Stanford University

LOCKHEED MARTIN

Gravity Probe B Relativity Mission

Gyroscope Suspension System (GSS) Critical Design Review

Part 1: Presentation Viewgraphs

23 October 1997
HEPL Conference Room, 8:30am - 5:00pm
Stanford University

GSS Critical Design Review (CDR)

23 October 1997 • HEPL Conference Room, 8:30am - 4:30pm

	Subject	Presenter	Time
	Breakfast		8:20
1.	Introduction	Bencze	8:30
2.	GSS Personnel	Bencze	8:50
3.	Requirements Review	Bencze	9:00
4.	PDR Action Item Review	Bencze	9:30
5.	GSS Development Flow	Bencze	9:40
6.	System Development Status	Gutt	10:00
6.1	Control System	Eglington, Irwin	10:20
6.2	Analog Design Status	Irwin	11:00
6.3	Digital Design Status	Lassa	11:40
	Lunch		12:00
7.	Flight System Development	Manner	13:00
7.1	Power Supply	Battel	13:40
7.2	Flight S/W	Larsen, Lassa	14:00
8.	Interfaces	Cliff	14:20
9.	Testing and Verification	Brumley, DiCarlo	14:40
10.	Reliability/FMECA	Pullen	15:30
11.	Quality Assurance	Pullen	15:50
12.	Schedule & Resources	Bencze	16:10
13.	CDR Action Item Review	Bencze	16:30

The GP-B Gyro Suspension System (GSS) Team

October, 1997

Name	Role:	Affiliation:	Phone:	Office:
Sasha Buchman	Gyroscope System IPT Leader	Stanford	5-4110	Trailer
William Bencze	GSS Co-manager, system RE	Stanford	5-5691	HEPL 187
Prototype Engineering Team:				
Greg Gutt	GSS Co-manager, EU lead	Stanford	3-8213	HEPL 188
Paul Lassa	Digital systems lead engineer	Stanford	3-0854	HEPL 186
Michael Eglington	Control system architect	SU, Ph.D. student	3-9791	HEPL 194
Steve Larsen	Software lead engineer/guru	LMMS	3-6389	HELP 198
Scot Sulak	Software engineer	LMMS	3-8643	HELP 198
Jen-Nan Lay	Software engineer (Ops)	LMMS	5-9274	HEPL 190
Lawerence Goslinowski	Electronics technician	LMMS	3-4726	ESIII Lab
Michael Irwin	Analog system lead engineer	Stanford	5-2224	HEPL 186
Jay Dusenbury	Analog design engineer	LMMS	5-6351	HEPL 200
Christy Hartsell	Electronics technician	LMMS	3-4108	ESIII Lab
Flight Design team:				
Dave Manner	GSS Co-manager, FU lead	LMMS	3-6174	HEPL 187
Rodger Cliff	Senior system engineer	LMMS (50%)	3-8684	HEPL 195
Russ Tavernetti	Analog designer	Consultant (100%)	5-6349	HEPL 198
Jim Fitzpatrick	EMI/Power systems engineer	Consultant (50%)	5-9378	HEPL 201
Rich Matsui	FU design support engineer	LMMS (40%)	5-2213	HEPL 199
Son Tran	Electronics technician	Stanford	3-5733	ESIII Lab
Test and Verification team:				
Rob Brumley	Test and Verification Lead	Stanford	5-2221	HEPL 185
Leo DiCarlo	Electronics engineer	SU, Grad student	5-9256	HEPL 185
Howard Straus	Software engineer	Consultant (100%)	5-9274	HEPL 190
GSE/DDC Team:				
Yongming Xiong	GSE Lead engineer	Stanford	5-9212	HEPL 200
Lo Van Ho	Electronics technician	Stanford	5-2214	HEPL 125

GSS CDR Overview

Scope of Presentation:

- Overview of team goals and organization.
- Requirements applicable to the GSS.
- Review of the GSS prototype design.
  - Control scheme.
  - Hardware.
  - Software.
- Flight unit development status.
  - Hardware and software.
  - Definition of interfaces to the remainder of the spacecraft.
- Performance verification and testing.
  - Requirements flowdown and verification plans.
  - The GSS testbed: capabilities and verification and testing goals.
- Reliability assessment and quality assurance plans.
- Development schedule and resource issues.

The GSS Development Philosophy

1. **Science Mission operation compatibility is paramount.**
    - Designs start with Science Mission performance as the highest priority.
    - Compromises are made in favor of Science Mission performance over other operational modes (for example, ground test).

2. **Rigorously test the design before flight.**
    - Develop a ***GSS Testbed*** (hardware and procedures) to:
        1. Confirm performance of position control system from 10^{-7} g to 1 g under the full set of environmental disturbances.
        2. Demonstrate that the GSS *as built* meets Science Mission torque requirements.

3. **Flight-upgradeable design.**
    - No aspect of the preliminary design will make use of circuits/technology that is fundamentally incompatible with a flight-worthy replacement.

GSS Accomplishments Since PDR

1. **Suspension line shields driven to Tophat**
   - Simple, stable design eliminates thermally induced cable capacitance variations.

2. **GFAB (GSS Forward/Aft Bus) fully functional.**
   - Meets all data communication needs with minimal digital noise.

3. **Arbiter prototype complete.**
   - Tests demonstrate that analog controller arbitration scheme is effective.

4. **Testbed faithfully simulates a gyroscope in 1g.**
   - Testbed "lifts" with standard DDC system and flight prototype electronics.

5. **1g lift with RAD6000 is imminent.**
   - Agressive scrubbing of control code squeezes high bandwidth performance out of flight prototype computer.

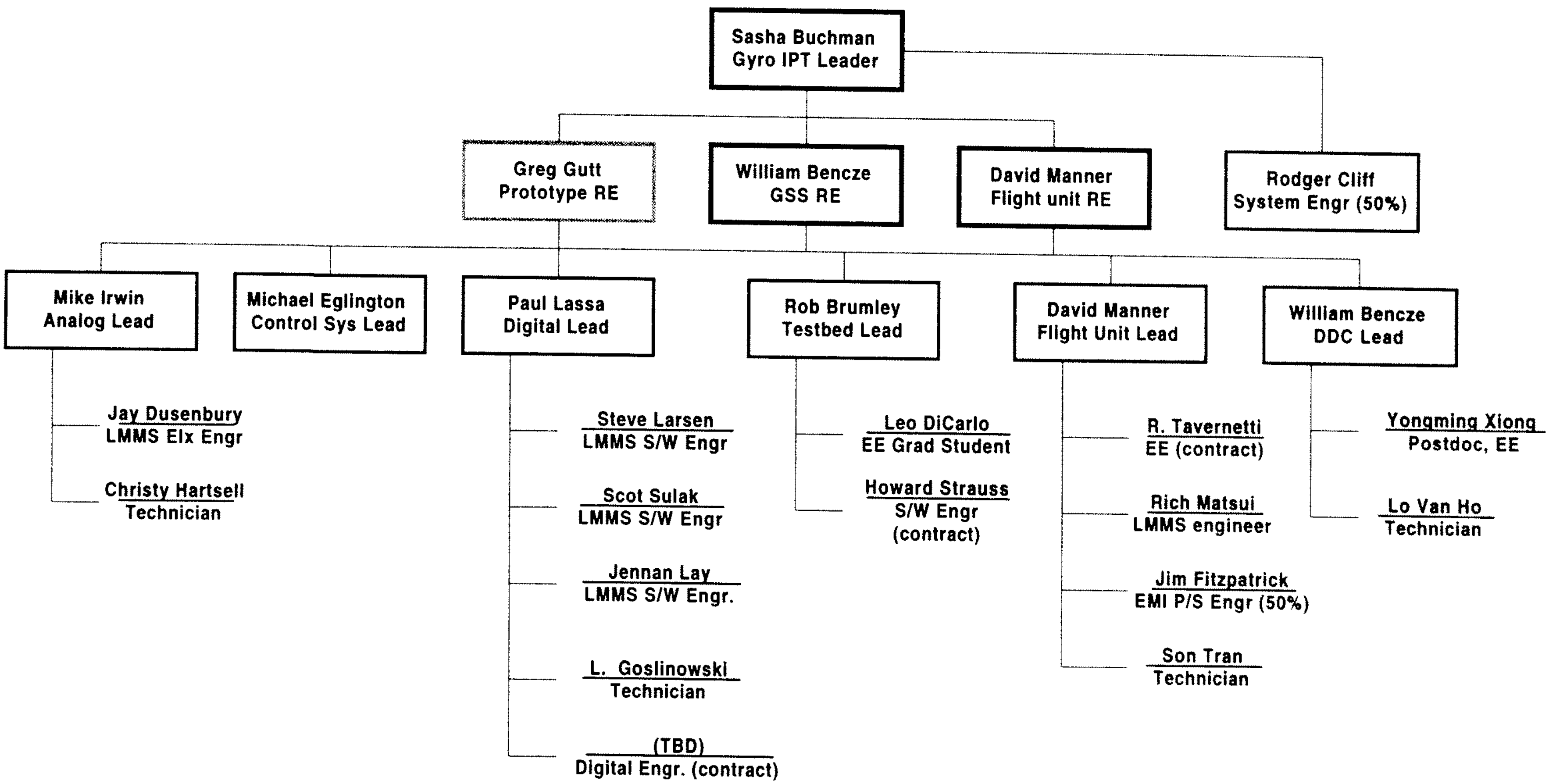
GSS Accomplishments (Cont.)

6. **1G version of BWOD (B/W on Demand) controller functional.**
   - Reacts to laboratory-induced "micrometeoroid" strikes by slewing B/W.
7. **GTU-2 EMC tests successful**
   - Used flight prototype electronics, cables, filters, excitation levels.
   - Generated no significant SQUID interference running a simulated Science Mission drive voltage set.
8. **Flight unit enclosure scheme finalized.**
   - Partitions and aggressively shields EMI sources.
9. **Flight power supply system prototype complete, in test.**
   - Flight deliveries to start in April 1998.

2. GSS Personnel

William Bencze

The GSS Team


Sasha Buchman
Gyro IPT Leader
Greg Gutt
Prototype RE
William Bencze
GSS RE
David Manner
Flight unit RE
Rodger Cliff
System Engr (50%)
Mike Irwin
Analog Lead
Michael Eglington
Control Sys Lead
Paul Lassa
Digital Lead
Rob Brumley
Testbed Lead
David Manner
Flight Unit Lead
William Bencze
DDC Lead
Jay Dusenbury
LMMS Elx Engr
Christy Hartsell
Technician
Steve Larsen
LMMS S/W Engr
Scot Sulak
LMMS S/W Engr
Jennan Lay
LMMS S/W Engr.
L. Goslinowski
Technician
(TBD)
Digital Engr. (contract)
Leo DiCarlo
EE Grad Student
Howard Strauss
S/W Engr
(contract)
R. Tavernetti
EE (contract)
Rich Matsui
LMMS engineer
Jim Fitzpatrick
EMI P/S Engr (50%)
Son Tran
Technician
Yongming Xiong
Postdoc, EE
Lo Van Ho
Technician

Consultants and Offsite Resources

1. **Prof. Gene Franklin**	Automatic control systems.
2. **Prof. Dan DeBra**	Automatic controls, precision design.
3. **Steve Battel** *Battel Engineering*	GSS power system design, flight design issues consulting.
4. **Danny Gross**	Rapid PC board design and fab.

3. Top-Level Requirements Review

William Bencze

Fundamental GSS Requirements

Primary Function: Suspend gyroscope in its housing.

- The gyroscope is a nonlinear, multi-input/multi-output (MIMO) system.
- Gyroscope system is open-loop unstable.
- High dynamic range needed; forces must span 8 orders of magnitude.

Design drivers:

1. Science Mission support.
2. High reliability:
   - Must operate through computer failures.
   - Robust to micrometeoroid impacts.
   - Immune to on-orbit radiation and thermal environment.
3. Testability:
   - Science Mission type performance must be verifiable on the ground.
   - Entire system (flight computer + S/W + H/W) testable "on the pad" w/o GSE.

GSS Compatibility Requirements

1. **Science Mission compatible.**
   - Minimize suspension torques on the gyroscope.
   - Provide data for Science Mission measurements.
   - Support calibration and initialization operations (spin up, torque enhancement, etc.)

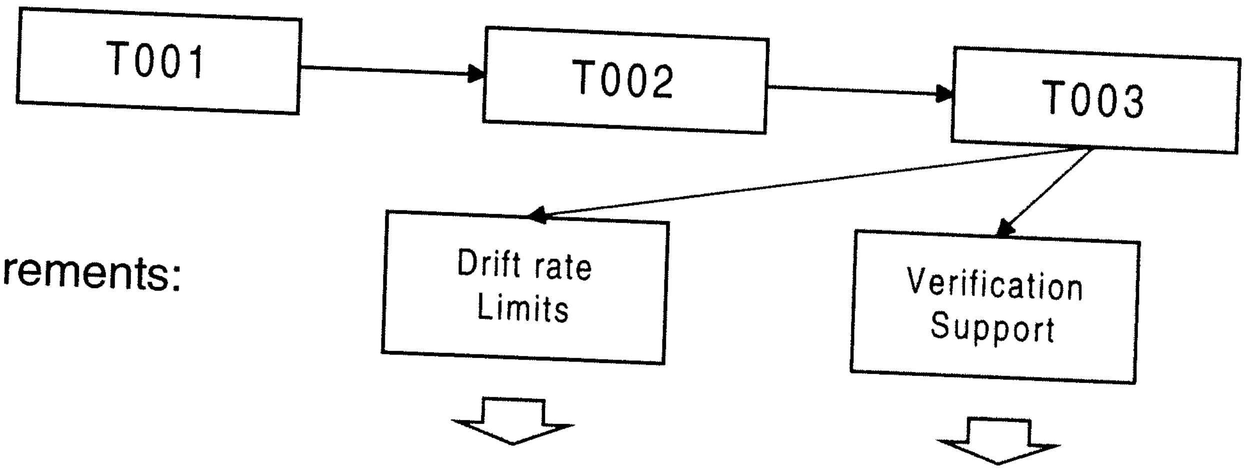
2. **SQUID compatibility.**
   - Do not generate EMI which interferes with SQUID operation.

3. **ATC support.**
   - Provide drag-free suspension mode for each gyroscope.
   - Supply the gyroscope position sense measurements to the drag-free controller.

Science Mission Requirements Overview

GP-B Mission Requirements:

GSS Subsystem Requirements:



Requirements on:

Drift rate Limits	Verification Support
• Electrode voltage variations. • Rotor miscentering. • Rotor charge control.	• Suspension data (position, etc.) • Commandable preload • Commandable rotor position.

Verified via:

Drift rate Limits	Verification Support
• Direct measurements. • Testbed simulation. • Analysis	• Direct test. • Testbed simulation.

T003-Derived Drift Rate Requirements for GSS

T003 Req.	Name	Requirement
2.2	Voltage Applied to Electrodes, $S_i = V_{i+}^2 + V_{i-}^2$	-
2.2.1	Average Value of S_i on any axis (year average)	< 0.08 $Volts^2$
2.2.2	Average difference between S_i on different axes(year average)	< 0.04 $Volts^2$
2.2.3	Variation in mismatch of S_i along different axes	-
2.2.3.1	Roll frequency variation of S_i on a and b axes (year average)	< 1.7×10^{-6} $Volts^2$
2.2.3.2	Random variation of mismatch of at roll +/- orbit	< 1.6×10^{-3} $Volts^2$ /rt(Hz)
2.2.4	Roll frequency variation in S_i along any axis (year average)	< 1.7×10^{-5} $Volts^2$
2.2.5	2 x roll frequency variation in S_i along any axis (year average)	< 1.7×10^{-5} $Volts^2$
2.3	Rotor Centering Accuracy (capacitive center)	-
2.3.1	Random rotor miscentering at roll	<1.4 μm/rt(Hz)
2.3.2	Zero frequency miscentering	< 0.6 μm
2.3.3	Sinusoidal miscentering	-
2.3.3.1	Sinusoidal miscentering at roll	< 0.3 nm
2.3.3.2	Sinusoidal miscentering at roll modulated by annual	< 1.0 nm
2.3.3.3	Sinusoidal miscentering at roll twice orbital	< 3 nm
2.4	Rotor charge measurement	Supported for 2.5
2.5	Rotor charge management	-
2.5.1	Rotor charge	< 15 pc (15 mv)
2.5.2	Induced rotor potential (wrt ground planes)	< 15 mv

SQUID Readout Compatibility 1

T-003, 2.7: Suspension Electrical Interface:

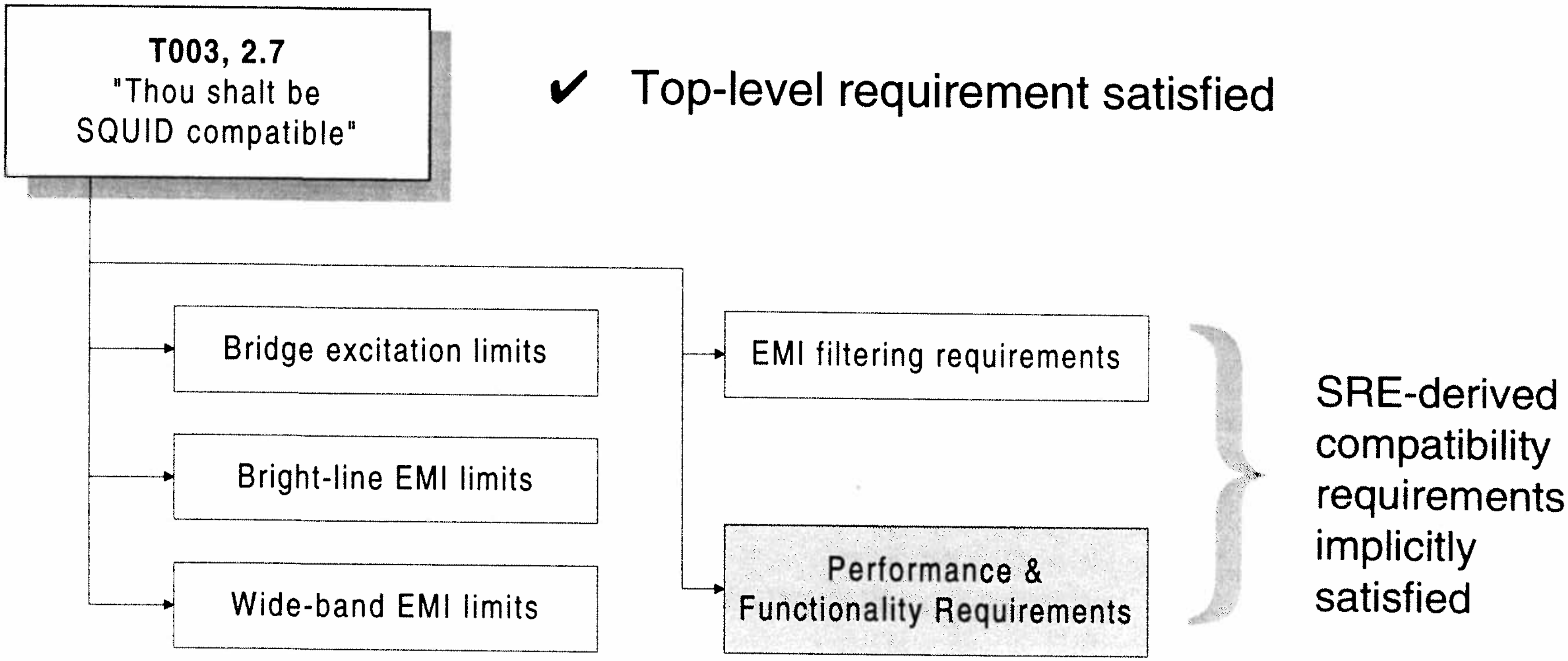
The [GSS] EMI coupled to the SQUID readout system under science data acquisiton conditions shall not cause violation of the readout resolution and noise requirements... This will be verified in ground test by operating the suspension bridge and control effort at science levels.

Test Operations in GTU-2 (consistent with T-003, Sec 2.7)

- Science mission bridge, 40 mv, 35 kHz
- Science drive amplifiers.
- Driven suspension cables.
- 20 Hz modulation scheme active.
- Bridge-noise derived suspension drive noise included.
- On-orbit like suspension drive signals injected.

SQUID Readout Compatibility 2

GTU-2 tests show full compatibility of SQUID/SRE with GSS system, to the limits of measurements made.



Detailed SQUID Compatibility Req'ts (review)

1. **GSS position sense and forcing outputs must be consistent with "Allowable Suspension Voltage" plot:**
   - This can be stated as:

     $V_{pp}(mV) < 10^5/f^2$ for f (in kHz) < 100 kHz

     $V_{pp}(mV) < 500/f$ for f (in kHz) >= 100 kHz
   - At a 35 kHz bridge frequency, this corresponds to a 80 mV p-p excitation

2. **Electrode currents near roll, spin, or calibration frequencies, or near spin frequency harmonics 2-6 must satisfy the following:**
   - Current at $f=f_{roll}$ +/- 1.5 mHz: < 1 pAp-p
   - Current at $f=nf_{spin}$ +/- 6 mHz: < 200 pAp-p for n = 3,5
   - Current at $f=nf_{spin}$ +/- 6 mHz: < 1 pAp-p for n = 2,4
   - Current at $f= f_{LM\ cal}$ +/- 1.5 mHz: < 1 pAp-p for $f_{LM\ cal}$ = 8 mHz
   - Current at $f= f_{HF\ cal}$ +/- 6 mHz: < 10 pAp-p for $f_{HF\ cal}$ = 110 Hz

Detailed SQUID Compatibility Req'ts (review)

3. **Electrode currents at other frequencies f must satisfy:**
   - Current < 50 nA p-p for f < 2 kHz
   - Current <100 μA-Hz/f p-p for f > 2 kHz

4. **No spurious signal in the frequency range 0 - 1 GHz on any conductor which connects to the probe shall be < 50 μVrms (measured prior to tophat filtering)**

5. **Each conductor which enters the probe shall be filtered with a low pass filter having a slope of -40 dB/decade, a -3dB frequency of < 1 MHz, and a stopband extending to at least 10 GHz**

6. **Readout Related GSS Performance Requirements**
   - Bridge excitation amplitude variation at f_{roll} +/- 1.5 mHz: < 0.1 %
   - Position modulation capability at 0.1 Hz: < +/- 5 μm from center
   - Position noise: < 300 nm/$Hz^{0.5}$
   - Position variation at f_{roll} +/- $2f_{orbit}$ in 0.5 year band: < 3 nm

ATC Data Requirements

1. **Drag-free sensor (GSS bridge on drag-free gyroscope)**
   - ✔ Filtering: Second-order low-pass,5 Hz, $\zeta = 0.5$.
   - ✔ Noise: < 1.5 nm/√Hz (one-sided).
   - ✔ Overall nonlinearity: < 6%.
   - ✔ Quantization: < 1nm.
   - ✔ Latency: 0.4 msec after 10 Hz ATC strobe.

2. **The drag-free bias shall have a maximum range of 15 mN (5×10^{-7} g)**
   - ✔ Interface to controller available via 1553 10 Hz command packet.

