produced independently. All VCDUs arc stored in the multiuse buffer, except for the priority VCDUs, which arc stored in the priority buffer, and fill VCDUs, which arc only created when necessary for the downlink and never take up space in any buffer.

4.6 Downlink

Telemetry frames arc produced whenever necessary, i.e., the downlink is never idle. Under normal circumstances, any available priority VCDUs arc packed into the telemetry frame, followed by any other available VCDUs. If no VCDUs arc available, fill data is packed into the telemetry frame. At times specified by the command sequence, only fill data is used for telemetry frames.

4.7 Graphical Display

The display program can be run either from a saved data file or while the model is executing. The display consists of a menu bar and a data display area. The data display area is divided into three areas: an alphanumerical status display and control area at the top; a graphical area, which is divided into four quadrants, at the middle; and a legend describing the colors used in the graphical area is placed at the bottom.

Any of the graphs described below can be displayed in any of the four quadrants. All four quadrants arc synchronized to display data for the same period of t imc and scrolling onc quadrant scrolls the others. The horizontal time scale of the graphs can be adjusted to display from 54 minutes to 54 days at onc time.

The multiuse buffer graph contains two lines, onc each for the maximum and minimum fill levels, and a number of stacked histograms. The histograms display the amount of multiuse buffer space used by each VCDU type: playback data, real time data, RRCC data, BDT record data, BDT real time data, BDT RRCC data, and fill data, plus non-VCDU data. The active stations (Goldstone, Canberra, and Madrid) arc indicated by initials at the bottom of the graph. The vertical scale on this graph is the percentage of the multiuse buffer used.

The priority buffer graph displays the status of the priority buffer. The amounts of the buffer used for engineering data (non-VCDU), OPNAV data (non-VCDU), and engineering VCDUs arc displayed as stacked histograms. The vert ical scale is the percentage of the priorit y buffer used.

The tape recorder capacity graph displays the percentage of the t apc recorder used. The graph contains stacked histograms displaying the amount of tape used for BDT data, BPT data, engineering data, "garbage" data ("garbage" data occurs when the tape speed changes), or "other" data (anything else). The vertical scale on this graph is the percentage of the tape recorder used.

The downlink graph displays the VCDUs being downlinked. The graph contains stacked histograms for every type of VCDU: playback data, real time science data, engineering data, RRCC data, BDT record data, BDT real lime data, BDT RRCC data, and fill data. There is also a line for the theoretical maximum downlink rate. Tbc vertical scale on this graph is the downl ink rate in bits per second.

The tape map display is a color coded map of tbc tape contents. Because of the large tape recorder capacity, it is impossible to display every bit of data on the tape recorder. The types of data were therefore prioritized in the order "other", engineering, BPT format data, "garbage" data, and BDT data, from lowest to highest. In other words, if BDT data maps to the same place in the tape map as BPT format data, the BPT format data will not be seen. The tape map is displayed as of the current time (defined by tbc position of the scroll bars in the other graphs).

The playback table display describes the status of the tables which control the playback process. The playback table is displayed as of the current time.

5. SUMMARY

Galileo orbital operations require substantial changes to spacecraft systems, in a relatively short development period, in order to accomplish the Galileo mission using the limited downlink capabilities of the I.GA.

The objectives of the Phase 2 mollifications arc met with the design described, it remains to implement and usc that design for the conduct of the orbital operat ions portion of the Galileo mission.

The usc of the end to end functional modeling tool greatly increased the confidence in tbc resultant systems design, and the specific objectives set down for the modeling effort were met, Some lessons were learned in the process: 1) the tool chosen was appropriate in that it allowed increasing detail and fidelity where it was needed, 2) the usc of the tool should have been applied earlier in the design cycle to increase its usefulness as a "design" tool rather than a "design validation" tool, and 3) the value of the graphical displays in understanding the functioning of the end to end system was initially underestimated and could have contributed more if additional emphasis had been placed on the development of those displays earlier in the application of the tool.

6. ACKNOWLEDGMENTS

The research described in this paper was carried out by tbc Jet I'repulsion Laboratory, California Institute of Technology, under a contract with tbc National Aeronautics and Space Administration.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, dots not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

7. REFERENCES

[1] W.J. O'Neil, N.E. Ausman, T.V. Johnson, M.R. Landano, "Galileo Completing VEEGA - A Mid-Term Report," IAF-92-0560, 28 August 1993.

[2.] W.J. O'Neil, N.E. Ausman, T.V. Johnson, M. Il. Landano, J.C. Marr IV, "Performing the Galileo Jupiter Mission with the Low-Gain Antenna (LGA) and An Enroute Progress Report," international Astronautical Federat ionpapcrlAI~-93.Q.5.411, October 16-23,1993.

[3] J.C. Marr, IV, "Performing the Galileo Mission Using the S-Band Low Gain Antenna," Proceedings of the 1994 IEEE Aerospace Applications Conference, Vail, Colorado, 5 to 12 February 1994.

[4] C.T. Russell, editor, "The Galileo Mission," Reprinted from Space Science Reviews, Volume 60/1 -4, 1992, Kluwer Academic Publishers, 616 pages.

[5] M.R. Landano and C. P. Jones, "The Galileo Spacecraft System Design," AIAA-83-0097, January 10-13,1983.

[6] W. Kohl, "Galileo Orbiter Command and Data Subsystem," Proceedings of industry/Space Division NASA Conference and Workshops on Mission Assurance, Los Angeles, 28 April to 2 May 1980, Pages 326-333.

[7] W. Chain, "Development of integer cosine transformations by the principle of dyadic symmetry," IEEE Proceedings, Vol. 136, Pt. 1, No. 4, August 1989.

[8] K-M Cheung and K. Tong, "Proposed data compression schemes for the Galileo S-band contingency mission," 1993 Space and Earth Science Data Compression Workshop, pp 99-109, Proceedings of a workshop held at the Snowbird Conference Center, Snowbird, Utah, April 2, 1993, NASA CP 3191.

[9] R.F. Rice, "Some Practical Universal Noiseless Coding Techniques, Part III, Module PSI 14, K+," JPL Publication 91-3, 15 November 1993.

[10] "SES/Workbench Reference Manual", Release 2.1, February 1992, Scientific anti Engineering Software, Inc., 4301 Westbank Drive, Building A, Austin, TX 78746

[11] "A Users' Guidcto PVM Parallel Virtual Machine'', A. Beguelin, etal., ORNL/TM-11826 Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831