EIGHT MICROPROCESSOR-BASED INSTRUMENT DATA SYSTEMS IN THE GALILEO ORBITER SPACECRAFT*

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The Galileo Orbiter spacecraft carries nine scientific instruments, all but one of which are controlled by individual microprocessors. Scientific investigations include interplanetary measurements of charged atomic particles, magnetic and electric fields, and dust. In orbit, Galileo will investigate Jupiter's magnetosphere and atmosphere, and surface properties of the four largest satellites. Launch is scheduled for early in 1984.

While the complexity of the instruments and their data systems varies widely, all utilize components from the RCA 1800 microprocessor family, and all perform the same basic functions. The decisions to utilize microprocessors in the instruments were heavily influenced by the spacecraft distributed Command and Data System (CDS) design which uses this same LSI family.

A typical instrument data system consists of a microprocessor, 3K Bytes of Read Only Memory (ROM) and 3K Bytes of Random Access Memory (RAM). It interfaces with the spacecraft data bus through an isolated user interface with a direct memory access bus adapter. Microprocessor control and data lines provide interrupts, serial, and/or parallel data from instrument devices such as registers, buffers, analog to digital converters, multiplexers, and solid state sensors. These data systems support the spacecraft hardware and software communication protocol, decode and process instrument commands, generate continuous instrument operating modes, control the instrument mechanisms, acquire, process, format, and output instrument science data.

The approach has resulted in many specific improvements over past missions. Some of the most important include: increased instrument autonomy, functional commanding, and macro mode generation; enhanced telemetry output from both operational and scientific points-of-view; and additional flexibility for in-flight optimization, problem work-arounds, and instrument generalization for support of multiple missions.

There was a significant but manageable underscoping of the microprocessor development tasks and costs. This was related to difficulty in establishing firm requirements at an early date, interfacing complexity, parts acquisition problems, and a general lack of extensive experience in microprocessor hardware and software design.

While the Galileo entry-level introduction into instrument microprocessor appears to be proceeding well, additional effort is needed for standard use of microprocessors in science instruments to achieve a significant part of its high potential benefit. This includes generation and clarification of spacecraft system level requirements in concert with the objectives of the end-to-end information system design, improved use of microprocessor development tools and practices, and justification for increased instrument funding compatible with the increase in capability and cost.