ATC Interface Requirements

1. **Required data at 10 Hz in ATC 1553 packet:**
   - ✔ Position from drag-free sensor.
   - ✔ Drag-free status of all gyros.
2. **Inputs at 10 Hz in GSS 1553 command packet:**
   - ✔ Bias force for orbit trim to drag-free sensor.
   - ✔ Charge control carrier.
   - ✔ Charge control bias.
3. **Commands**
   - ✔ Enable-drag free command/resume suspension to each gyro.

All ATC requirements fully suppored

4. PDR Action Item Review

William Bencze

PDR Action Items 1

	Action item:	Action by:	Assignee:	Disposition:	Status:
1	When will a revised GSS requirements document be available?	B. Parkinson	B. Bencze, R. Brumley	Available at CDR; box and board specifications in work.	**OPEN, In work**
2	Reexamine the use of SG3 and SG4 as possible drag free sensors.	J. Kasdin	GSS	Baseline changed to allow any gyroscope to act as proof mass.	Closed
3	How much margin does the control system have with a 1 kg-m/s micrometeoroid impact?		M. Eglington	At 30v maximum control authority in SM drive amplifier, there is essentially no margin above a worst-case 1 kg-m/s micrometeoroid impact	Closed
4	Examine driven shield stability requirements.		M. Irwin, G. Gutt	Inner shield driven by excitation signal (no bootstrapping). Amp stability not an issue.	Closed
5	What are the specifications on the GSS cable/tophat EMI filters?		B. Bencze, G. Gutt	First-order low pass filter found to satisfy SQUID interference requirements. Baseline in place.	Closed
6	ICD signoff, mid April 1997 target		R. Cliff	ICD revision 2 available at CDR.	Closed
7	Consequences of a SRE 10 Hz loss.		R. Cliff, S. Larsen	Unreliable communication with CCCA; no 1553 sync. Will compromise science data from that gyroscope. Safe mode may be required	Closed

PDR Action Items 2

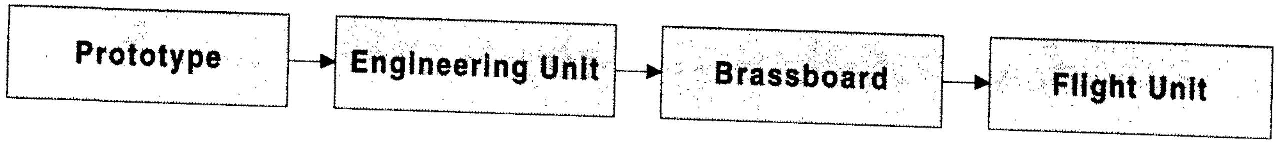
	Action item:	Action by:	Assignee:	Disposition:	Status:
8	What is the orientation of boxes and power flow to minimize noise.		D. Manner	Integrated box and power filtering scheme in place. Described at CDR	Closed
9	Converge on details of GSS boxing scheme		D. Manner, C. Mulberg	Forward and aft box designs nearing release. Details at CDR.	Closed
10	Location of boxes with respect to tophat connectors		D. Manner, C. Mulberg	Mechanical details defined. Forward box design nearing release. Details in CDR	Closed
11	Generate long lead parts list.		D. Manner	70% complete parts list generated; more detail in CDR	Closed
12	Redundancy on 600v spinup supply	G. Green	D. Manner	Addressed in current power system design	Closed
13	Temperature sensors near bridge?	G. Green	D. Manner	Temperature sensors part of flight unit baseline; exact locations TBD	**OPEN, In work**
14	Arbiter seems to lack redundancy and is too complex. Revisit design and examine these issues.	H. Dougherty	B. Bencze, G. Gutt, M. Irwin	Mode register triply redundant; arbiter designed to meet contingency needs. Description of design in CDR.	Closed

5. GSS Development Flow

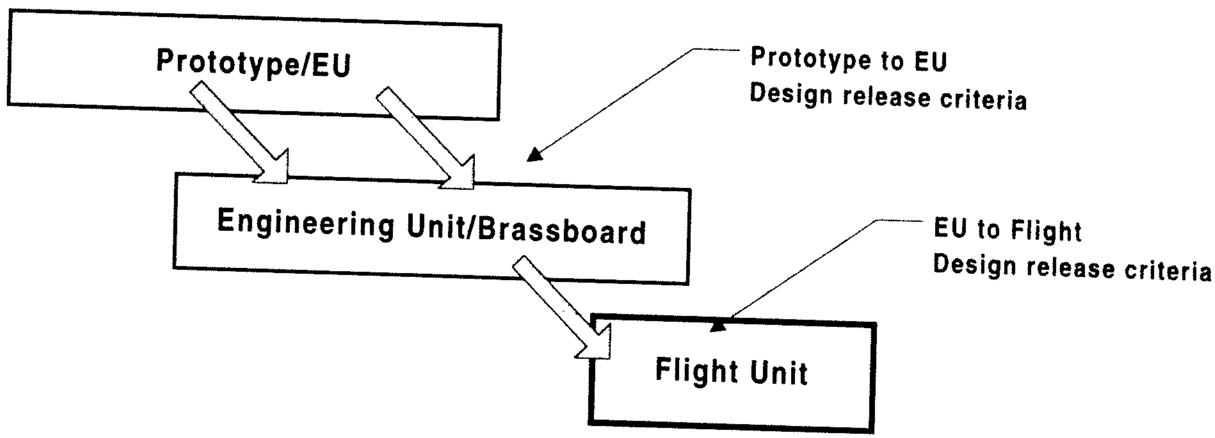
William Bencze

GSS Development Plan

Typical: 4 step, sequential system development flow:



GSS: 3 step, overlapped development flow:



Process designed to accelerate the development process by transitioning designs from prototype to EU to flight status as early as possible.

Prototype Design Release Criteria

Required for transition from prototype to EU design:

1. Design specification.
2. Interface definition.
3. Abbreviated test specification.
4. Complete design
   - Schematics
   - Printed circuit board (PCB)
5. Tested prototype.
6. Prototype release design review (GSS internal review).

Flight Unit Design Release Criteria

Required for transition from EU to Flight manufacture:

1. Design specification.
2. EU interface definition.
3. Acceptance test plan.
4. Complete design:
   - Schematics
   - Flight printed circuit board (PCB).
   - Flight parts scrub.
5. Tested EU prototype.
6. Measured power/weight/volume statistics.
7. Manufacturing Readiness Review (MRR).
   - PCB/Interconnect peer review.
   - Enclosure peer review.

Manufacturing and Test

1. **Manufacturing to be performed per LMMS plan.**
   - GSS version of GP-B wide manufacturing plan.
   - Discussed in more detail in Flight Unit section.
2. **Test and Verification performed under both LMMS and Stanford/GSS plans.**
   - LMMS to run Acceptance Test Plan (ATP) to verify design specifications during environmental test.
   - Performance Verification Plan.
     - Verify Science Mission performance of system on GSS Testbed, 1g gyroscope for flight unit.
   - Post-integration tests.
     - Check for SQUID EMC.
   - Post-space vehicle qualification.
     - Verify functionality of GSS after Thermal/Vacuum tests.

6. GSS Architecture & System Design

Gregory Gutt

GSS Primary Design Features

1. Full Testability

- 1G ground operation exercises all major subsystems.
- Embedded test points and connectors allow for extensive system monitoring during operation.

2. Ground / Flight Operation

- The EU allows for full operation in 1G as well as all SM modes.
- Provisions have been made to incorporate all backup systems as they become available.

3. Readout System Compatible Design

- Extensive testing in GTU-2 confirms readout compatible design within the resolution of the experiment.
- Low frequency forcing signals are AC coupled and modulated at 20Hz to prevent interference at roll (and to mitigate temperature induced drift).
- The 30kHz 40mVpp SM bridge excitation signal better than spec. by a factor of 2.

GSS Primary Design Features

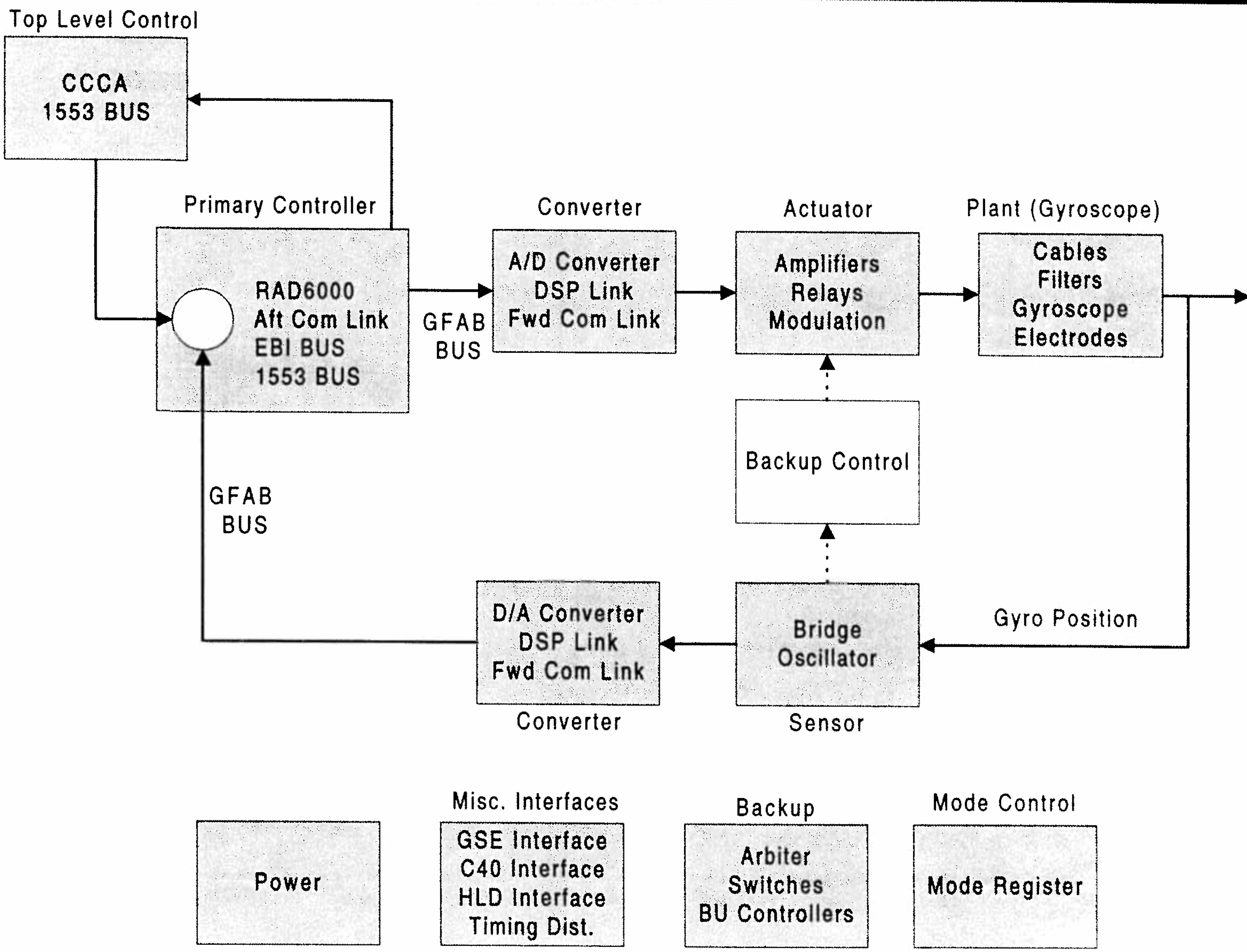
4. Fore / Aft Partitioning

- EMI generators (computers / clocks etc.) in the Aft system.
- Low noise analog electronics (bridge etc.) and specially designed low frequency digital systems (A/D D/A) are located forward.
- All frequency signals are derived from $16f_0$ signal from SRE that interfaces with the Aft GSS. Forward frequency references can free-run in the event of computer or bus failure.

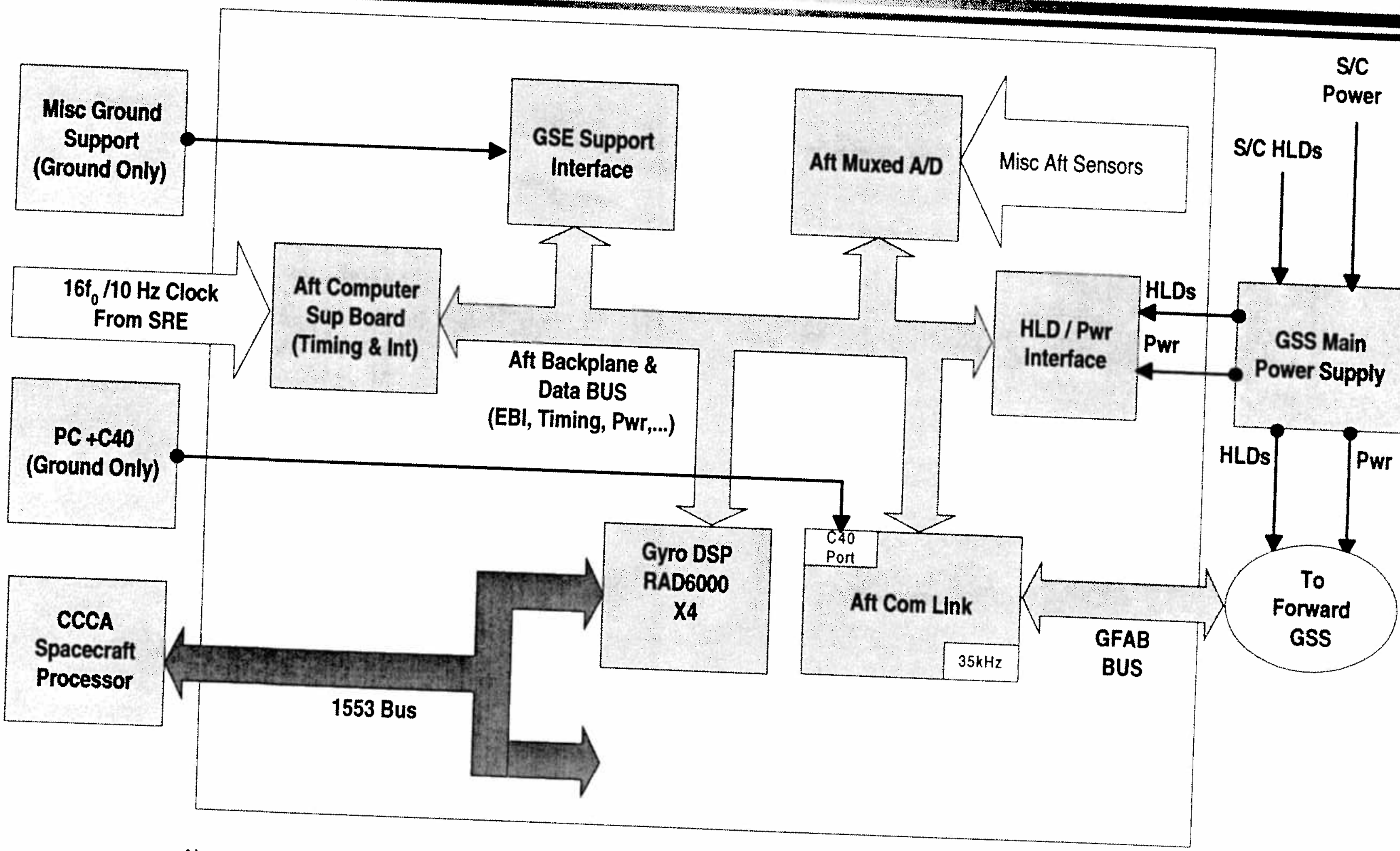
5. Top Level Control Scheme

- Two primary controllers:
  - Science Mission Adaptive Authority (high performance, digital)
  - Spin-Up Fixed Authority (robust, digital)
- Three backup controllers
  - Science Mission Low Backup (preserves science, low torque, analog)
  - Science Mission High Backup (for micro meteorites etc., analog)
  - Spin-Up Backup (prevents gyro crash during SU/SA, analog)
- 1G Mode for Ground Testing (high bandwidth, digital)

GSS Overview "The Big Picture"

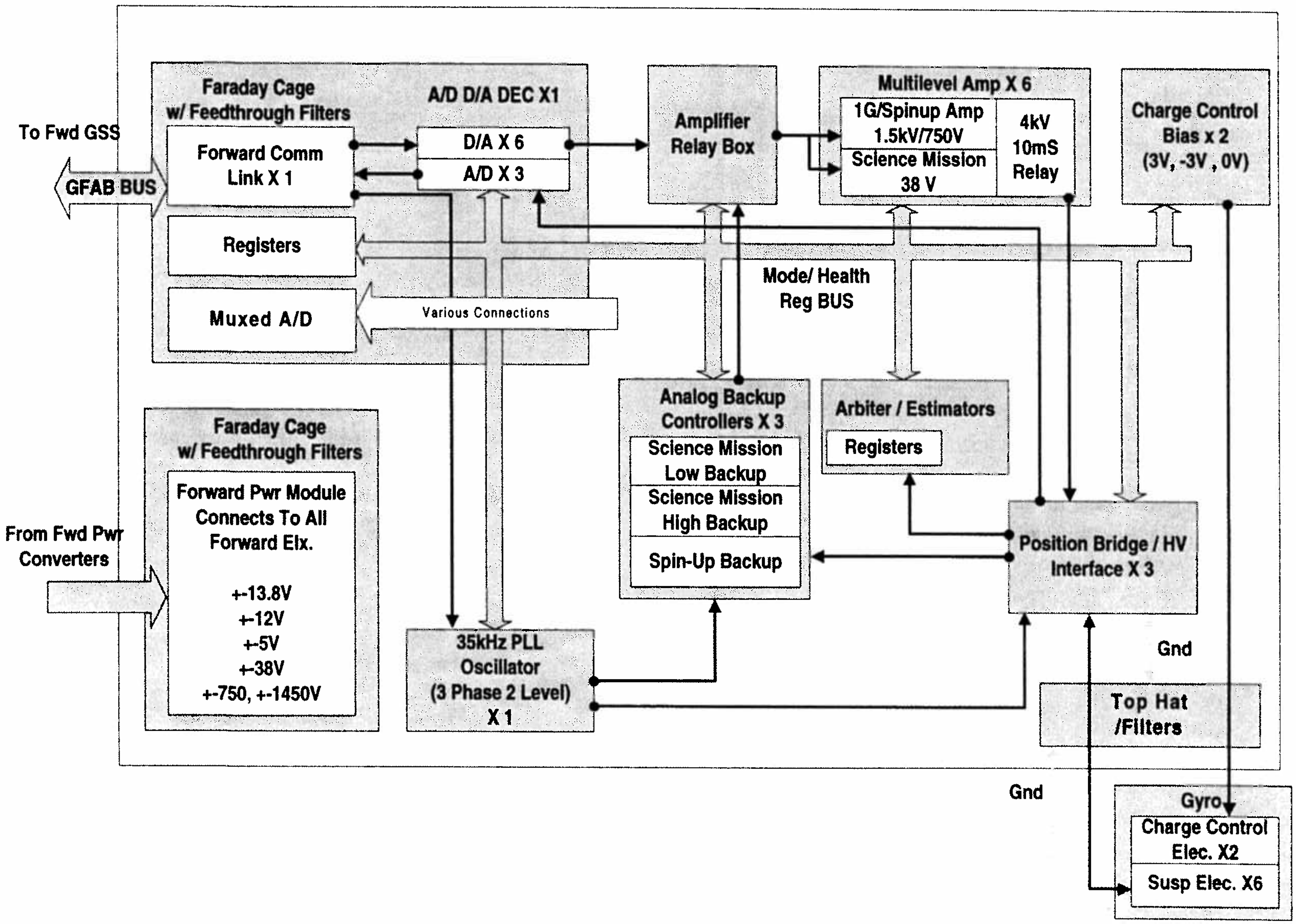


System Overview (GSS Aft Architecture)



Notes:
1) All processors maintain independent free running clocks in the event of failure of the primary $16f_0$ clock.
2) The GFAB clock rate for data transfer is 1MHz maximum.
3) A reference 35KHz clock is embedded in the GFAB bus. This clock is the reference for the forward GSS.

System Overview (GSS FWD Architecture)



System Changes / Deltas Since PDR

- Removed C&DH Computer
  - Preliminary Results Indicate RAD6000 is 1G Capable
  - Added C40 Ground Support Functions (Contingency)
- Added 2 Level Support for Bridge Excitation
  - Science: 40mVpp
  - Ground / Spinup: 120mVpp
- Fully Defined GSS Forward MR Bus
- Fully Defined Arbiter Function and States
- Added General Ground Support Interfaces
- Added Aft Muxed A/D for Sensor Monitoring (temps etc.)
- Refined Timing and Interrupt Distribution
- Refined General Aft Architecture
- Refined Gyro Cabling and Filtering (Tested in GTU-2)

Hardware Designs

GSS Design Priorities:

Defines architecture, SM issues and performance

Needed for 1G Lift

1a) Control System Design

1b) Forward Core Modules (Bridge, Amplifiers...)

1c) Aft Core Modules (Computer, Comm Link...)

2) Backup Systems (Arbiter, Backup Controllers...)

3) Interface / Support Modules (Timing distribution, GSE interface...)