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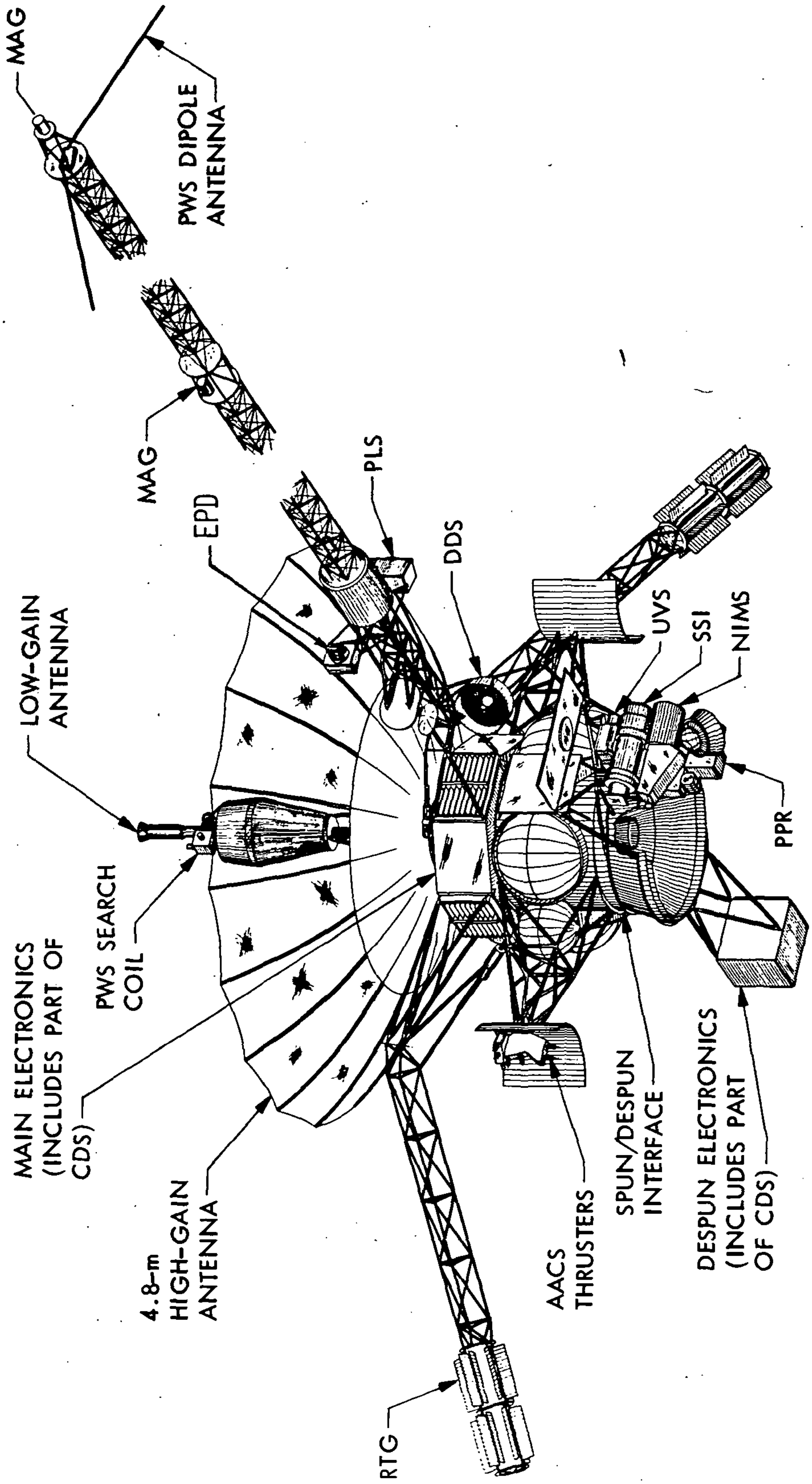
MAG
PWS DIPOLE ANTENNA
MAG
PLS
EPD
DDS
LOW-GAIN ANTENNA
UVS
SSI
NIMS
PPR
PWS SEARCH COIL
MAIN ELECTRONICS (INCLUDES PART OF CDS)
4.8-m HIGH-GAIN ANTENNA
AACS THRUSTERS
SPUN/DESPUN INTERFACE
DESPUN ELECTRONICS (INCLUDES PART OF CDS)
RTG

INTRODUCTION

- HISTORICAL ASPECTS OF INSTRUMENTS ON JPL SPACECRAFT
  - INCREASING COMPLEXITY
  - HIGHLY INTEGRATED SPACECRAFT
  - HIGHLY INTEGRATED MISSION OPERATIONS & FLIGHT TEAM
  - EXTENSIVE DATA PROCESSING & CORRELATION THE NORM
- WHAT ROLE DO INSTRUMENT MICROPROCESSORS PLAY IN THIS?
  - NOT A DRAMATIC CHANGE, A NATURAL EVOLUTION
  - VERY FLEXIBLE, EXPANDABLE CONCEPT
  - GALILEO IS THE STARTING POINT
- LIMITATIONS OF THIS PRESENTATION
  - RESTRICTED TO A HIGH-LEVEL, BRIEF REVIEW
  - TIME RESTRICTIONS FORCE GENERALIZATION
    - ACCENTUATE COMMON ELEMENTS
    - LITTLE DISCUSSION OF UNIQUE IMPLEMENTATIONS

MATERIAL TO BE COVERED

- REASONS FOR USE OF MICROPROCESSOR-BASED DATA SYSTEMS IN THE INSTRUMENTS
- FUNCTIONS PERFORMED BY THE μPs
- SUMMARY OF THE INSTRUMENTS
- SELECTED HIGHLIGHTS FROM THE GALILEO APPLICATIONS
- PROBLEM AREAS ENCOUNTERED
- EVALUATION OF THE GALILEO APPROACH

WHY USE MICROPROCESSORS IN THE GALILEO INSTRUMENTS?