GSS Design Status At-A-Glance

Major Forward GSS Subsystems

Sub Syst.	Spec.	Design Concept	Sim.	Schem.	Proto PCB	Proto Test	EU Design	EU PCB	EU Test
HV Amp	-	X	X	X	X	X	X		
Science Drive	-	X	X	X	X	X			
Charge Ctrl Bias	-	X	X	X	X	X			
Bridge	-	X	X	X	X	X			
BU Controller	X	X	X	X					
Arbiter	X	X	X	X	X	X			
Amp Switch	-	X	X						
Oscillator	-	X	X	X					
AD/DA Deck	X	X	X	X	X	X			
Fwd Com Lnk	X	X	X	X	X	X			
Mode Mux DEC	X	X							
Gyro Cables & Filters	-	X	X	X	X	X			

GSS Design Status At-A-Glance

Major Aft GSS Subsystems

Sub Syst.	Spec.	Design Concept	Sim.	Schem.	Proto PCB	Proto Test	EU Design	EU PCB	EU Test
GSE Support Interface	-	X							
Aft Comp Sup (Timing etc.)	X	X	X	X	X	X			
Aft Com Lnk	X	X	X	X	X	X			
HLD / Pwr Interface	-	X	X	X	X				
Aft Muxed A/D	-	X							

Control System Design

1. Overall Design Goals

- Never Drop The Gyro
- High Performance During Science Mission (Quiet, Low Torque etc.)
- Independently Watch The Computer & Gyro (Arbiter)
- Temporary SM Performance During Computer Failure

2. Compatibility Issues That Affect Control

- Modulation of Forcing Voltages During SM (20Hz)
- Low Control Effort During Science
- SQUID Compatible During Spin Axis Alignment

3. Compromises

- Reduced Performance During Backup Control, May Effect Readout Performance.
- Once In Science Mode, Stay in Science Mode

Detailed System Overview

1) **Michael Eglington:**
   - Control System Lead
   - Oversight of All Control Issues

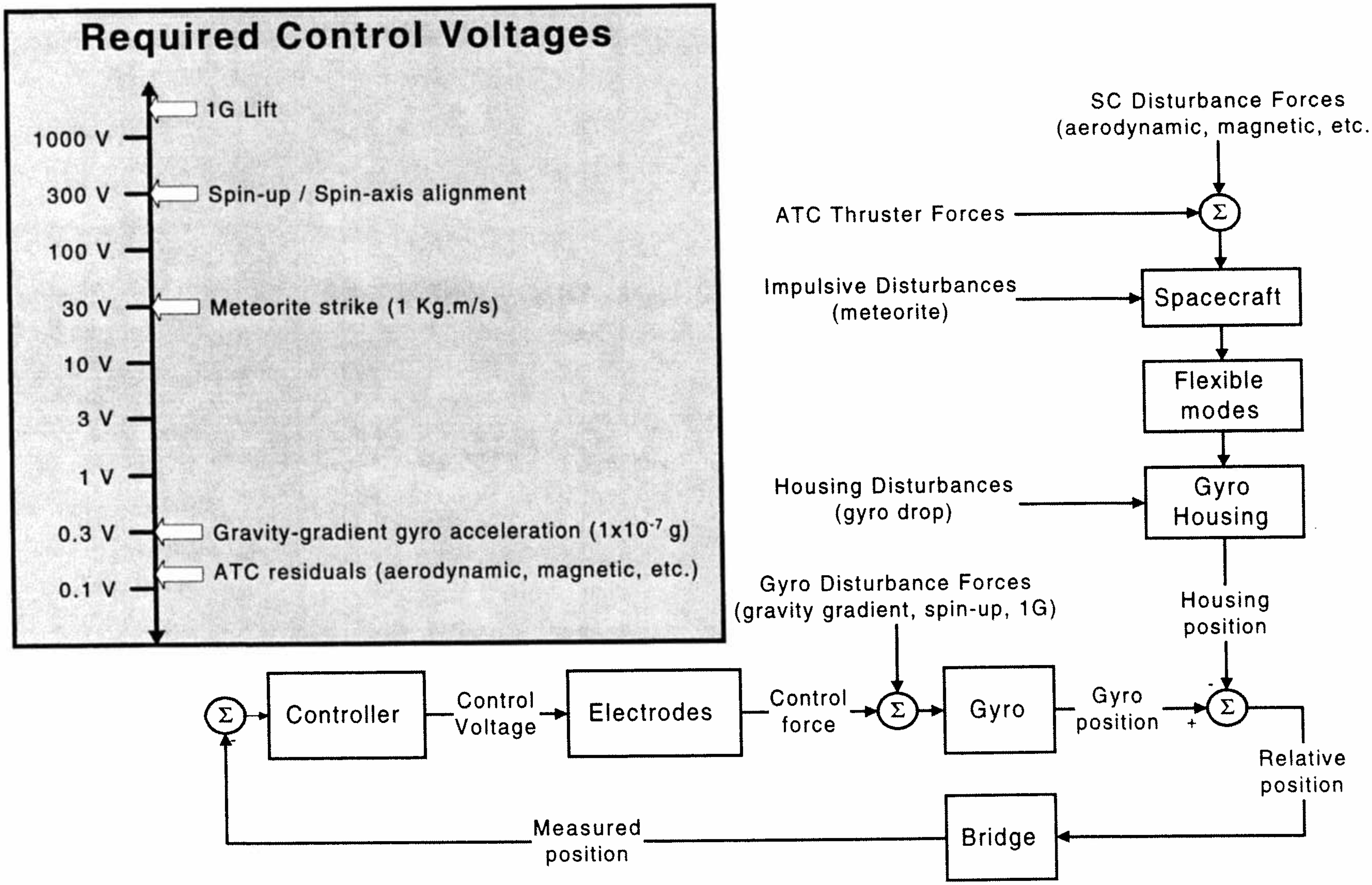
2) **Michael Irwin:**
   - Analog System Lead
   - Manages Forward Systems

3) **Paul Lassa:**
   - Digital System Lead
   - Manages Aft Systems / System Communication

6.1 Control System Design

Michael Eglington and Michael Irwin

Overview of Gyroscope Suspension System



Control System Drivers, Reqs., and Goals

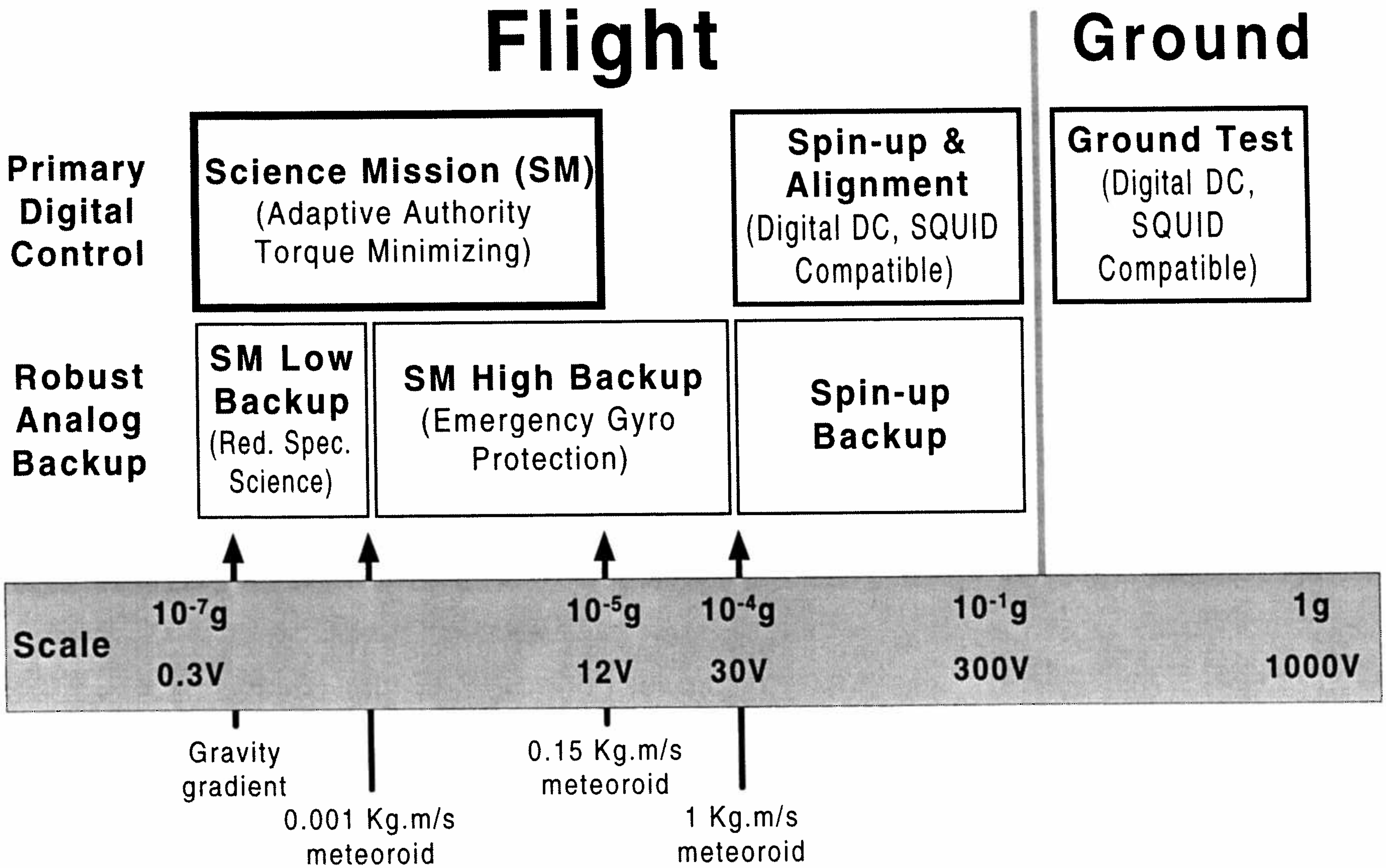
Drivers

- Suspension voltages produce gyro drift
- Wide range of disturbances
- Limited maximum control effort (30V science mode amplifiers)
- Nonlinear actuators (electrodes)
- Reliability

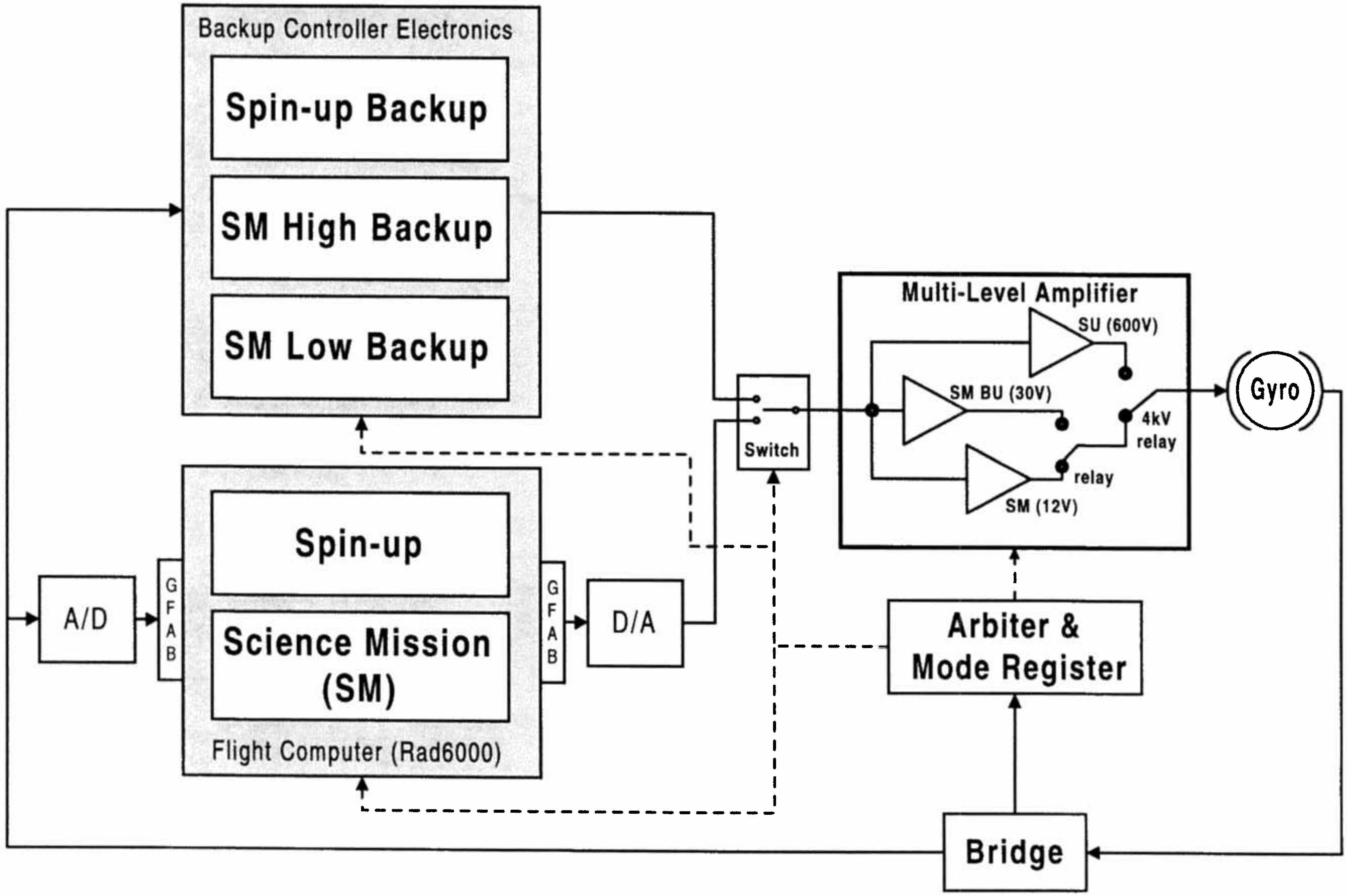
Requirements and Goals

- Minimize torques (gyro drift)
- Compatible with and friendly to SQUID readout system
- Support spin-up and spin-axis alignment (high forces)
- Support charge measurement and control
- Smooth, contiguous, analyzable science controller

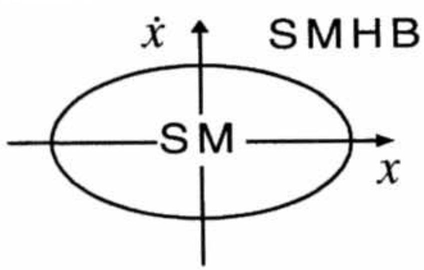
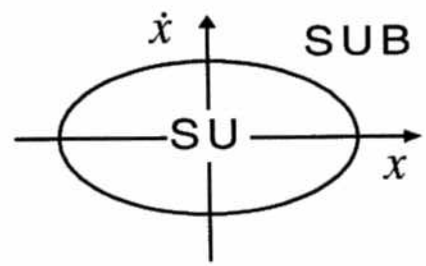
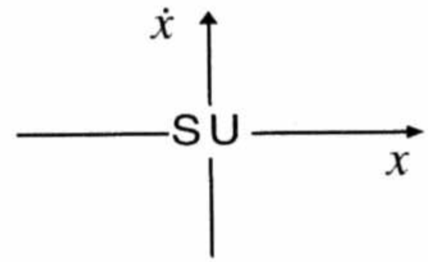
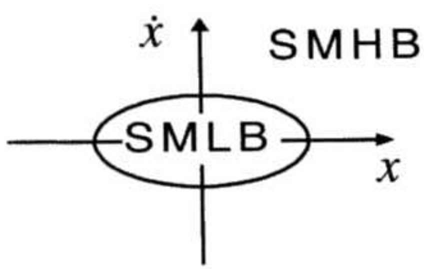
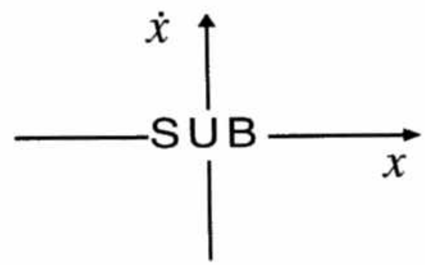
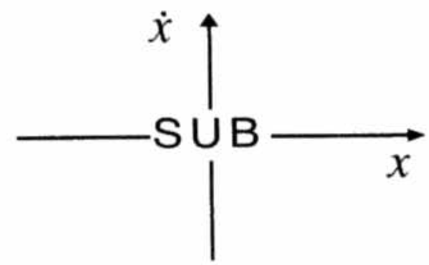
Summary of Gyro Suspension Controllers



Implementation of Controllers



Active Controller Selection Table

DSP OK?	Science Mode	Spin-Up Mode: Centered Gyro	Spin-Up Mode: Off-Centered Gyro
Yes	 SMHB; SM	 SUB; SU	 SU
No	 SMHB; SMLB	 SUB	 SUB

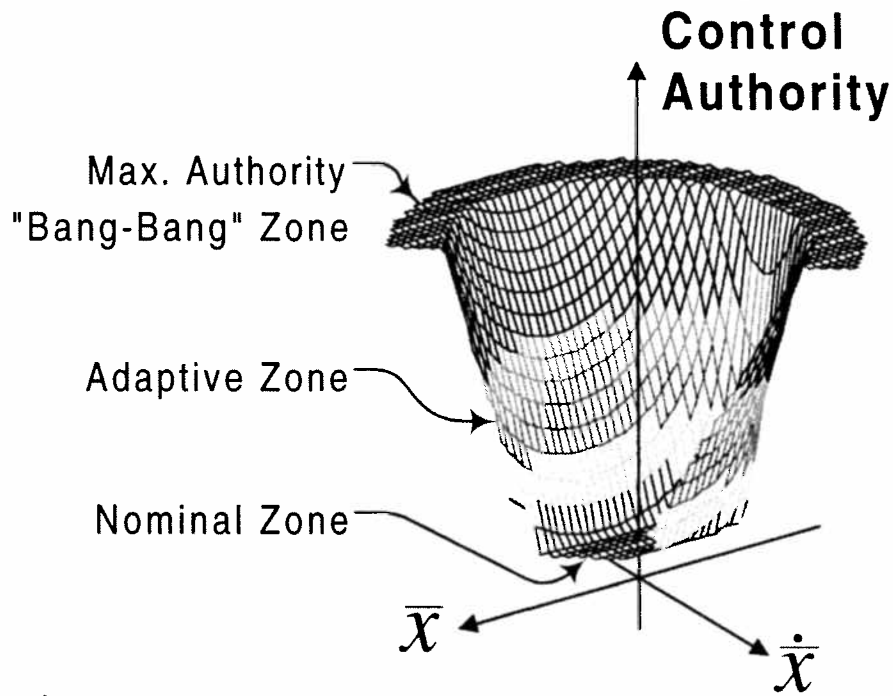
Controller Key

SM - Science Mission (Adaptive Authority Digital)
SMLB - Science Mission Low Backup (Low Authority Analog)
SMHB - Science Mission High Backup (High Authority Analog)
SU - Spin-up (Fixed Authority Digital)
SUB - Spin-up Backup (Fixed Authority Analog)

Science Mission: Adaptive Disturbance Rejection

Assumptions:

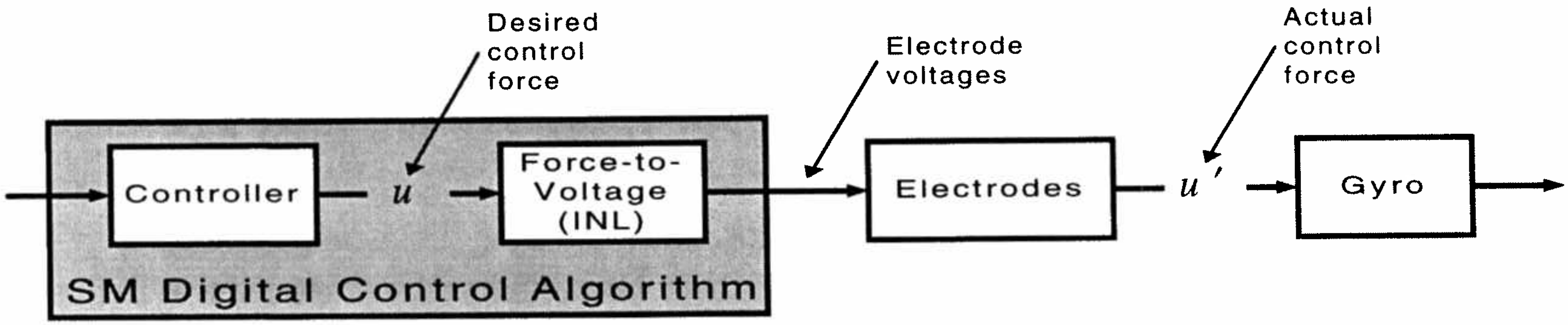
- Nominal Case:
  - Control effort is expensive
  - Sensor (bridge) noise significant
  - Plant noise (pos. dist.) insignificant
- Occasional plant disturbances:
  - Short duration, varying magnitude
  - Bridge noise constant
  - Max. control effort limited (30V)



Adaption Strategy:

- Nominal Zone:
  - Penalizes control effort, Filters bridge noise
  - → Slow control and estimator poles (low bandwidth)
- Adaptive Zone:
  - Smoothly increase authority (penalize state excursion; filtering less important)
  - → Increase freq. of control and estimator poles (increase bandwidth)
- Max. Authority Zone:
  - Actuators saturating; Disturbance rejection paramount
  - → Analog "Bang-Bang" for maximum disturbance rejection and robustness

Science Mission: Force-to-Voltage Conversion



Electrode Force is a Nonlinear Function of Voltage and Position:

$$F = \frac{\varepsilon_0 A_e}{2}\left[\frac{(V_+ - V_r)^2}{(d_0 - \alpha x)^2} - \frac{(V_- - V_r)^2}{(d_0 + \alpha x)^2}\right]$$

Inverse Nonlinearity Control (INL):

- Invert nonlinearity in DSP, i.e. calculate electrode voltages so that: $u' \approx u$
- Separates control problem into control of a linear plant + INL design
- GSS SM and SU Digital Controllers use Wu's (SUDAAR 638, 1993) INL method
- Proven in DDC and GSS 1G suspension systems, and in GSS simulations
- See Controller Design Technical Appendix for details

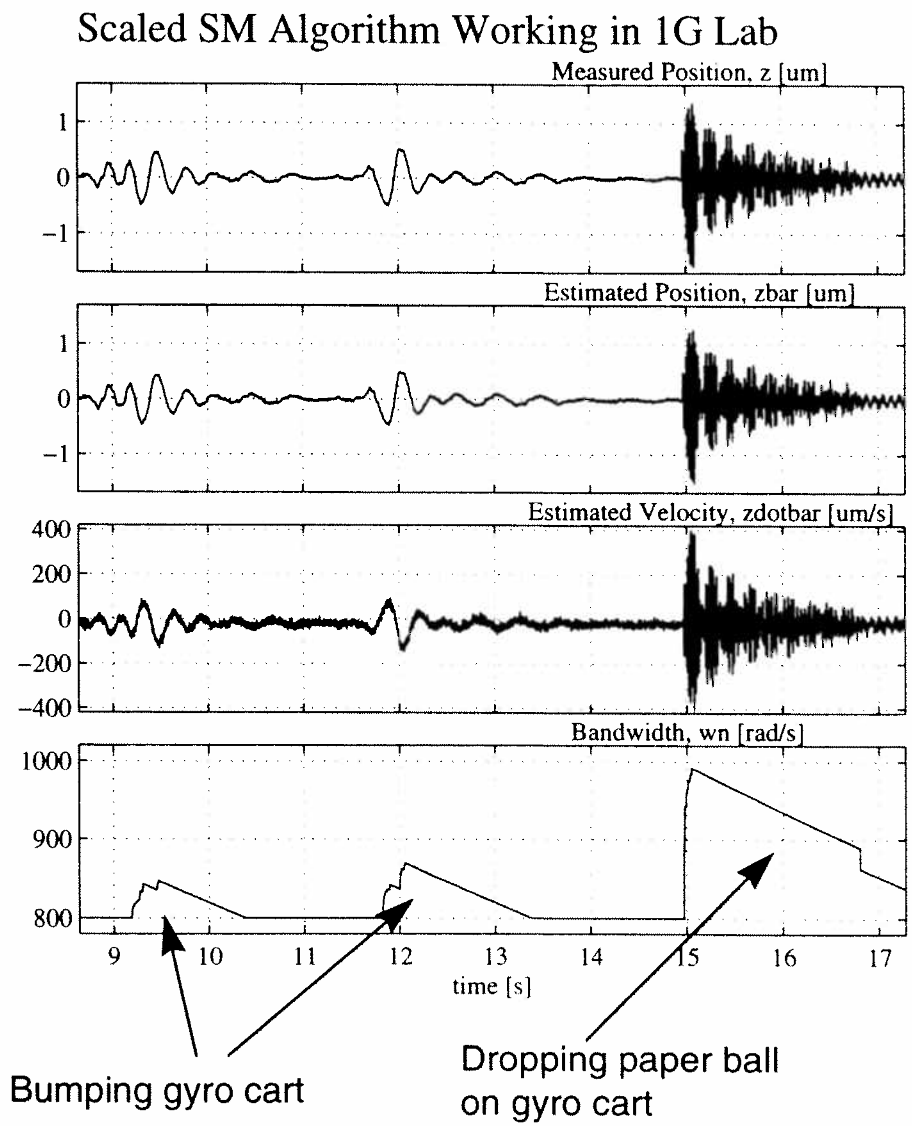
Science Mission: Status and Flight Development

Base Design and C-code Complete

- Working science-mission and scaled-algorithm-1G-lift simulations
- Scaled SM algorithm successfully demonstrated in lab in 1G

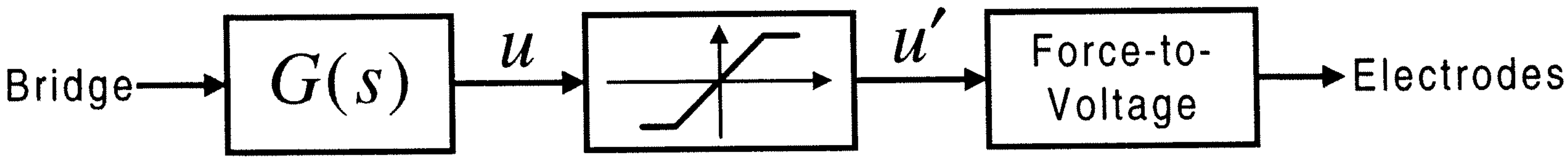
Flight Software Development

- Control code compiles and runs on both C40 and Rad6000
- ➔ Control code now being written according to LMMS guidelines
- ➔ Extensive Testing and Verification of Flight Code
  - 2 independently developed simulations
  - Testbed
  - Scaled 1G tests use same code



Analog Backup Controllers

Basic Structure:



Configurable into three Backup Controllers:

- Science Mission Low-Authority Backup
  - PID controller (saturation not active)
  - Reduced specification science mission performance
  - Handles steady-state disturbances and small meteoroids (0.001 Kg.m/s)
- Science Mission High-Authority Backup
  - Sliding-Mode (Bang-Bang) with linear region for no chattering (saturation active)
  - Optimal disturbance rejection given limited control effort (30V)
  - Default controller for large meteoroids (0.15 - 1 Kg.m/s)
- Spin-up Backup
  - PD controller (saturation not active)

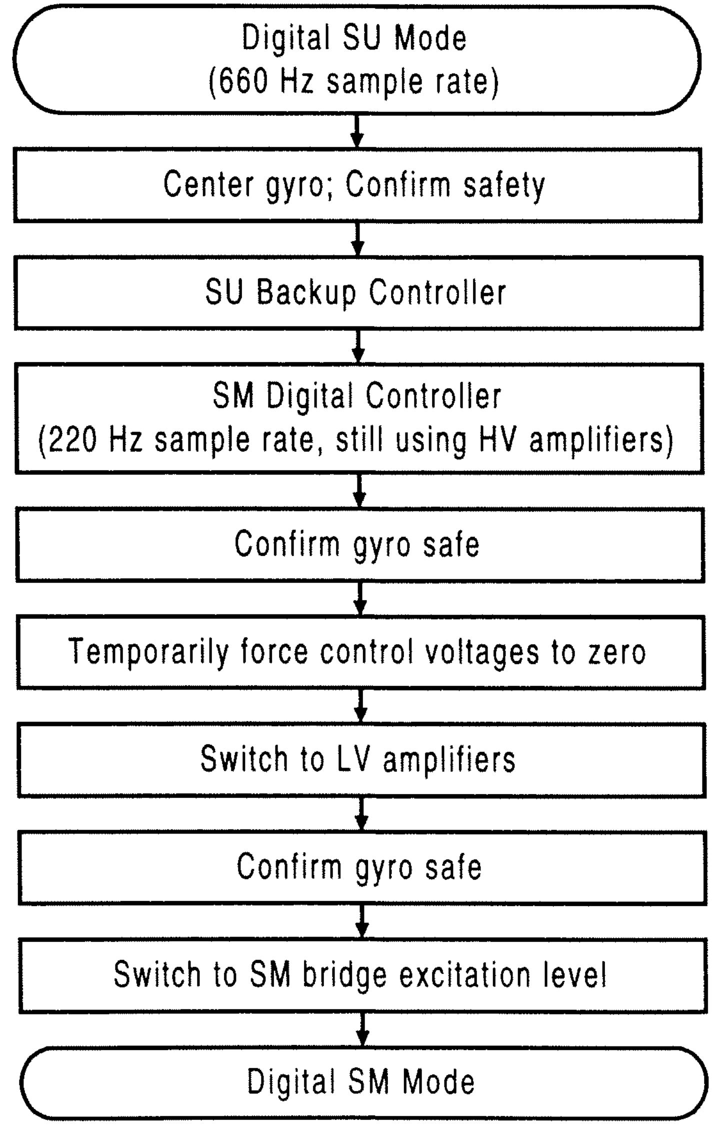
Spin-up Controller

Nominal Digital Controller

- Scaled version of proven 1G controllers
- Digital implementation facilitates spin-axis alignment

Transition between Spin-up and Science Modes

- Always commanded, i.e. never in response to emergencies
- For example: transition from SU controller to SM controller
- Other transitions similarly controlled



Special Considerations

SM Control Voltage Modulation

- Drivers
  - DAC temp. coefficients
  - SQUID friendliness
- Procedure
  - DSP flips voltage signs at 20 Hz
  - LV Amp sub-system bandpass filters
  - Electrodes demodulate (voltage squared)
- Current Status
  - Control compatibility verified by simulation
  - SQUID compatibility verified in GTU-2 "Wiggle Test"

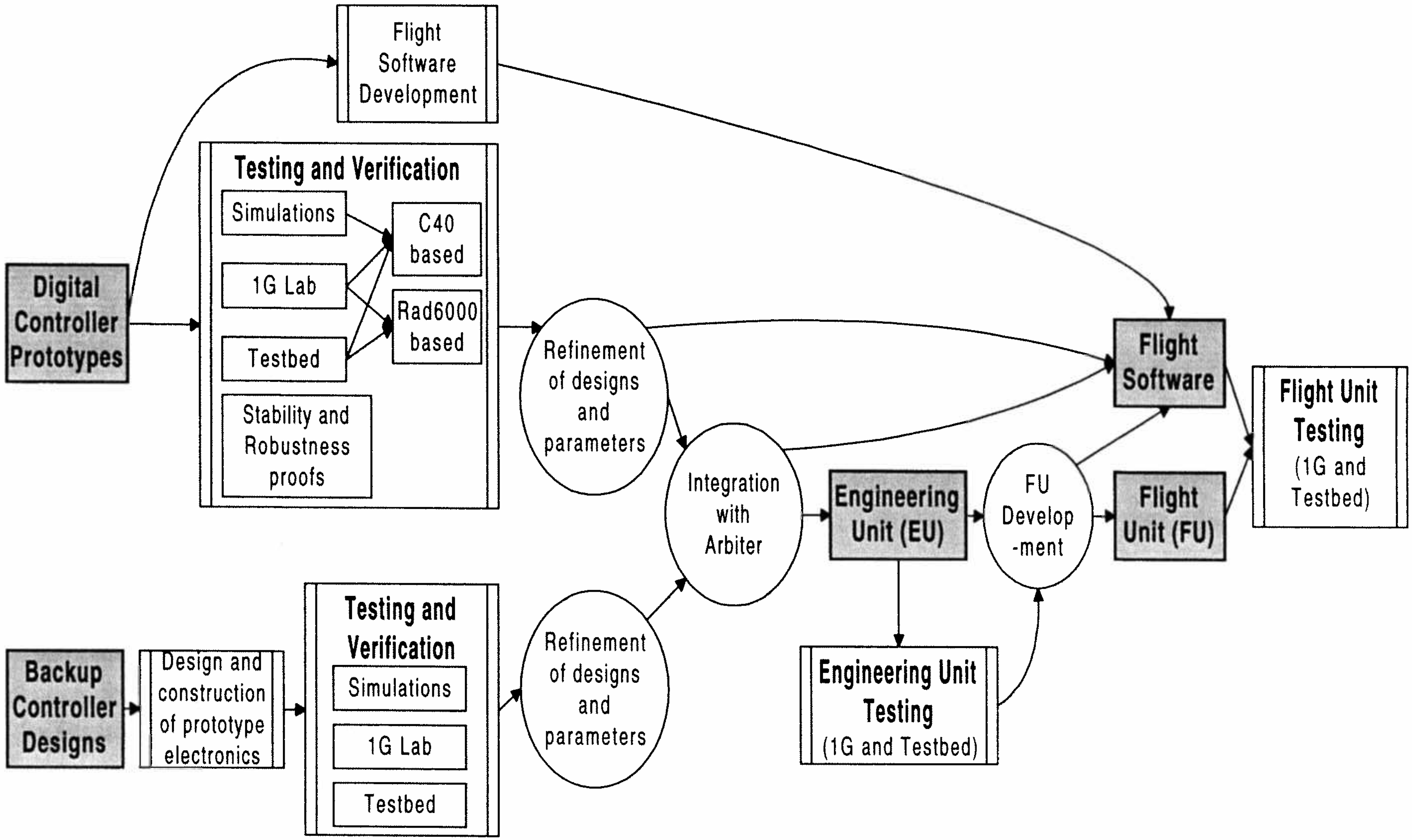
Preload Voltage Axis Swapping

- Voltage preloads will be rotated periodically to average out torques created by preload mismatching on different electrode axes

Dragfree Sensor Controller (DFS)

- Scaled version of SM controller
- Nominal zone scaled commensurate with Attitude and Translation Control's centering accuracy
- DFS controller exerts zero control in nominal zone
- Estimators remain active, and adaptive control takes over if gyro exceeds nominal zone
- Arbiter and backup scheme remain active throughout

Flight Development Path



Control Scheme Demands on Hardware

Driver:

Wide disturbance range, and contingencies, demand adaptable control loop:

- Five controllers.
- Reconfigureable actuators and position sensor.

Requirements:

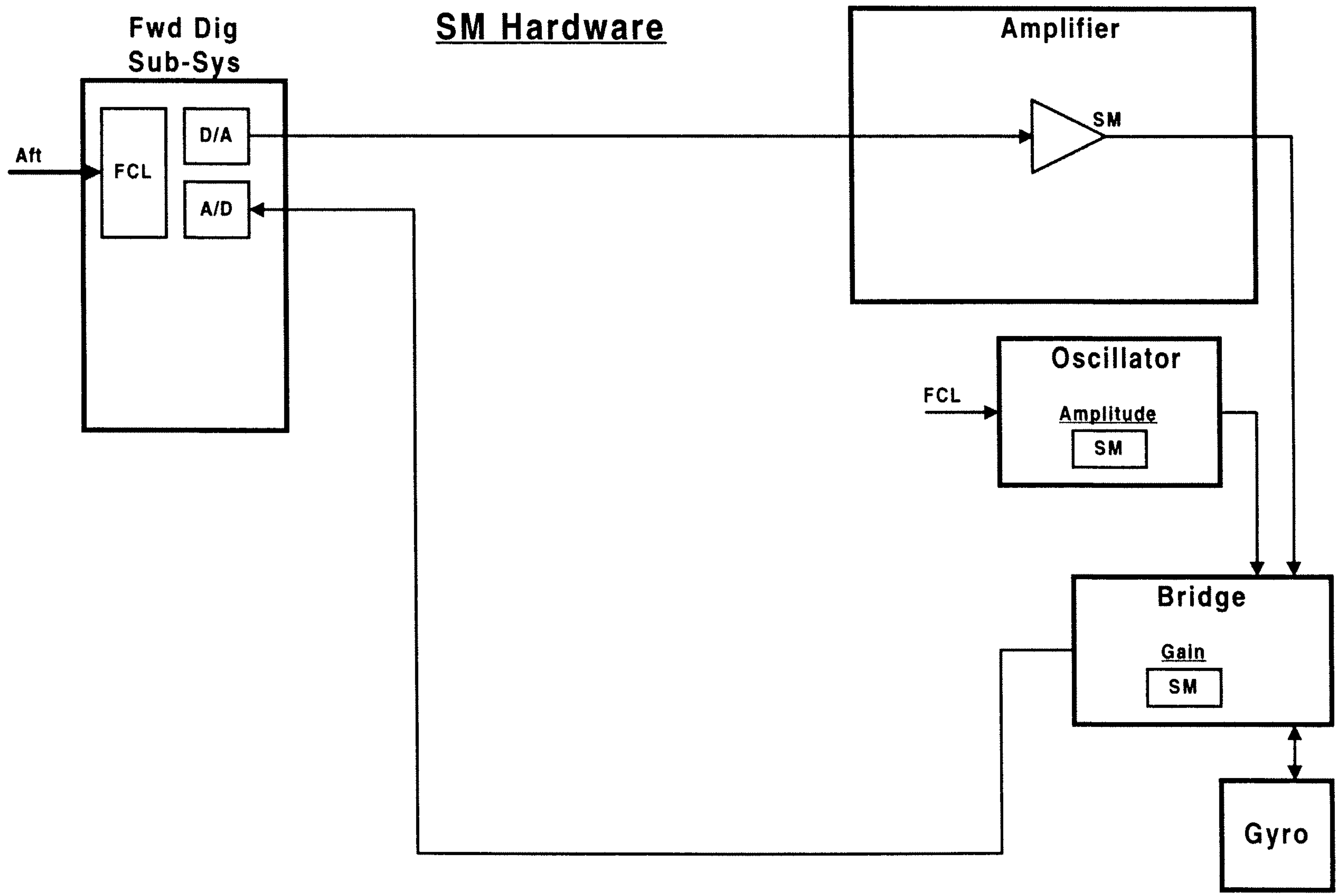
Supplemental control loop hardware.

Hardware must be reconfigureable.

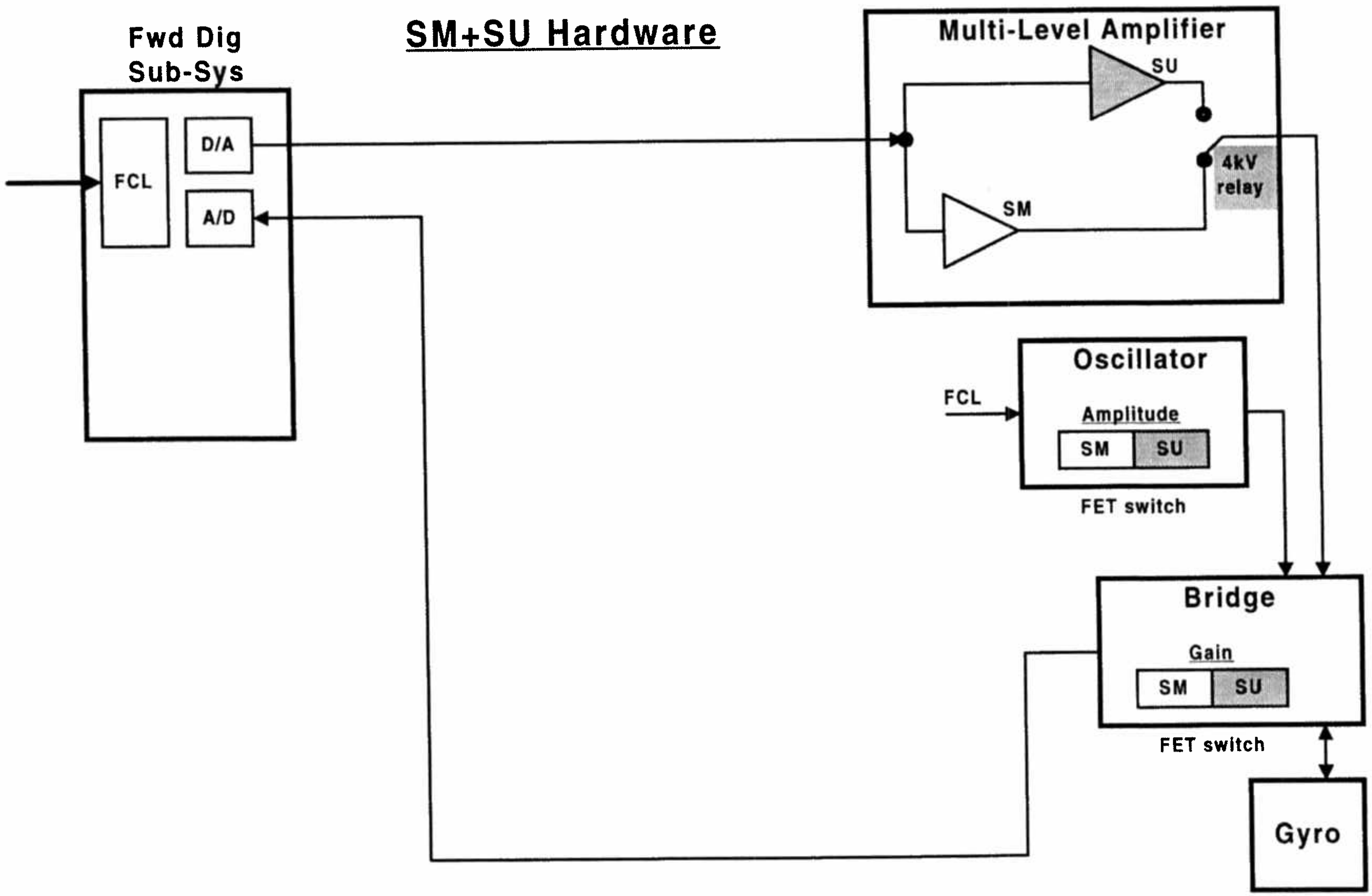
Something must manage hardware configuration.

- Must be robust.
- Must maintain environment in the event of a computer failure.

Baseline Control Loop Hardware



Baseline Control Loop Hardware



Backup Requirements

Driver: **Handle computer failure -- uncontrolled gyro.**

Requirements:

- Add robust Backup Controller (and switch).
  - Must function in SM and SU. **
  - Must be low-torque, science data friendly (in case of prolonged computer failure). **

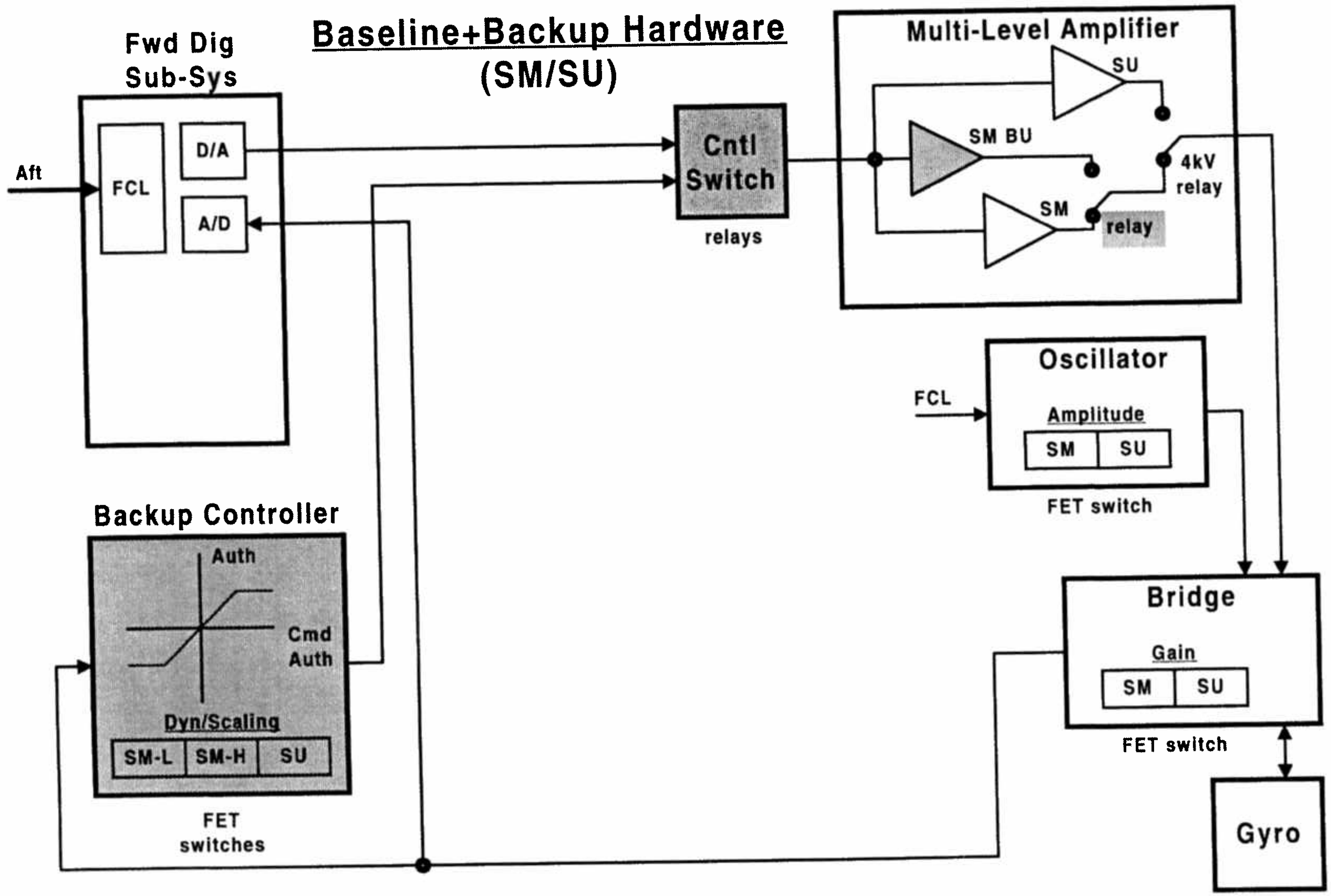
Driver: **Handle micrometeoroid impact -- gyro excursion.**

Requirements:

- Backup must be time-optimal. **
- Add 30V amplifier for 10e-4g disturbances.