- SUPPORT THE GENERALIZED SPACECRAFT SYSTEM INTERFACE (BUS)
- PROVIDE INCREASED INSTRUMENT AUTONOMY
  - REDUCE REQUIREMENT FOR SPACECRAFT SERVICES
  - INCREASE INSTRUMENT DESIGN CONTROL
- UTILIZE SEMICONDUCTOR INDUSTRY ADVANCES
  - AVAILABLE, PROVEN LSI PRODUCTS (RCA CDP1800 SERIES)
  - DECREASE POWER AND MASS REQUIREMENTS (CMOS LSI)
  - INCREASE RELIABILITY (REDUCE PARTS COUNT)
  - SIMPLIFY DESIGN (REPLACE DISCRETE, MSI LOGIC)
- EXTEND INSTRUMENT CAPABILITY (FALLOUT, NOT A REQUIREMENT)
  - ADD FLEXIBILITY TO ACCOMODATE CHANGING REQUIREMENTS (SOFTWARE)
  - PROVIDE ENHANCED MODE GENERATION AND CONTROL (MINIMAL H/W)
  - GENERALIZE INSTRUMENT
    - MODIFY OR UPGRADE FOR FUTURE USE ON OTHER SPACECRAFT

INSTRUMENT DATA SYSTEM FUNCTIONS

- SUPPORT SPACECRAFT INTERCOMMUNICATION BUS AND PROTOCOL
- DECODE AND PROCESS INSTRUMENT COMMANDS
- GENERATE INSTRUMENT OPERATING MODES
- CONTROL MECHANISMS
- PROCESS SCIENCE DATA FOR OUTPUT

DATA SYSTEM FUNCTIONS

- SUPPORT OF SPACECRAFT BUS AND PROTOCOL
  - SERIAL, SYNCHRONOUS DATA AT 403.2 KBPS
  - ISOLATED USER INTERFACES (TRANSFORMERS)
  - MEMORY TO MEMORY TRANSFER USING DIRECT MEMORY ACCESS
  - S/C COMMAND DATA SYSTEM (CDS) INITIATES AND CONTROLS ALL ACTIVITY ON A TIME MULTIPLEXED BASIS

- DECODING AND PROCESSING OF INSTRUMENT COMMANDS
  - ACCOMODATE VARIOUS INPUT DATA
    - COMMANDS
    - MEMORY LOAD
    - S/C TIME AND SPIN DATA
  - PROCESS COMMANDS
    - ERROR CHECKING & VALIDATION
    - UPDATE OF INSTRUMENT STATE DATA

DATA SYSTEM FUNCTIONS (CONT'D)

- GENERATION OF INSTRUMENT OPERATIONAL MODES
  - ALLOW FUNCTIONAL LEVEL COMMANDING (TYPICALLY 3 TO 8 MAJOR MODES)
  - REDUCE INTER-SUBSYSTEM COMMUNICATION
  - SYNCHRONIZE WITH SPACECRAFT TIMING
  - PROVIDE MORE MODE GENERATION FLEXIBILITY TO THE INSTRUMENT

- MECHANISMS CONTROL FUNCTIONS (SENSORS, FILTER WHEELS, MULTIPLEXERS, ETC.)
  - SENSE MECHANISM STATUS
  - GENERATE CONTROL SIGNALS
  - ACQUIRE AND BUFFER DATA

- SCIENCE DATA PROCESSING
  - APPLY ALGORITHMS TO PROCESS DATA (COMPRESSION, STATISTICS, DE-SPIN, ETC.)
  - FORMAT DATA (CONTROL SUBCOMMUTATION, ADD ENGR & STATUS, ETC.)
  - OUTPUT TO BUS UPON REQUEST