** **Requirement:** **Backup controller dynamics and scaling must be reconfigureable.**

Backup Control Loop Hardware



Control Loop Management

Drivers:

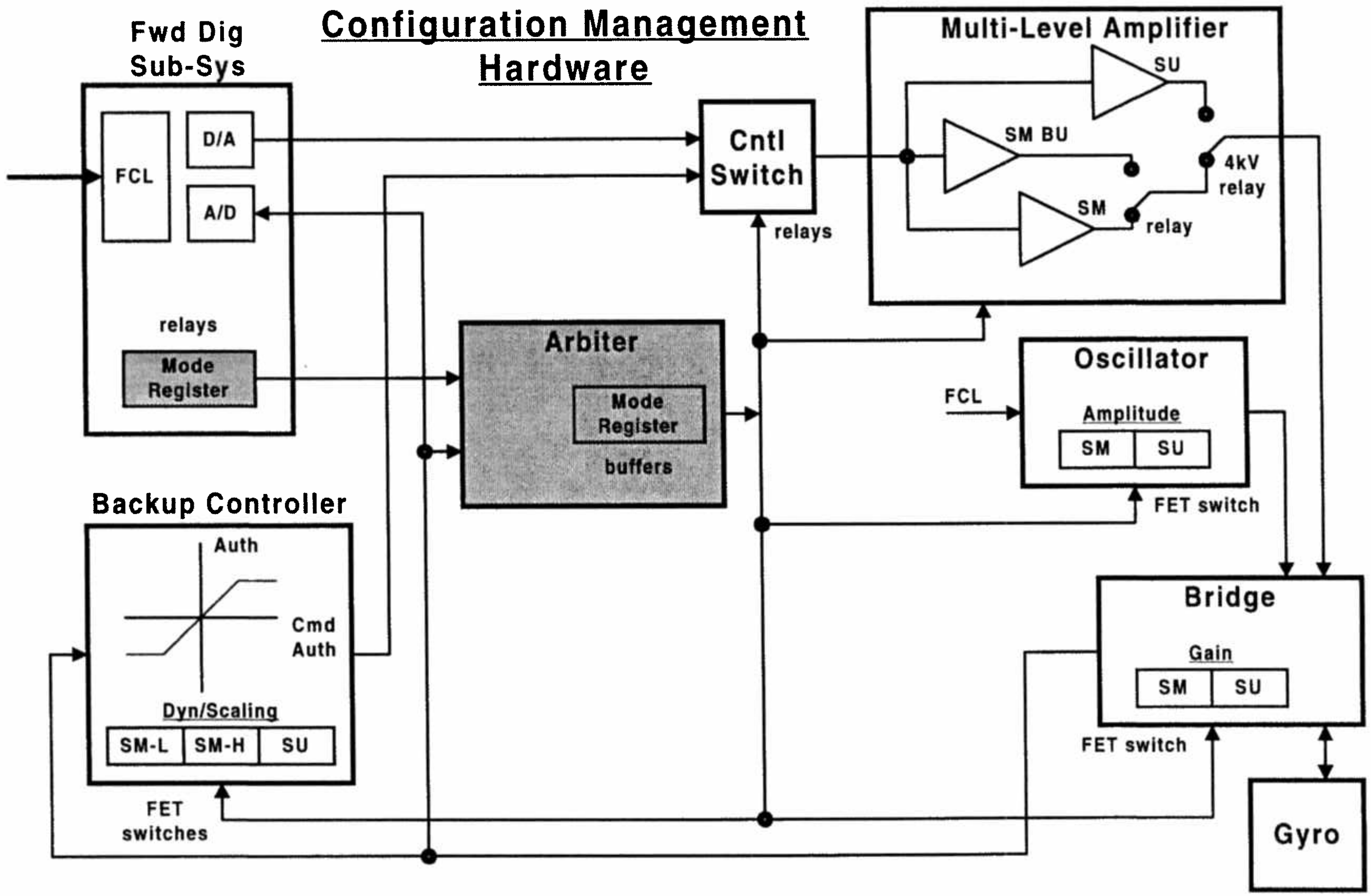
- Control loop hardware configuration requires management.
- Management should NOT be exercised by computer.
- Need non-computer judge of: GSS state, and backup-event detection.

Requirements:

- **Mode Register:** Preserves last-set computer commands.
- **Arbiter**
  - Determines GSS state.
  - Manages hardware configuration.
  - Assumes backup-control of GSS.

GSS State	Controller	Amplifier	Osc Amplitude	Bridge Gain
SM Baseline	SM	SM (12V)	SM (40mVpp)	SM
SM Backup	SMLB	SMBU (30V)	SM (40mVpp)	SM
	SMHB	SMBU (30V)	SM (40mVpp)	SM
SU Baseline	SU	SU (600V)	SU (120mVpp)	SU
SU Backup	SUB	SU (600V)	SU (120mVpp)	SU

Control Loop Management



6.2 Analog Hardware Design

Michael Irwin

Arbiter: Overview

Inputs/Outputs -- See diagram.

Estimator with two threshold sensors

- Determines which controller(s) is suitable for controlling/capturing gyro.

Backup Counter (resets when high-auth. backup is selected)

- Assumption: large disturbance occured.
- Action: Include elapsed backup-time (~10s) to other decision criteria, when determining return to computer control.

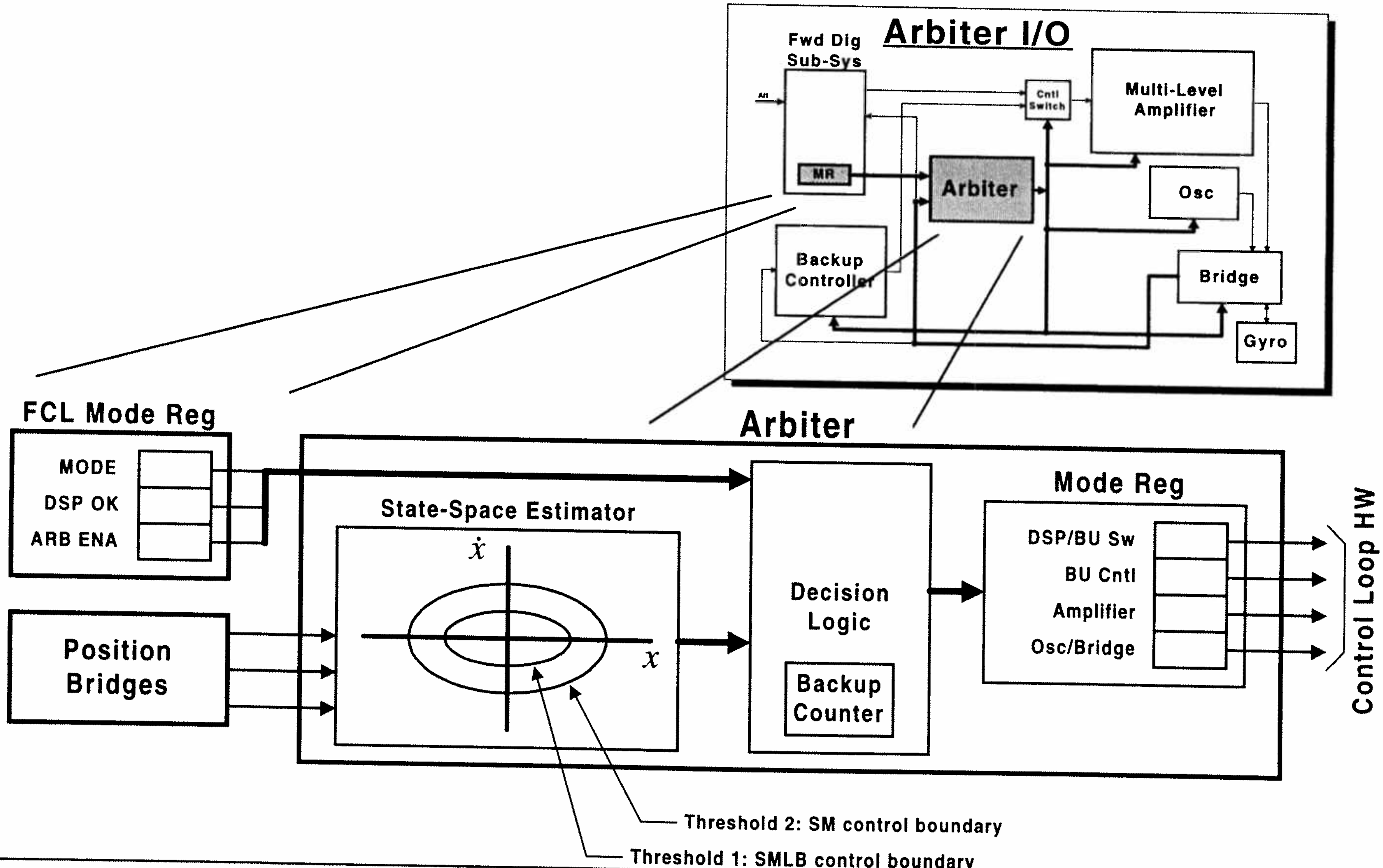
Arbiter functions:

- In a given mode, assess GSS state.
- Configure Osc/Bridge per given mode.
- Assume control of GSS.
- Configure Amp and select Controller per GSS state.

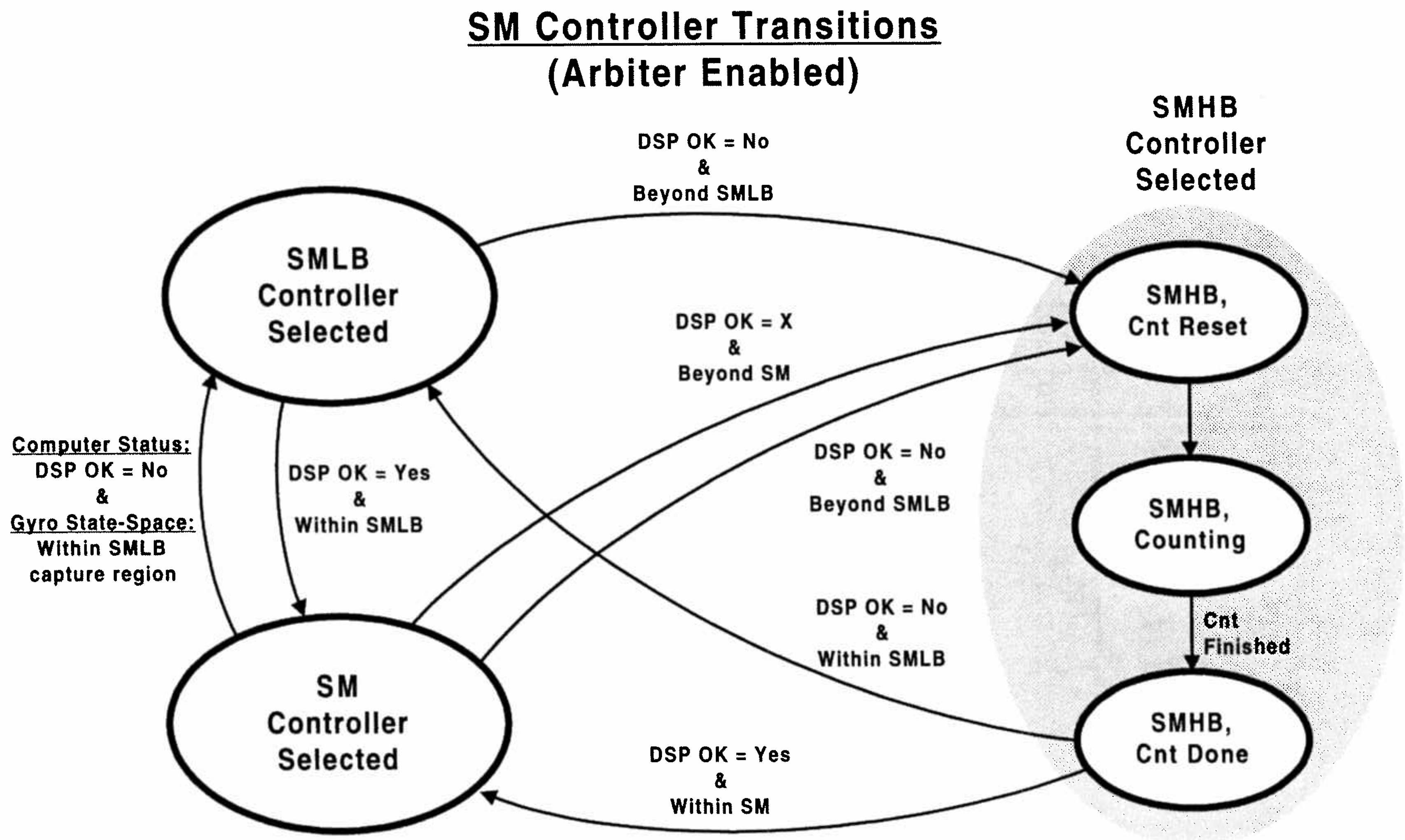
Control Loop Configurations

GSS State	Controller	Amplifier	Osc Ampltude	Bridge Gain
SM Baseline	SM	SM	SM	SM
SM Backup	SMLB	SMBU	SM	SM
	SMHB	SMBU	SM	SM
SU Baseline	SU	SU	SU	SU
SU Backup	SUB	SU	SU	SU

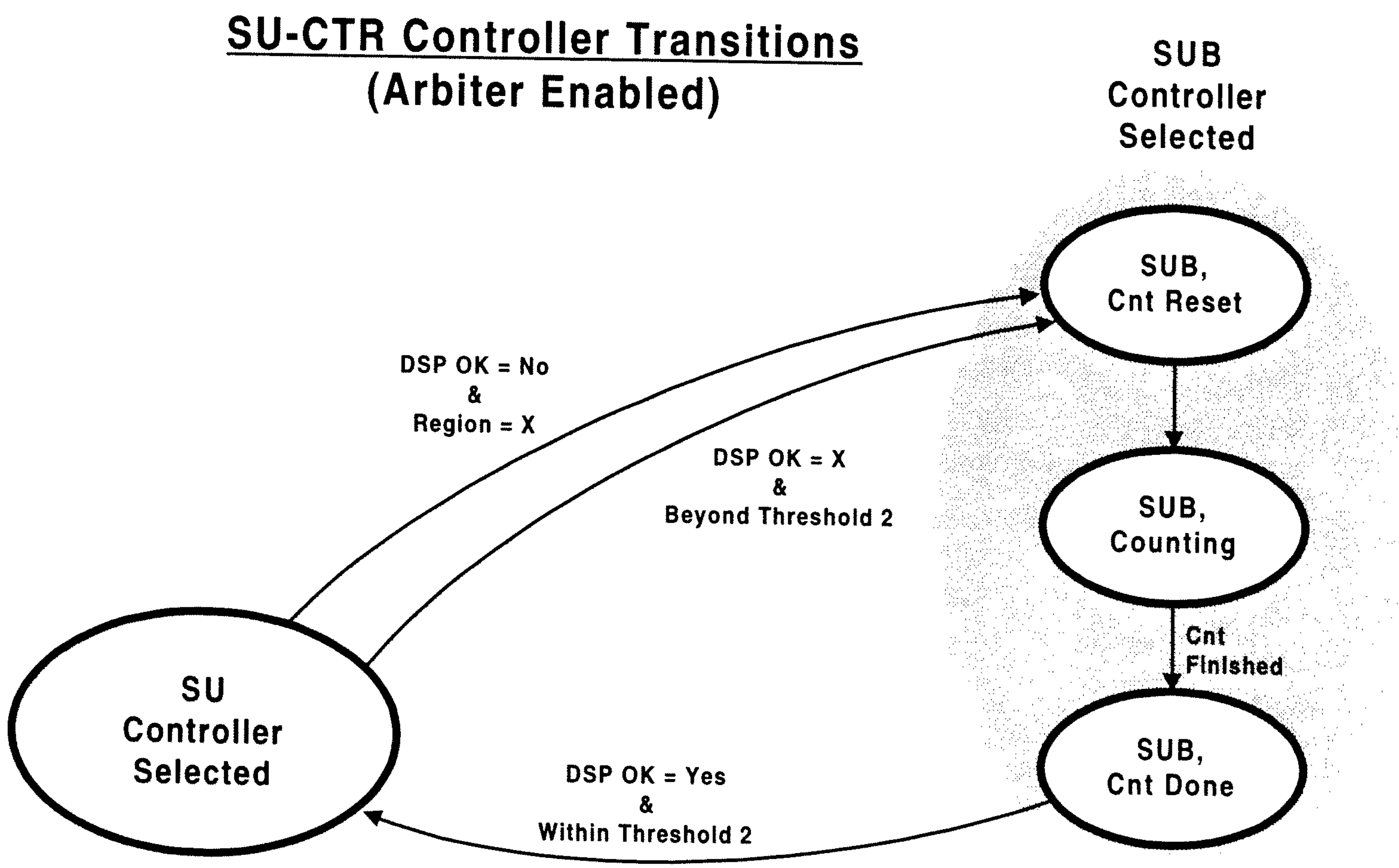
Arbiter: Overview



Arbiter: Controller Selection



Arbiter: Controller Selection



* Arbiter Threshold 2 is reused in SU-CTR mode for simplicity of design.

Arbiter: Controller Selection

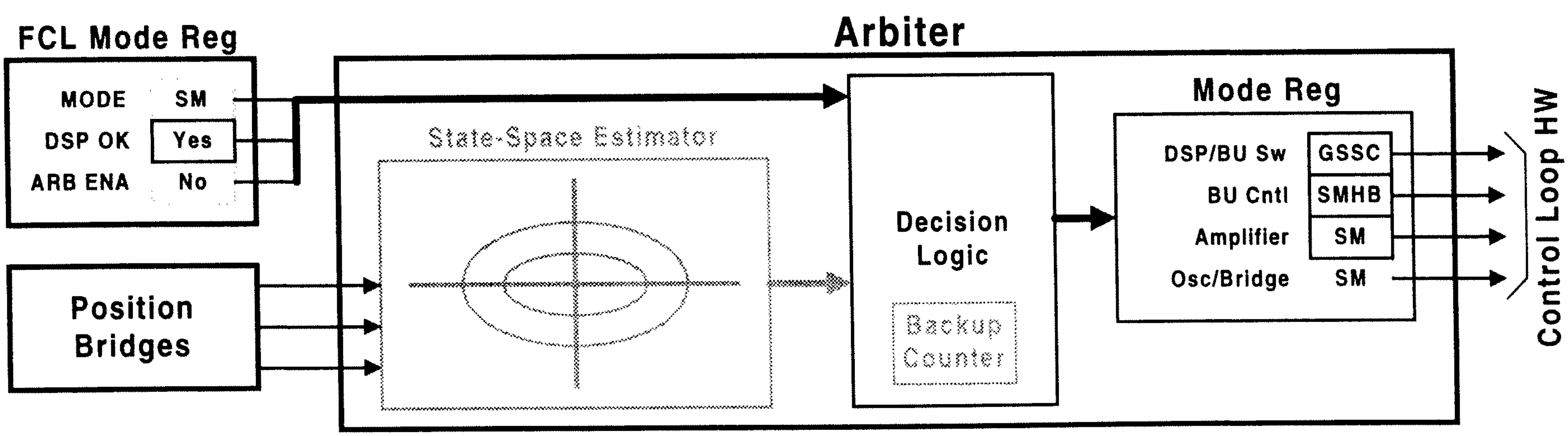
Arbiter Disable Feature

Selected through the Mode Register.

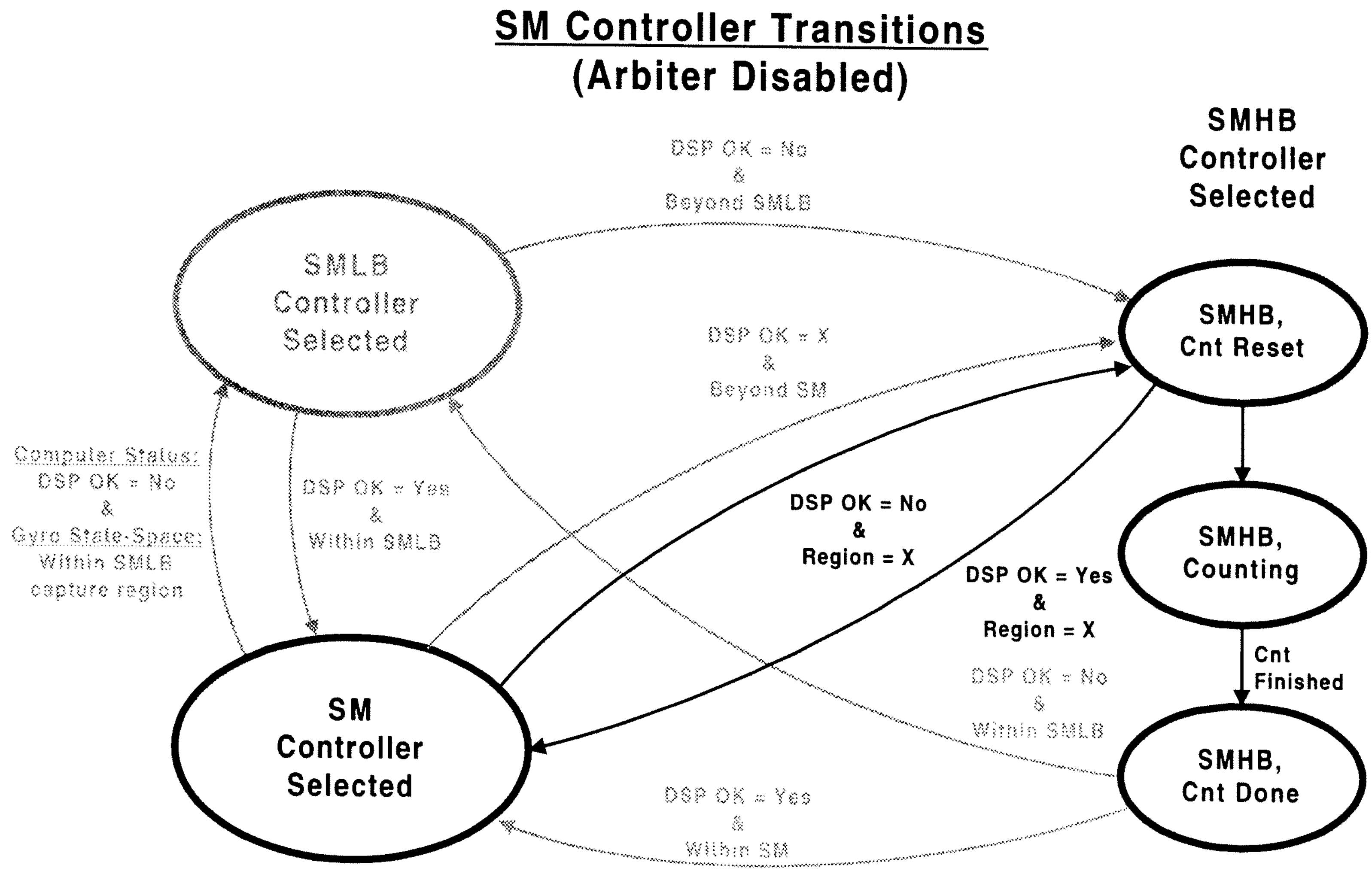
Estimator and Backup timer are disregarded.

Simplifies Arbiter's decision logic.

- Collapses controller-selection truth table.
- Eliminates Arbiter autonomy.

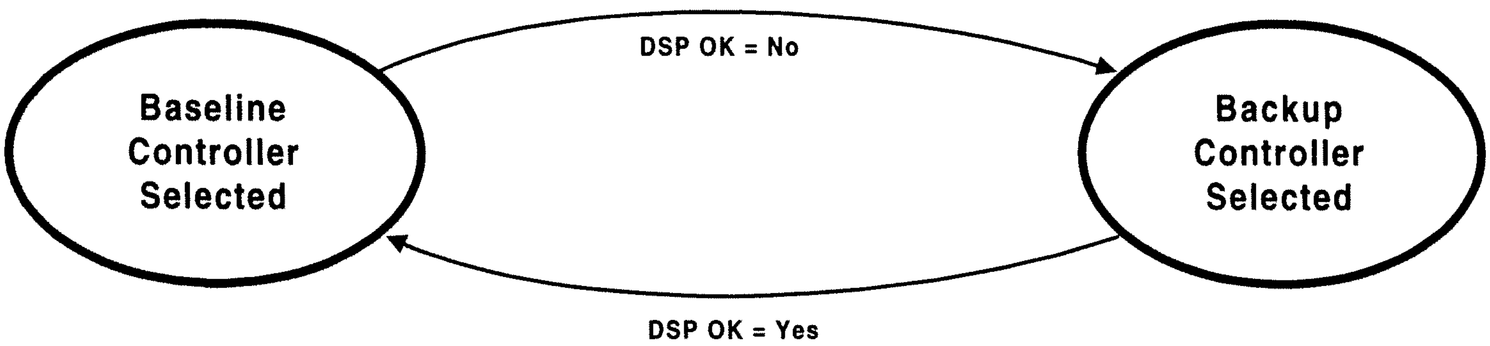


Arbiter: Controller Selection



Arbiter: Controller Selection

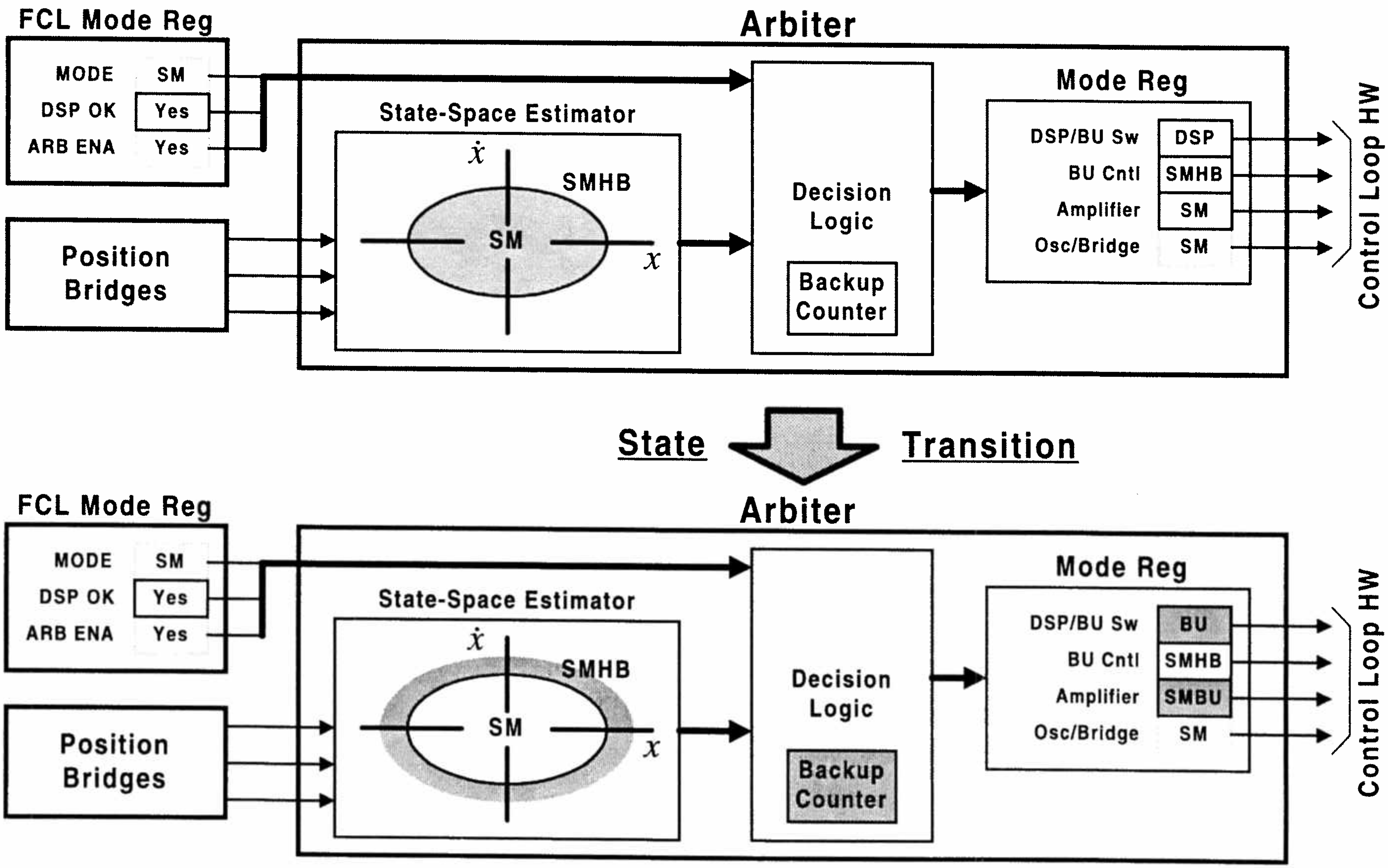
Controller Transitions
(Arbiter Disabled)



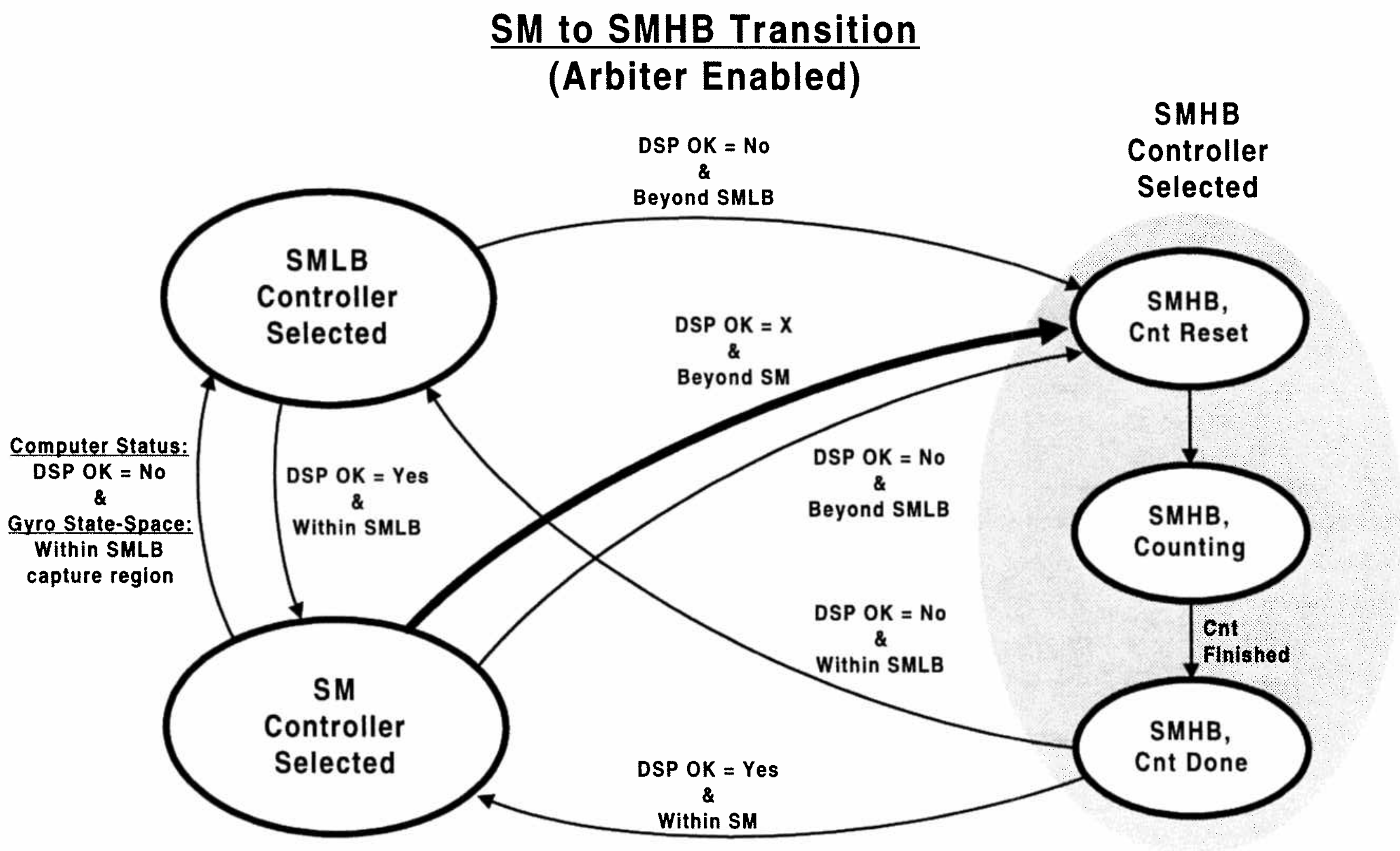
Mode	Baseline	Backup
SM	SM	SMHB
SU-CTR	SU	SUB
SU-OFF	SU	SUB

* SMHB is default SM backup since it has higher control authority than SMLB.
* SU-OFF is operated in this Arbiter state since this mode requires no use of Arbiter thresholds.

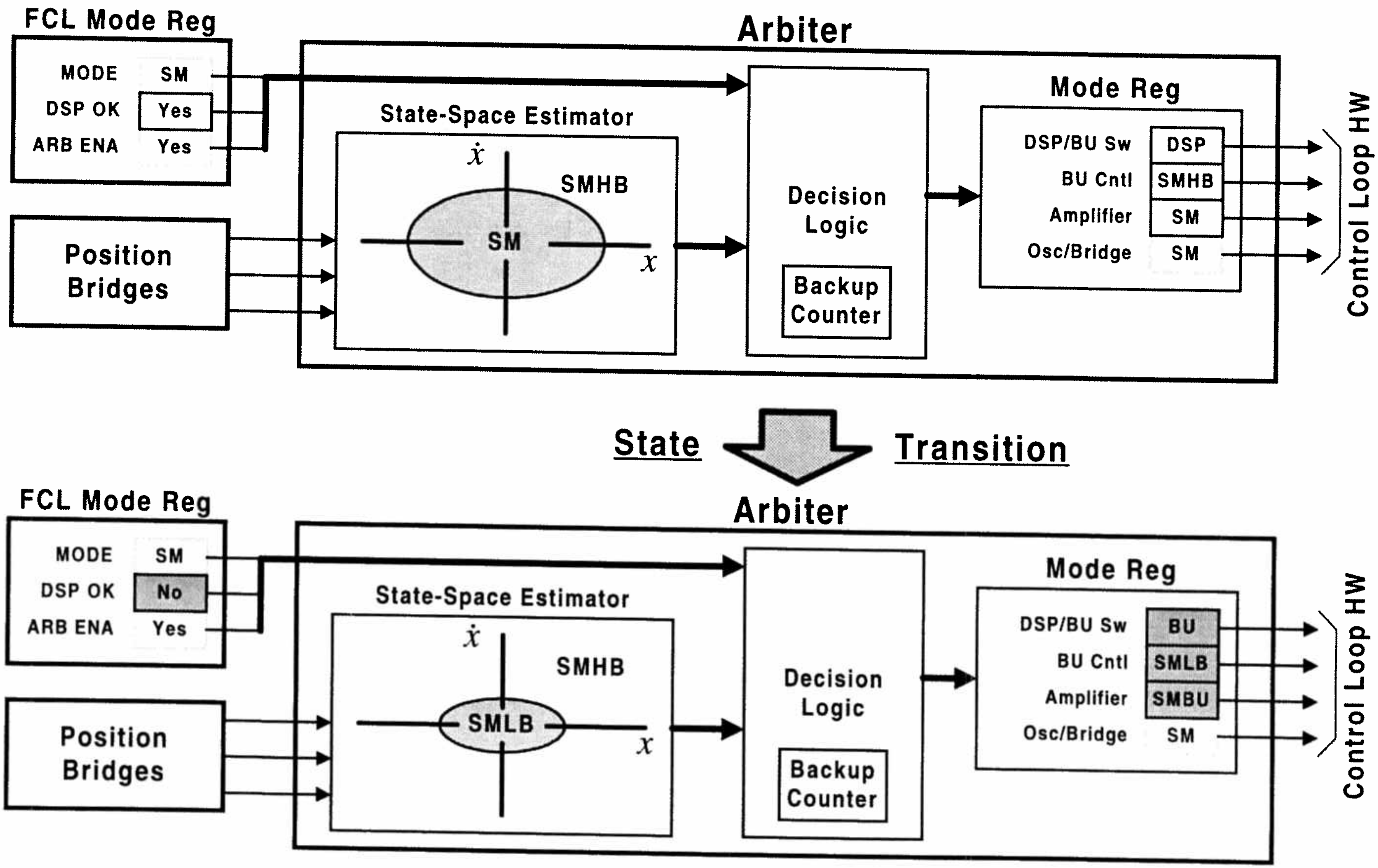
Arbiter: Micrometeoroid Strike Example



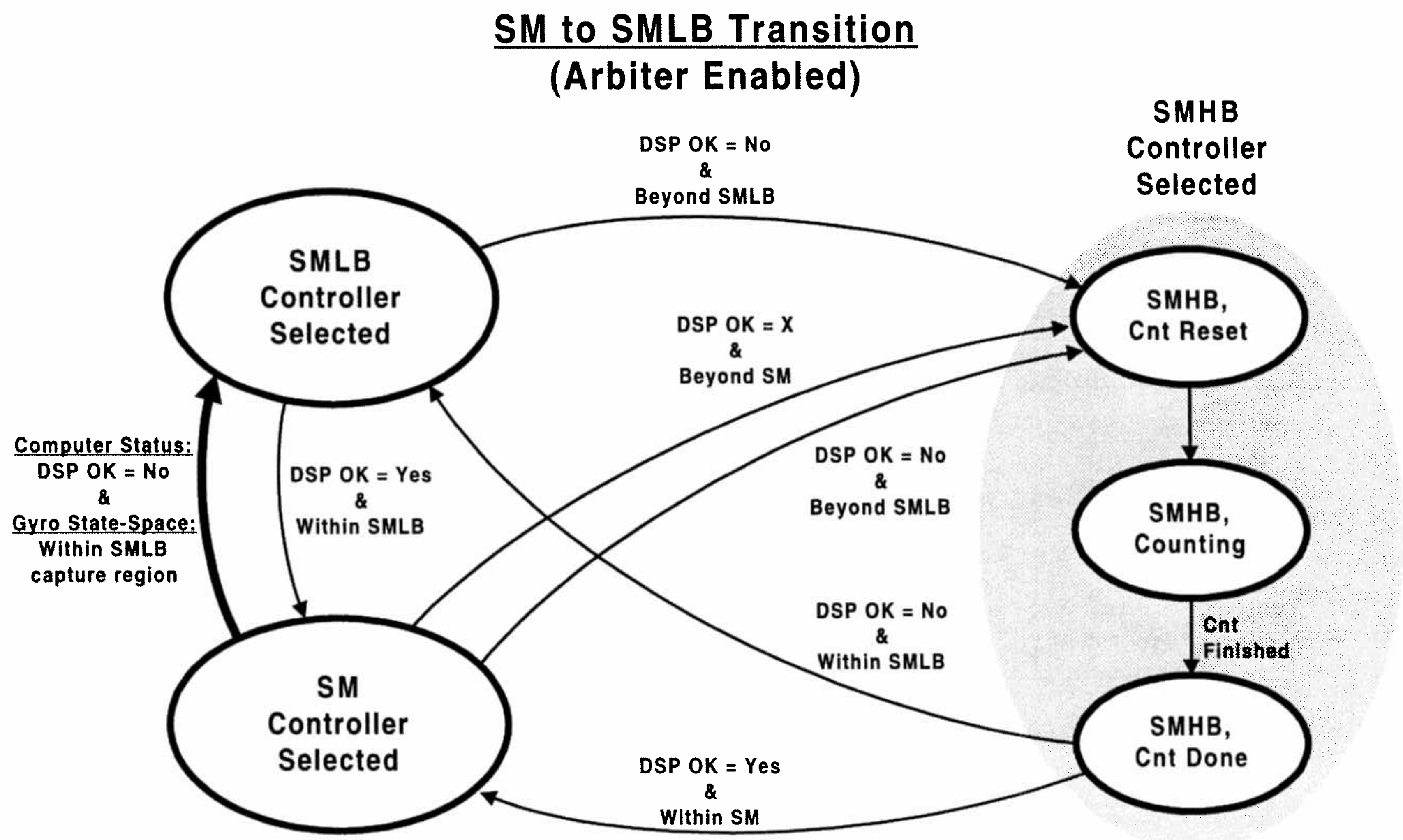
Arbiter: Micrometeoroid Strike Example



Arbiter: Computer Failure Example



Arbiter: Computer Failure Example



Arbiter: Design Status

Test/Verification.

- Initial Arbiter/Testbed experiment completed.
- Comprehensive Testbed experiments planned.
- Comprehensive MATLAB model testing planned.

Open Issues.

- Refining Estimator design.

Backup Controller

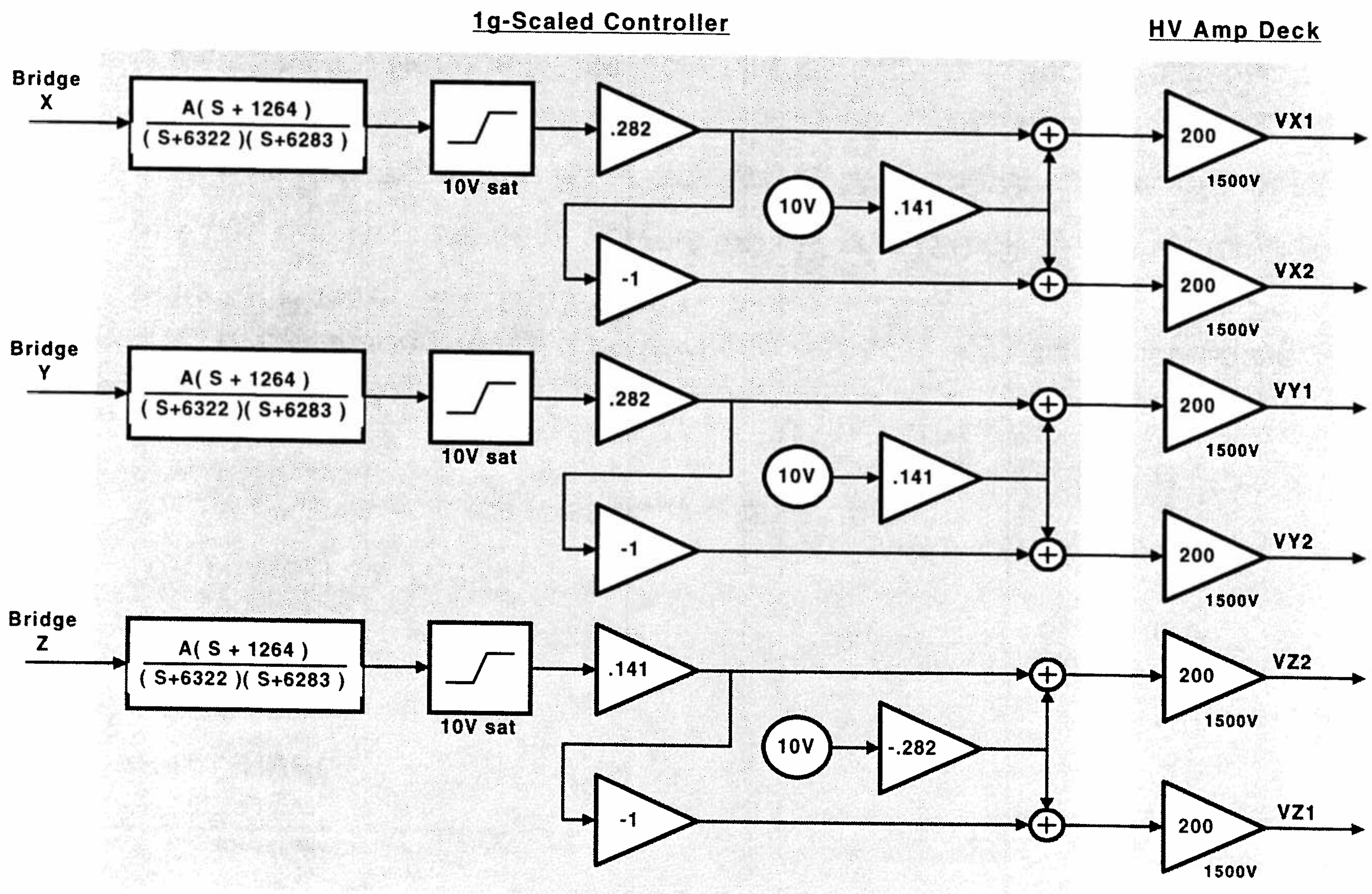
Design Drivers

- Single controller architecture with preload; linear and saturated region.
- Dynamics and scaling are configureable to meet varied demands:
  - SM low-level backup: Science-data friendly.
  - SM high-level backup: Manage gyro excursions.
  - SU backup: Manage high-g environment.

Test/Verification

- Proceeding with 1g-scaled version of design -- allows robust confirmation of architecture.
- Next prototype will be Testbed compatible; simulate SM reqs.

Backup Controller



Position Sensor

1. Design Drivers

- SRE Friendly
- Single, Simple Bridge Architecture
- Low Noise, Low Tempco
- MR Selectable Science Mission and Spin Up Modes

2. Prototype Design

- 35 kHz Excitation Provided By 3 Phase Analog Oscillator Which Locks To External Reference Or Free Runs If None Exists
- MR Bits Set Two Excitation Levels (40 mv and 120 mv p-p in Prototype)
- Amp/Gyro Interface With Balancing Loads Minimize Suspension Voltage Effect On Position Signal
- Driven Shields Reduce Cable Capacitance Change Effects On Position Signal

Position Sensor

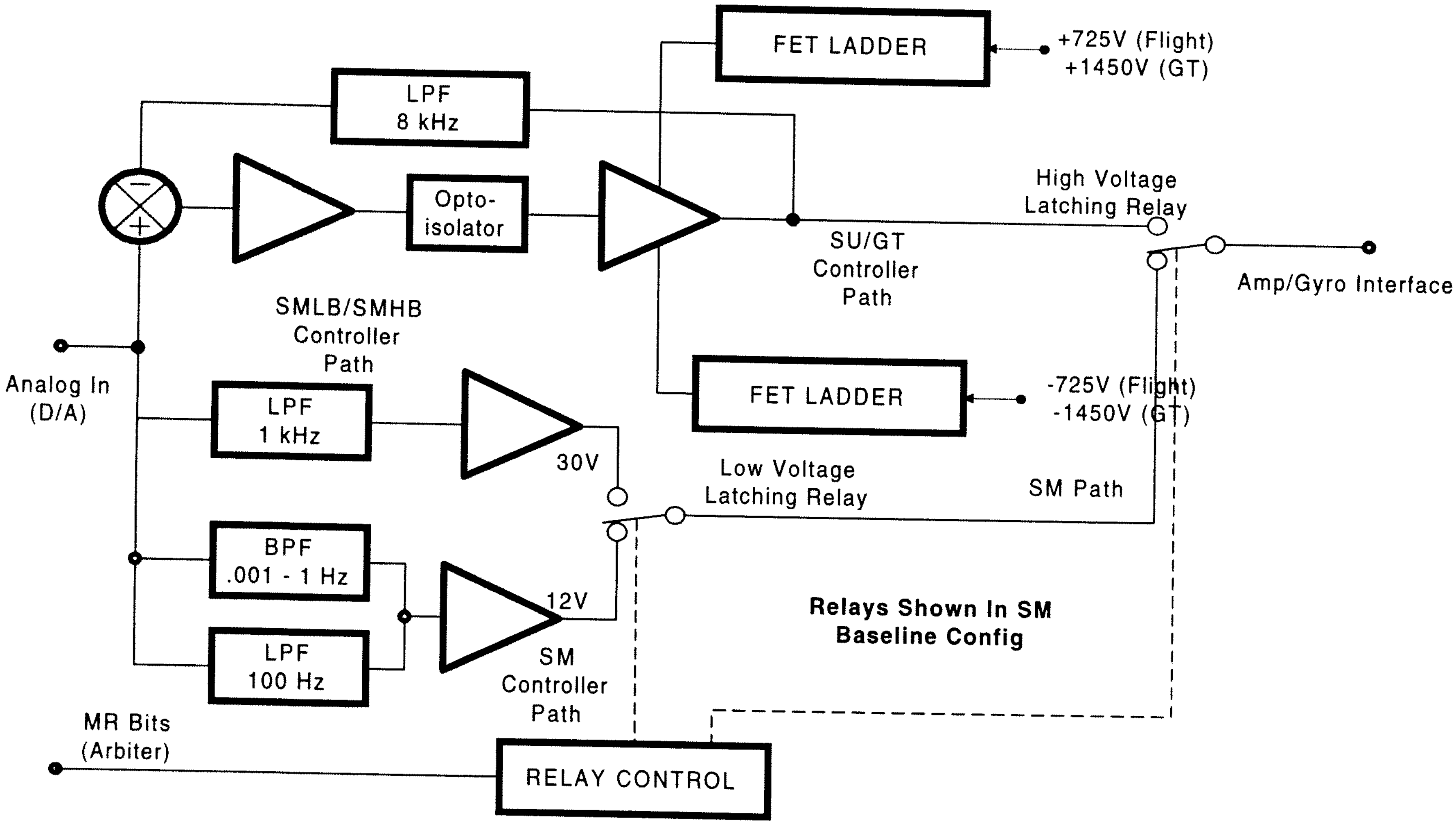
3. Design Verification

- SRE Friendliness Proven In GTU-2
- White Noise <1nm/SQRT(Hz) , 5 mHz to 5 kHz
- 50 pF Cable Capacitance Variation Tolerated During 1g Levitation
- Driven Shield Scheme Reduced Cable Capacitance Effects By Two Orders Of Magnitude:
  - 50 pF change when driven changed Position Output 14 mv, compared to 1.5 V when undriven.