INSTRUMENT SUMMARY

ABBR.	NAME	PRINCIPAL INVESTIGATOR	INSTITUTION
SSI	SOLID STATE IMAGING	DR. J.S. BELTON, (TEAM LEADER)	KIT PEAK NATIONAL OBSERVATORY, TUSCON, AZ
NIMS	NEAR INFRARED MAPPING SPECTROMETER	DR. R. CARLTON, (TEAM LEADER)	JET PROPULSION LABORATORY, PASADENA, CA
PPR	PHOTOPOLARIMETER RADIOMETER	DR. J.E. HANSEN	GODDARD INSTITUTE FOR SPACE STUDIES, NEW YORK, NY
UVS	ULTRAVIOLET SPECTROMETER	DR. C.W. HORD	LABORATORY FOR ATMOSPHERIC AND SPACE PHYSICS, BOULDER, CO
EPD	ENERGETIC PARTICLE DETECTOR	DR. D.J. WILLIAMS	NOAA SPACE ENVIRONMENT LABORATORY, BOULDER, CO
PLS	PLASMA SUBSYSTEM	DR. L.A. FRANK	UNIVERSITY OF IOWA, IOWA CITY, IOWA
MAG	MAGNETOMETER	DR. M. KIVELSON	UCLA LOS ANGELES, CA
DDS	DUST DETECTOR SUBSYSTEM	DR. EBERHARD GRÜN	MAX PLANCK INSTITUT FÜR KERNPHYSIC, HEIDELBURG, WEST GERMANY
PWS	PLASMA WAVE SUBSYSTEM (NO µP)	DR. D.A. GURNETT	UNIVERSITY OF IOWA, IOWA CITY, IOWA

INSTRUMENT COMPLEXITY COMPARISON

INST	ROM KBYTE	RAM KBYTE	TELM DATA (KBPS)	DATA MODES	NO COMMAND PARMS.	NO MECHANISMS	NO SENSORS	MASS (KG)	PWR (WATT)
SSI	3	3.5	768. TO 0.02	3	24	9	800 x 800 CCD	28.0	25.
NIMS	3	1.75	11.52	6	31	9	17	18.1	16.
PPR	4	0.25	0.18	5	12	10	3	4.3	12.
UVS	--	0.75	1.0	3	20	6	3	4.2	4.5
EPD-1	4	2.66	0.92	15	150	50	17	8.5	8.6
EPD-2	2	0.25	--	--	50	3	--	(INCL ABOVE)	
PLS-1	4	4	0.6	7	140	31	20	10.7	9.5
PLS-2	(SAME AS PLS-1)								
DDS	3	2	.024	3	33	9	4	4.0	1.8
PWS (NO µP)	--	0.25	645. TO 0.2	2	7	11	3	5.3	5.6

INSTRUMENT DATA SYSTEM HIGHLIGHTS
(SELECTED FROM AMONG THE EIGHT INSTRUMENTS)

1) FUNCTIONAL COMMANDING AND MACRO MODE GENERATION

2) TASK ALLOCATION BETWEEN MICROPROCESSOR AND OTHER INSTRUMENT HARDWARE

- HIGH RATE DATA TRANSMISSION
- SPECIALIZED PROCESSORS (FORMATTERS, MULTIPLIER, ENCODER/COMPRESSOR, ETC.)
- SOFTWARE OVERALL CONTROL
- HYBRID INSTRUMENT OPERATION (WITH OR WITHOUT μP)

3) ENHANCED DATA ACQUISITION & TELEMETRY OUTPUT

- SUBSYSTEM UNIFORMITY
- ADDED ENGINEERING VISIBILITY (SPECIAL HIGH-RATE MODES, SUBCOMS, ETC.)
- SOME ADDITIONAL ON-BOARD PROCESSING & BUFFERING (DATA DISCRIMINATION, DATA SEARCH, OPTIMUM AVERAGING, COMPRESSION, ETC.)

4) MEMORY RE-ALLOCATION AND REPROGRAMMABILITY FOR SCIENCE MODE OPTIMIZATION AND RESPONSE TO SUBSYSTEM OR SPACECRAFT FAILURES

- RAM MARGIN
- RAM REPLACEMENT OF ROM VIA BUS COMMAND
- ROM LINKAGES TO RAM FOR SUBROUTINE REPLACEMENT

INSTRUMENT DATA SYSTEM HIGHLIGHTS (CONT'D)

5) HIGHLY FLEXIBLE APPROACH

- ALLOWS SUBSYSTEM OPTIMIZATION
- WIDE RANGE OF DATA RATES
- 8 UNIQUE DESIGNS

6) CLEAR BENEFIT IN LOGIC REPLACEMENT OBSERVED

7) ADVANCED DATA SYSTEM TECHNIQUES

- MULTIPLE MICROPROCESSORS
- POWER HSARING, FAILURE ISOLATION
- AUTO-CALIBRATION
- BACKGROUND PROCESSING, HIGH LEVEL LANGUAGE (FORTH)