4. Flyability

- Prototype Bridge Module Represents Flyable Design
- Existing Oscillator Uses Digital PLL and Non-Flyable Parts. All Analog Flyable Design Is In Breadboard Stage.

Multi-Level Amplifier



Multi-Level Amplifier

1. Design Drivers

- SRE Friendly
- MR Reconfigurable Amp Which Spans SM/SU (Baseline and Backup) Control Authority Needs

2. Design Verification

- Ground Test Mode Operation Verified In Extensive 1g Testing
- Science Controller SRE Compatibiltiy Demonstrated In GTU-2
- White Noise In Science Mode < 1 μV/SQRT(Hz) above 1kHz

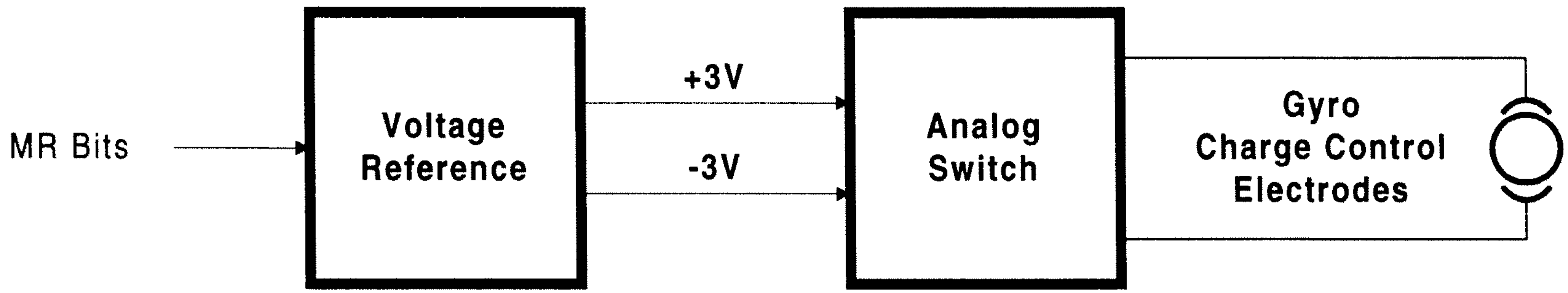
3. Flight Issues

- High Voltage FETs Will Change For Flight
- Prototype Relay Driver Design In Modification
- All Other Parts and Designs Flyable

Charge Control Bias

Charge Control

- Decodes MR Bits From Forward Comm Link
- Applies +3 v, -3 v, or 0 v To Charge Control Electrodes

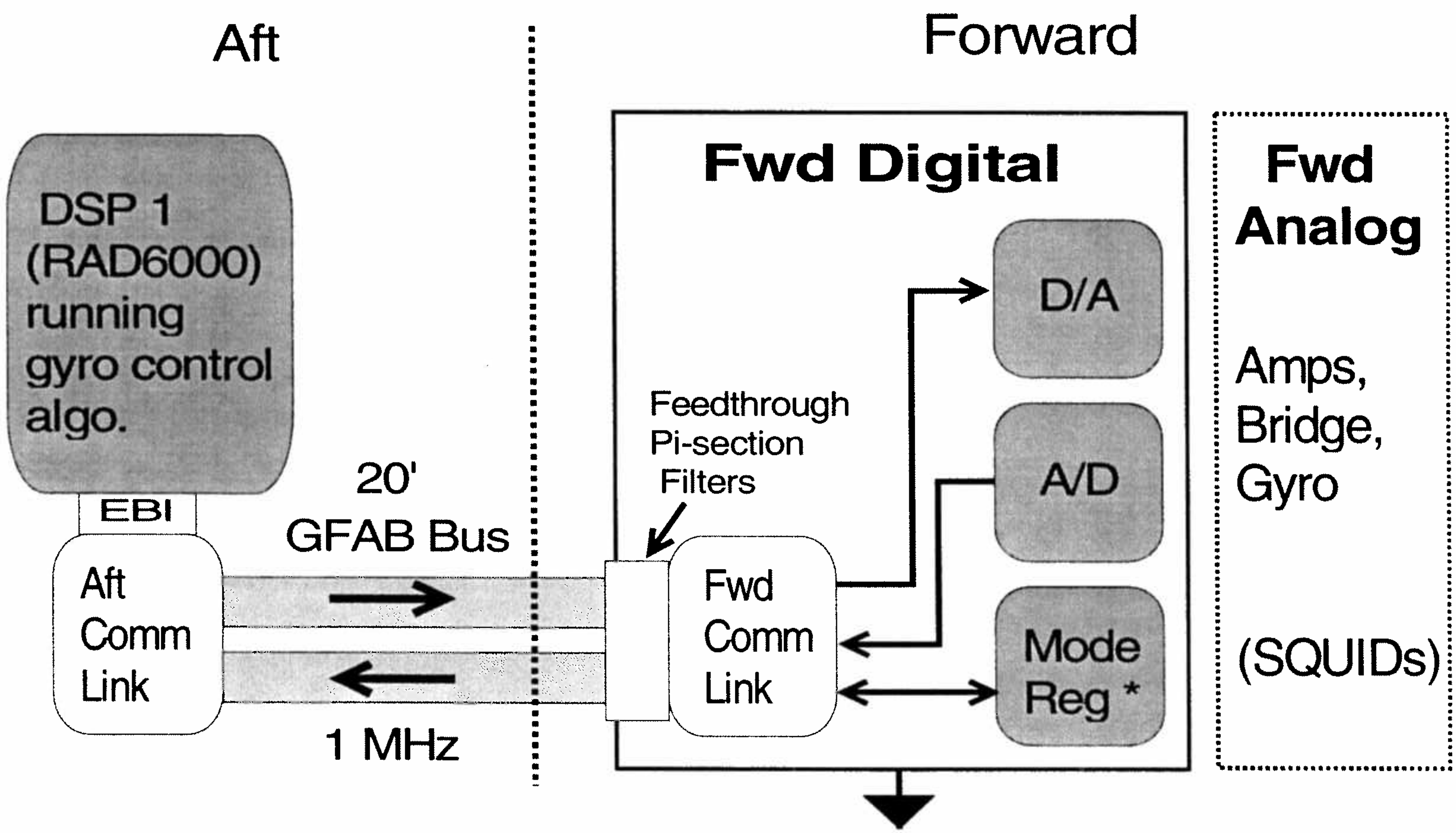


Charge Control System

6.3 Digital Hardware Design

Paul Lassa

Simplified Digital Control Subsystem

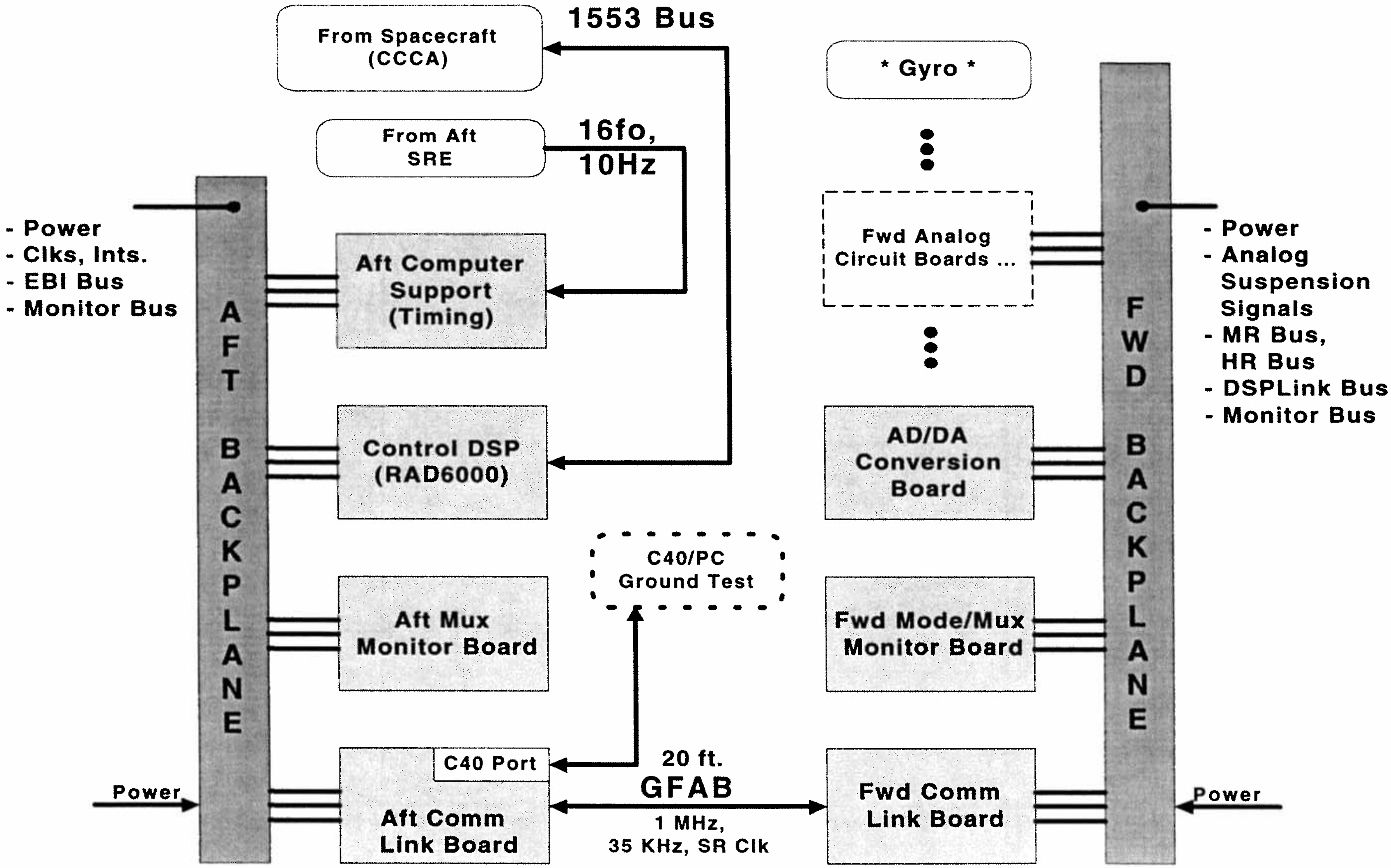


GFAB = Gyro Forward-Aft Bus

GSS Digital Systems Mission

1. Communications with Spacecraft/CCCA (Commands,Telemetry).
2. Develop and Test Flight-Qualified Suspension Control Program and Embedded O/S running on RAD6000.
3. Provide Monitoring and Diagnostics support H/W and S/W.
   - Ensure Health/Integrity of Digital Control Path
4. Develop Aft to Forward Extension Bus Communications (GFAB).
5. Develop all Electrical Interfaces from RAD6000/DSP to Fwd Analog Subsystems (EBI, AD/DA, Mode Register, Backplanes).

GSS Digital System



GSS Digital Subsytems

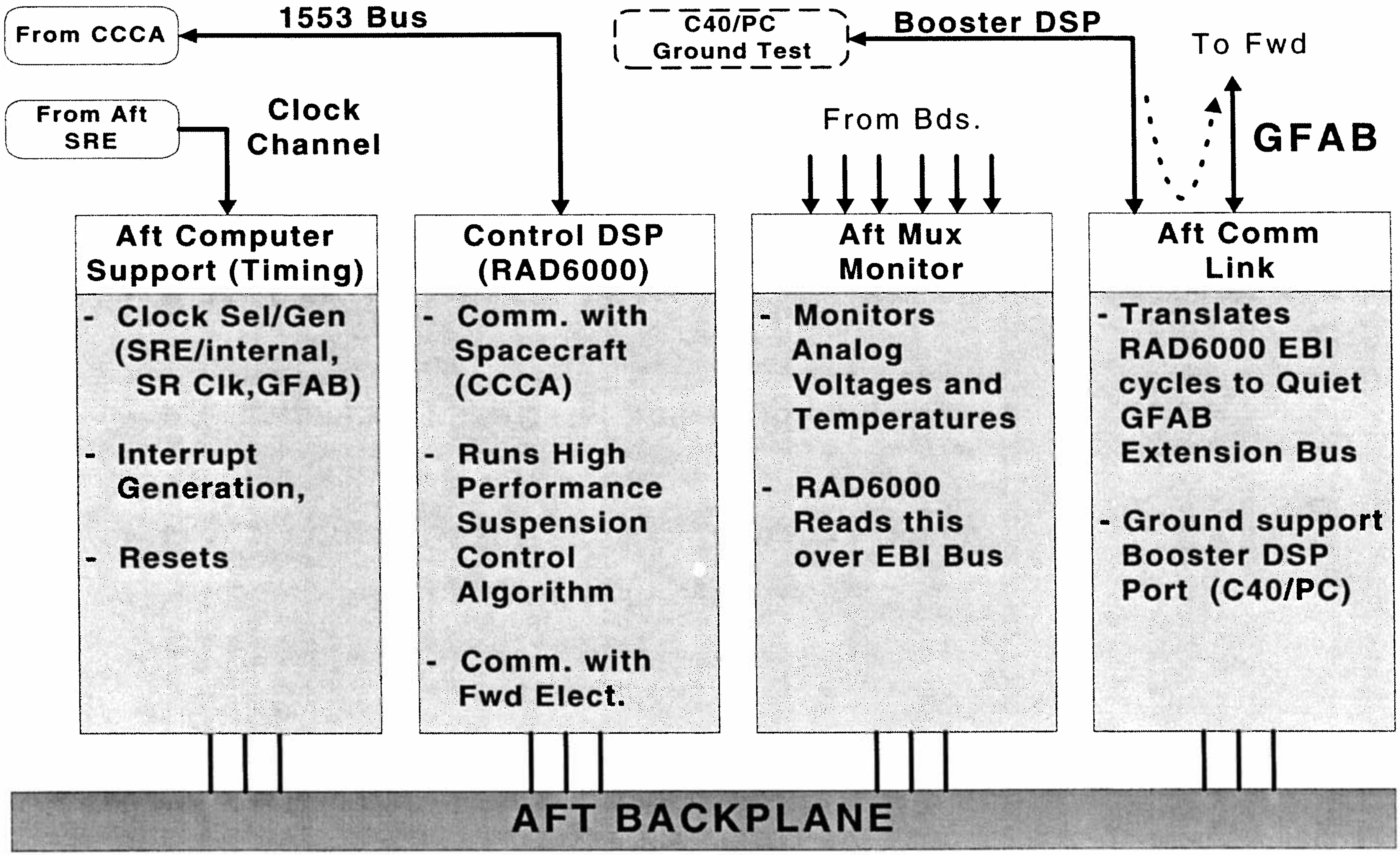
Aft Section

- Aft Backplane Bus
- Aft Computer Support (Timing, Ints.) Board
- Digital Control DSP (RAD6000) Computer Board
- Aft Mux Monitor Board
- Aft Comm Link (GFAB Controller) Board ☆

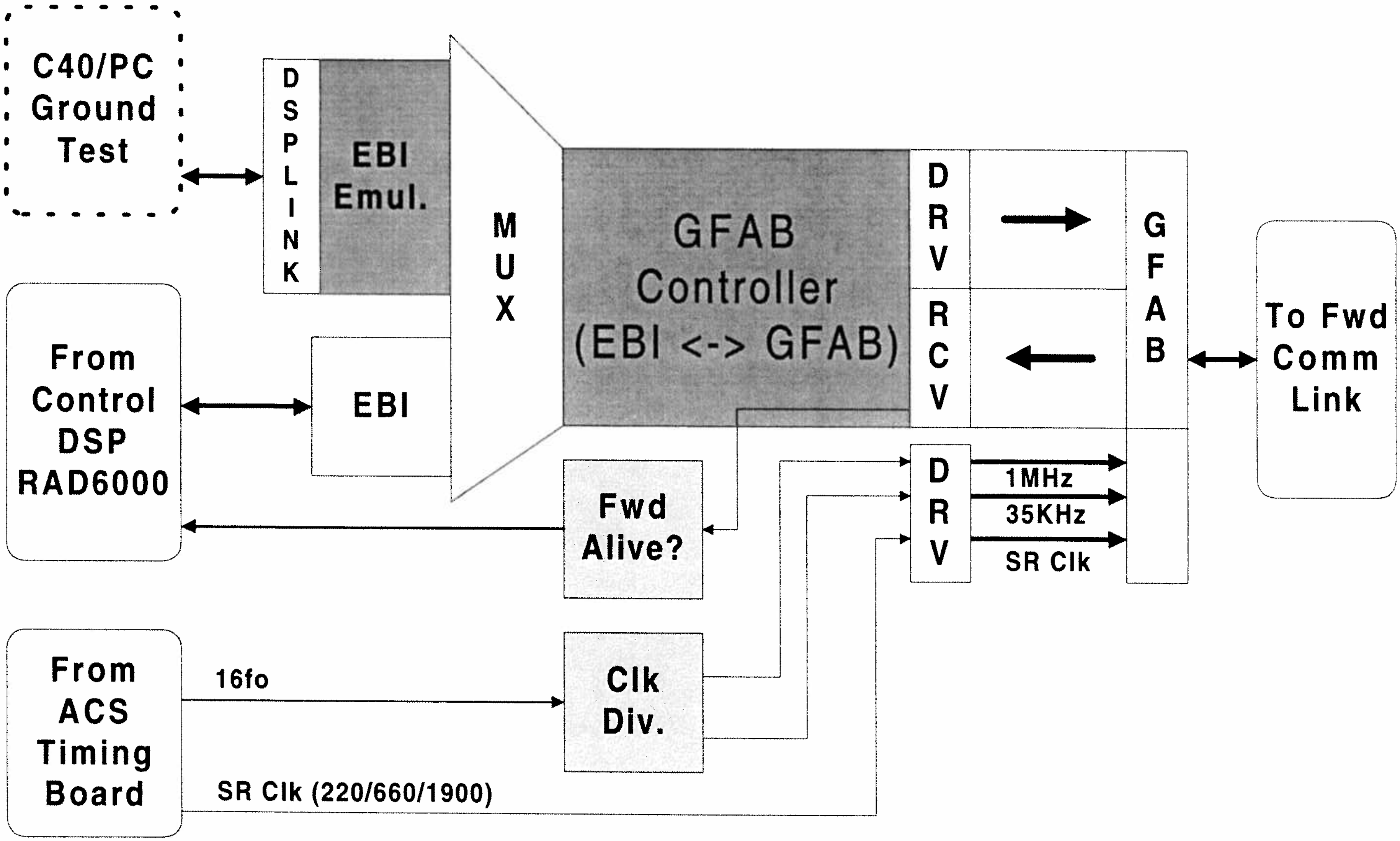
Forward Section

- Fwd Backplane Bus
- Fwd Comm Link (GFAB Receiver) Board
- Fwd Mode/Mux Monitor Board (Mode Register) ☆
- AD/DA Board

Aft Control Unit (ACU)