8) COMPATABLE WITH LONG-RANGE DEEP SPACE EXPLORATION DESIGNS AND GOALS

- PACKET TELEMETRY
- ADDED AUTONOMY
- EEIS

PROBLEM AREAS ENCOUNTERED

1) HARDWARE DESIGN LIMITATIONS AND CONSTRAINTS
   - SPACECRAFT MASS, POWER, AND RELIABILITY REQUIREMENTS
     - LIMITED OPTIONS IN μP AND CHIP FAMILY SELECTION (1802, 1852, 1856, 1834, TC244)
     - LIMITED MEMORY SIZE (RAM IS 256 x 4 BITS)
   - JUPITER MISSION REQUIRED HIGH RADIATION TOLERANCE
     - PARTS DEVELOPMENT AND ACQUISITION PROBLEMS
     - CAUSED INCREASED COST, SCHEDULE PROBLEMS

2) USE OF READ ONLY MEMORY (ROM) AS PRIMARY PROGRAM MEMORY
   - INCREASED COSTS AND SCHEDULING PROBLEMS
   - DECREASED FLEXIBILITY
   - INCREASED NEED FOR EARLY SYSTEM-LEVEL VALIDATION

3) UNDERSCOPING OF MICROPROCESSOR DEVELOPMENT TASKS AND COSTS
   - SOFTWARE, SOFTWARE MANAGEMENT AND DOCUMENTATION
   - DEVELOPMENT SYSTEMS AND SUPPORT EQUIPMENT
   - INTERFACE REQUIREMENTS STABILITY
   - ADDED TESTING COMPLEXITY

PROBLEM AREAS ENCOUNTERED (CONT'D)

4) BUS DESIGN
   - BUS ADAPTER COMPLEXITY
   - LOW ERROR REQUIREMENT
   - OPEN-LOOP PROTOCOL (NO HANDSHAKE)

5) SYSTEM LEVEL REQUIREMENT IMMATURITY
   - END-TO-END INFORMATION SYSTEM (EEIS) GOALS REDUCED
   - EARLY INTERFACE REQUIREMENT STABILITY AND DETAILED DESCRIPTION

6) PERSONNEL EXPERIENCE AND TRAINING
   - μP
   - SOFTWARE

EVALUATION OF THE GALILEO APPROACH

- CURRENT STATUS
  - MOST INSTRUMENTS HAVE AN OPERATIONAL BREADBOARD DATA SYSTEM NOW
  - EXPECT ON-TIME DELIVERY OF ADVERTISED CAPABILITY
- EXPECT TO SIGNIFICANTLY ENHANCE THE SCIENCE VALUE OF THE MISSION
  - EACH INSTRUMENT PROVIDES SCIENCE OPTIMIZATION FOR ITS INVESTIGATORS
  - EACH HAS PROVIDED FOR INCREASED IN-FLIGHT FLEXIBILITY
- ADDITIONAL EFFORT MUST BE EXPENDED TO SOLVE PROBLEMS ASSOCIATED WITH:
  - SYSTEM REQUIREMENTS DEFINITION
  - IMPROVED USE OF MICROPROCESSOR DEVELOPMENT TOOLS
  - FUNDING CONSISTENT WITH THE ENHANCED CAPABILITY AND COST

FUTURE PROJECTIONS

- TECHNOLOGY IMPROVEMENT
  - SEMICONDUCTOR TECHNOLOGY (ADVANCED μP, DENSE MEMORY, HIGHER SPPED, ETC.)
  - ADVANCED ARCHITECTURE AND SOFTWARE DESIGN (MULTIPLE MICROPROCESSORS, HIGH LEVEL LANGUAGES, ETC.)
- APPLICATION ADVANCES
  - INSTRUMENT AUTONOMY
  - HIGHLY FUNCTIONAL COMMANDING
  - EXTENSIVE ON-BOARD PROCESSING (ESPECIALLY FRONT-END APPLICATIONS)