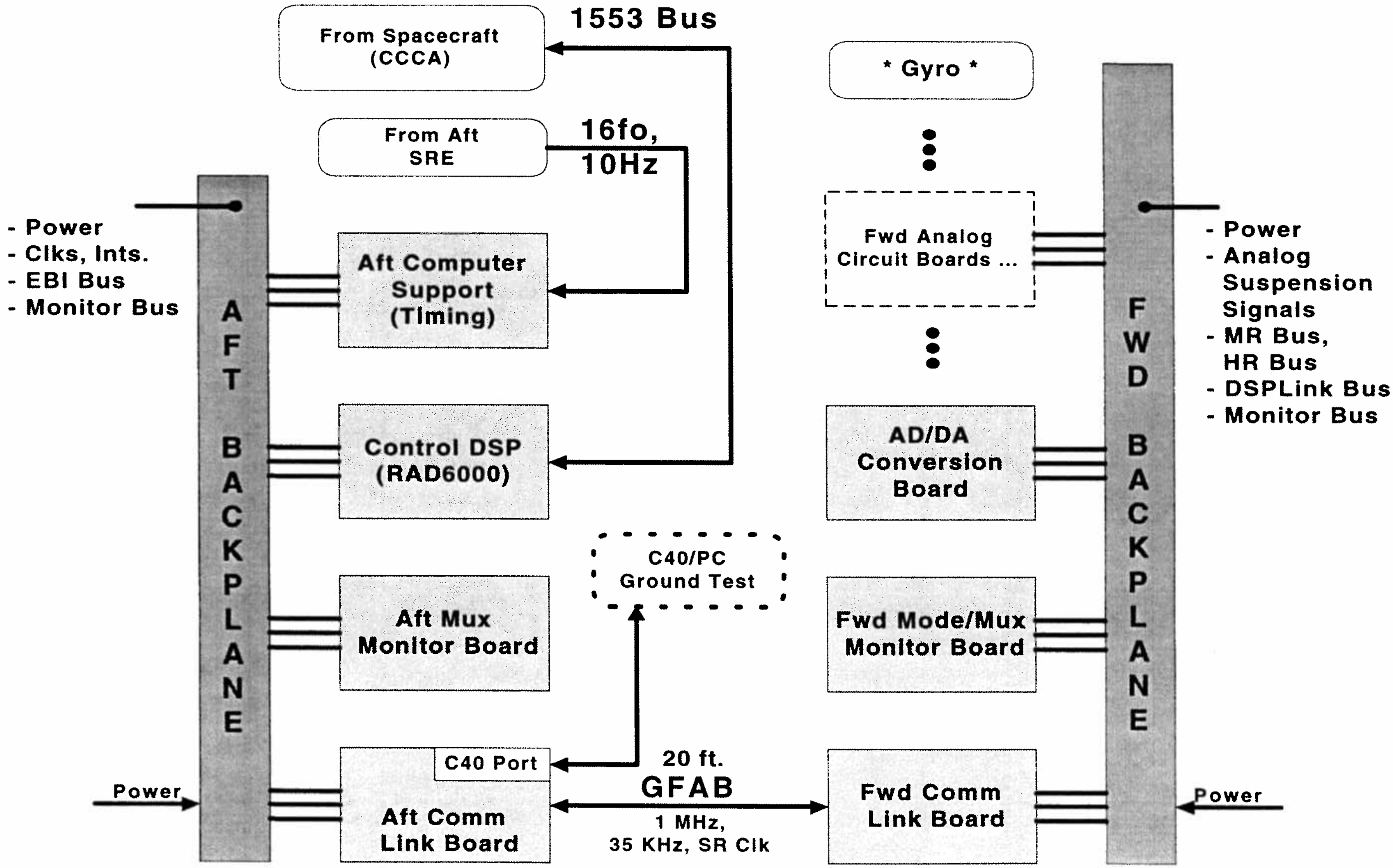
Aft Comm Link Block Diagram



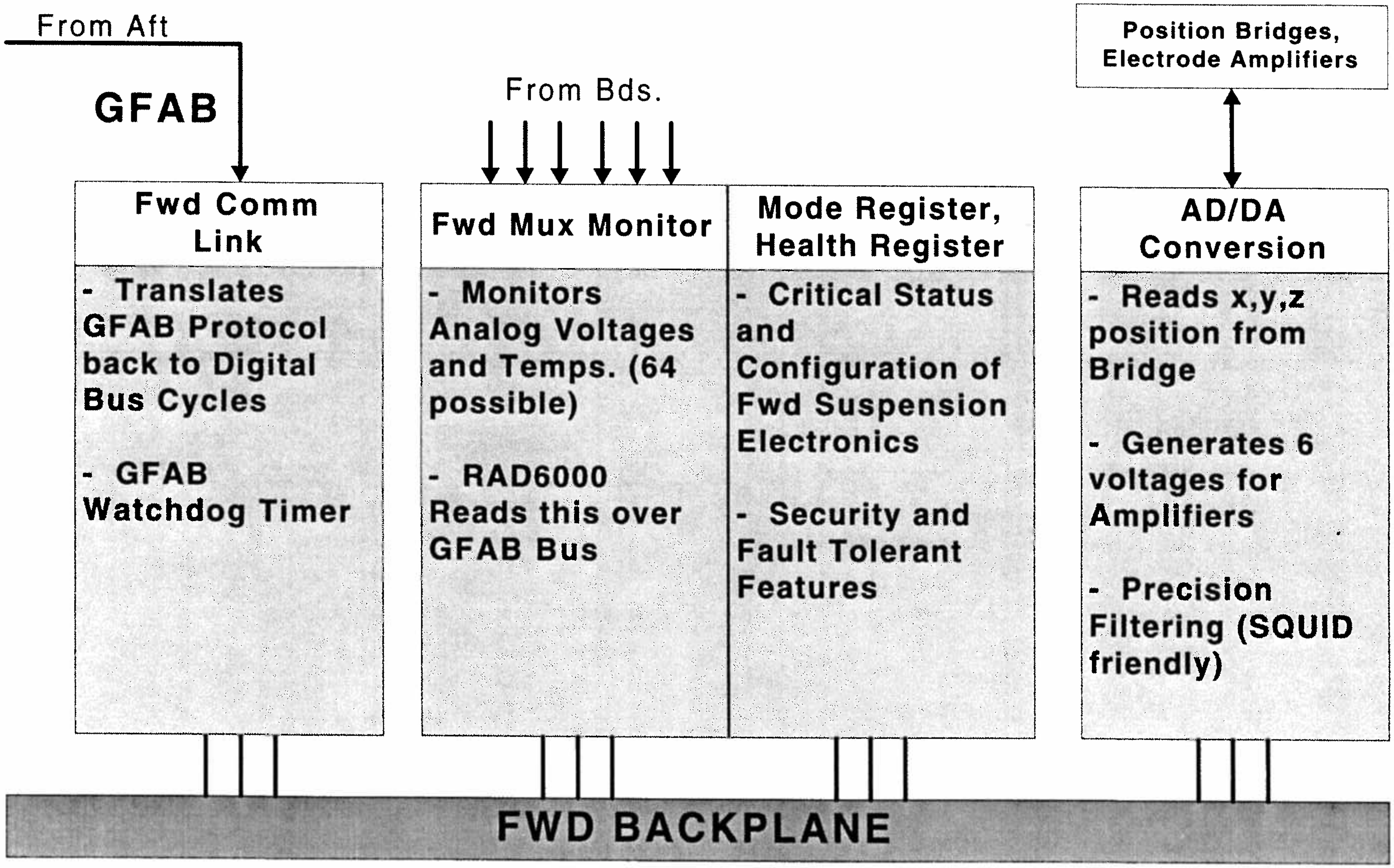
Aft Comm Link/GFAB Controller

- **Interfaces with RAD6000 over Expansion Bus Interface (EBI)**
- **Drives GFAB Comm Cable (20 foot, 80-pin, differential, shielded)**
- **Contains Ground Test Computer Port (C40 + EBI Emulator)** ☆
- **Design Details...**
  - SQUID compatible design emphasis
  - Receives $16f_o$ and Sample Rate Clock from ACS Card
  - Generates 1MHz GFAB, 35 KHz bridge excitation clock from $16f_o$
  - Supports SM to Ground Test Control Data Transfer Data Rates.
  - Provides EBI loop-back diagnostics.
  - Employs 54HC04/LM119 differential line driver/receiver circuits as used in SRE FAB design.
  - Robust Hardened discrete logic design

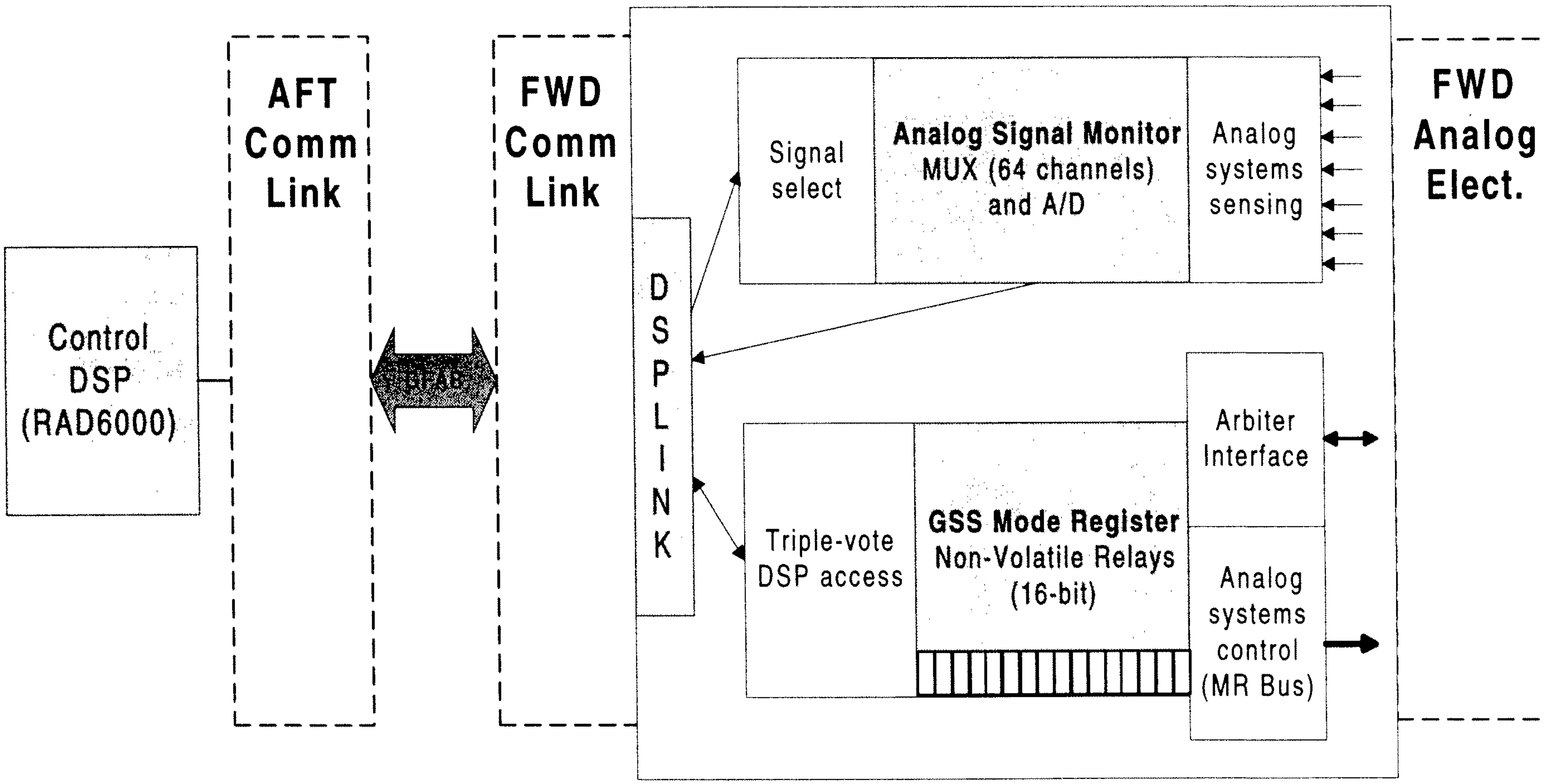
GSS Digital System



Fwd Suspension Unit (FSU)



Mode/Mux Monitor Block Diagram



Mode/Mux Monitor Deck – Analog Signal Monitor

Interfaces:

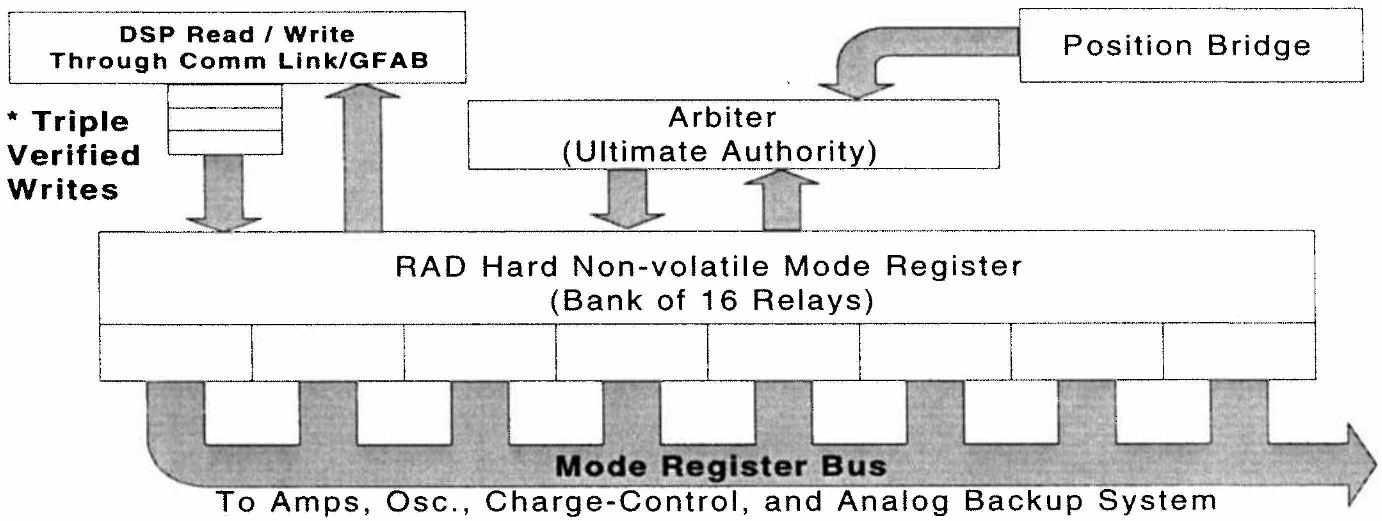
- Monitors Analog Inputs from Fwd Backplane (Fwd Cards)
- Interfaces with Fwd Comm Link over DSPLink.

Mode/Mux/Monitor Functions:

1. Analog Signal Mux/Monitor (MM)

- Supports local diagnostics, monitoring
- Monitors Fwd temperature and voltage analogs, discretes
- Includes multiplexer and analog to digital converter
- 64 channels of analog monitoring
- Common design with Aft Mux Monitor Deck

Mode/Mux Monitor Deck – Mode Register



1. Holds critical status and configuration information for the GSS system.
   - Computer reads arbiter mode/state decision results
   - Computer writes mode change request (Mission Mode, UV bias, etc.)
2. Arbiter portion of Mode Register configures control loop H/W.
   - MR Bus is broadcast to Fwd cards over Fwd Backplane.
3. Security and Fault-Tolerant Features, S/W Issues
   - Rad-Hard Non-volatile Latching Relays / Stable through computer crashes or re-boots
   - Parity check and Triple-Vote Write
   - Maintains a Watchdog timer on the GFAB bus to identify GFAB/Computer crashes.

Mode/Mux Monitor Deck – Health Register

3. Health Register (HR)

- Provides secondary status Register for Fwd Cards
- Augments status on MR, Arbiter, Comm Path
- Is a read-only from Computer

4. Mode Register Emulator Fixture

- Static MR switches
- For development / testing

Digital System H/W Wrap-up

1. **Support Boards and Backplanes in Specification Stage.**

2. **Fwd, Aft Comm Links, AD/DA Conversion Board**
   - Prototypes Functional in GTU-2.
   - Refinements have been identified.
   - Further development planned.

3. **Mode Register Board**
   - Test emulator built
   - Preliminary Spec released
   - Design in progress

4. **RAD6000 1G Lift imminent.**

Information in Technical Appendix

The following digital subsystems will not be discussed in the presentation, however, information on them is included in the technical appendix package:

- Aft Backplane Bus
- Aft Computer Support Card
- Aft SRE Emulator Card
- RAD 6000 DSP Features
- Aft Mux/Monitor Deck
- Forward Backplane Bus
- Forward Comm link/GFAB receiver
- AD/DA Conversion Board
  - Board features
  - AD/DA board block diagram

System Design Summary

Top Level Design Status:

100%	Design Concept
77%	Prototype Schematic
58%	Tested in Prototype

☆ **All high risk subsystems have been prototyped except backup controller (prototype schematic in place).**

Design Issues

Critical Issues to be Resolved ASAP:

- Demonstrate BU Controller in 1g.
- 1G Lift w/ RAD6000.
- Test of Spin-Up Mode Backup Near The Wall.

Major Risks:

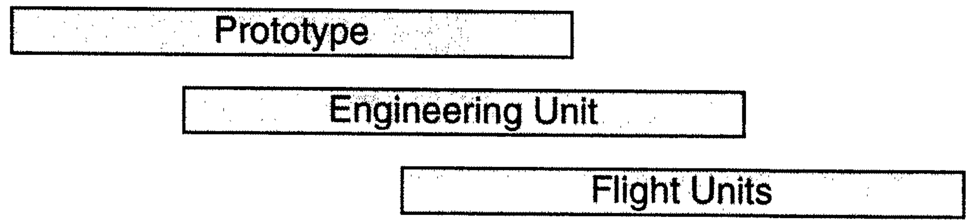
- Single String System
  - 4 Independent Systems (However Catastrophic Failure May Couple)
- Aggressive Schedule.
- Spin-Up Mode Backup.
- > 1kg-m/s Disturbance During Science Mode.

7. Flight Development

David Manner

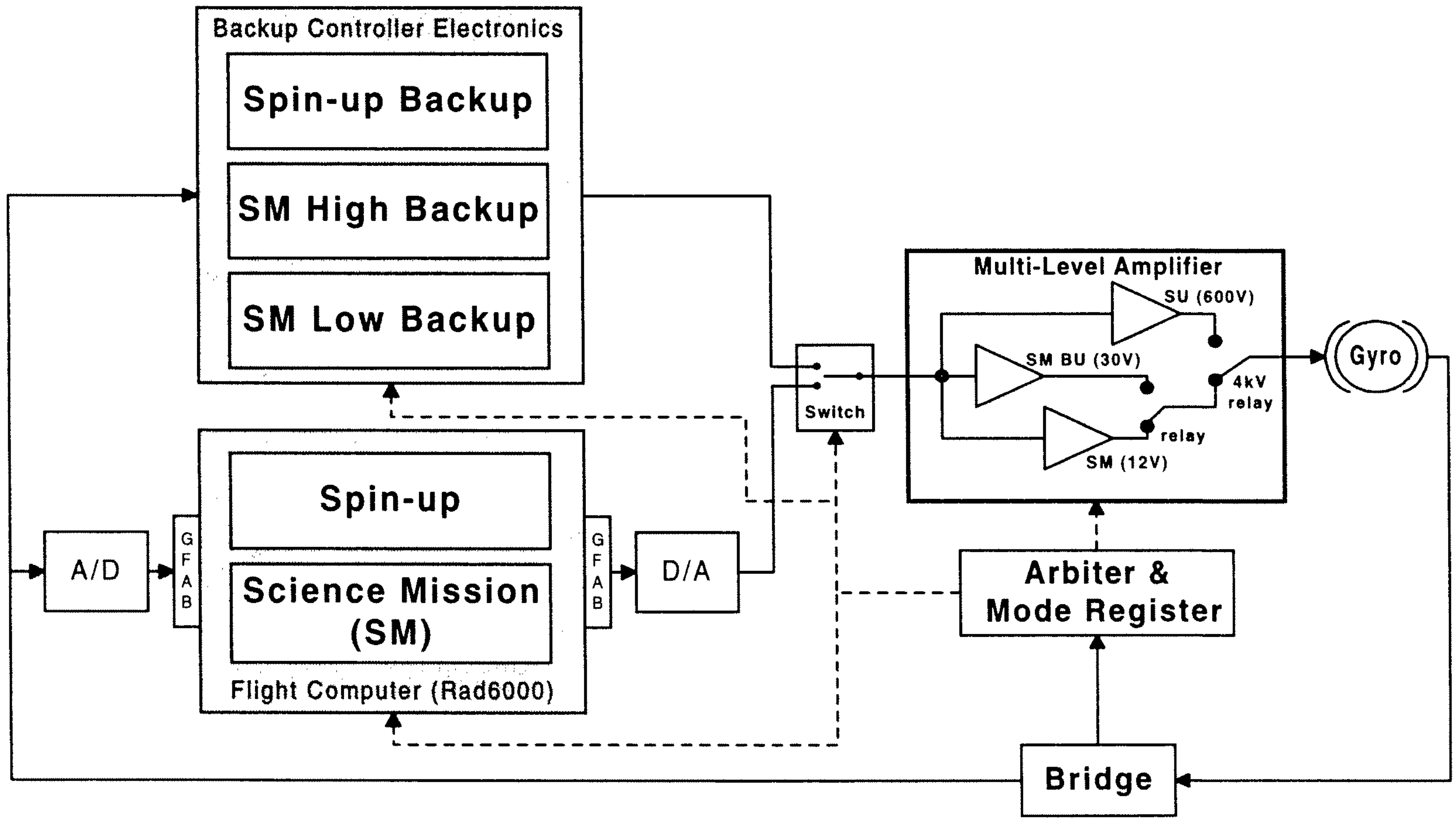
Flight System Development Approach

- **Parallel Development:**
  - Prototype
  - Engineering Unit
  - Flight Units

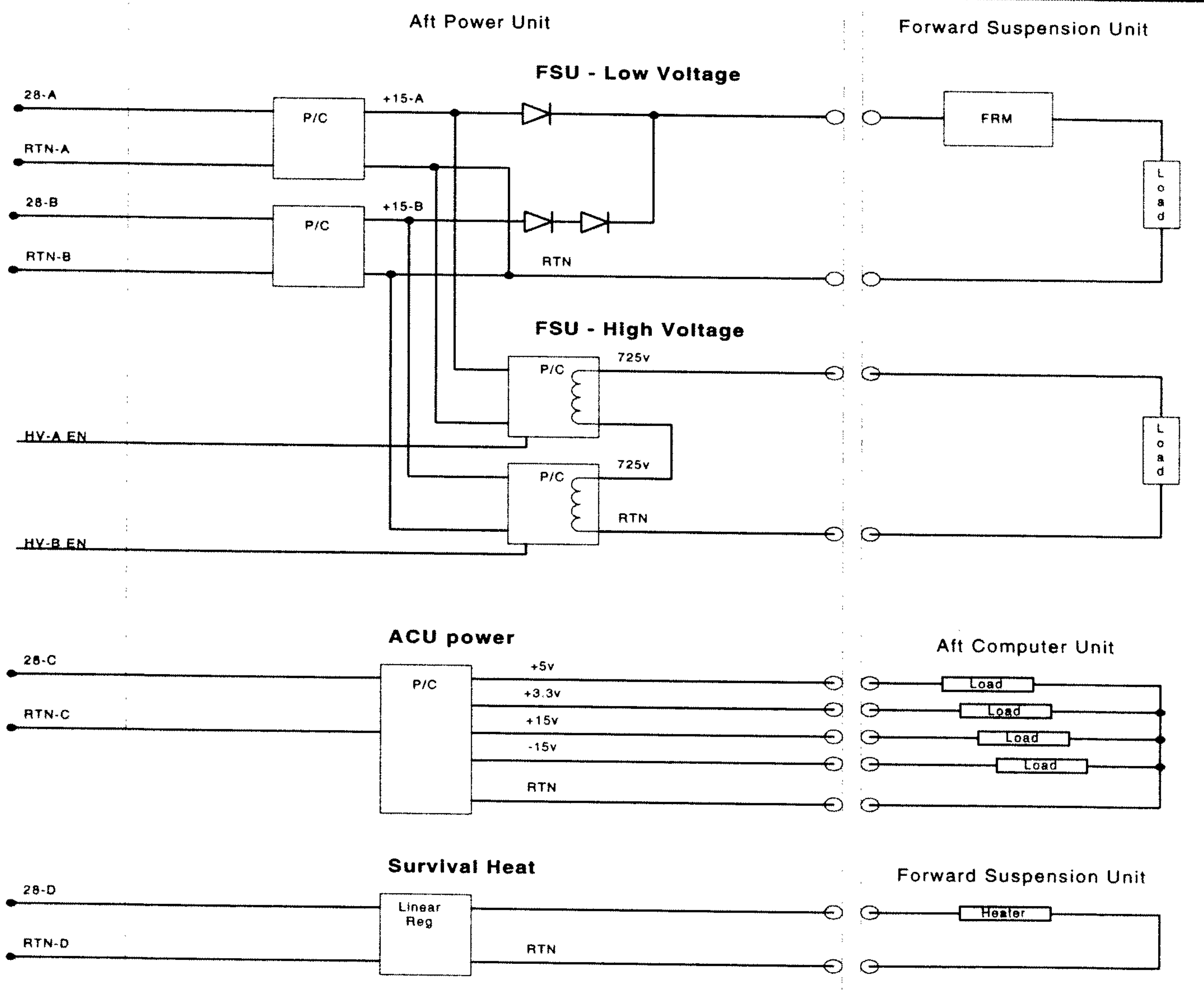


- **Fault Tolerant Architecture**
  - primary / backup controllers
  - redundant power supply
- **High Fidelity - Full Range Test Bed**
- **Radiation Tolerant Components**
  - flight qualified
  - radiation testing program

Flight System Architecture

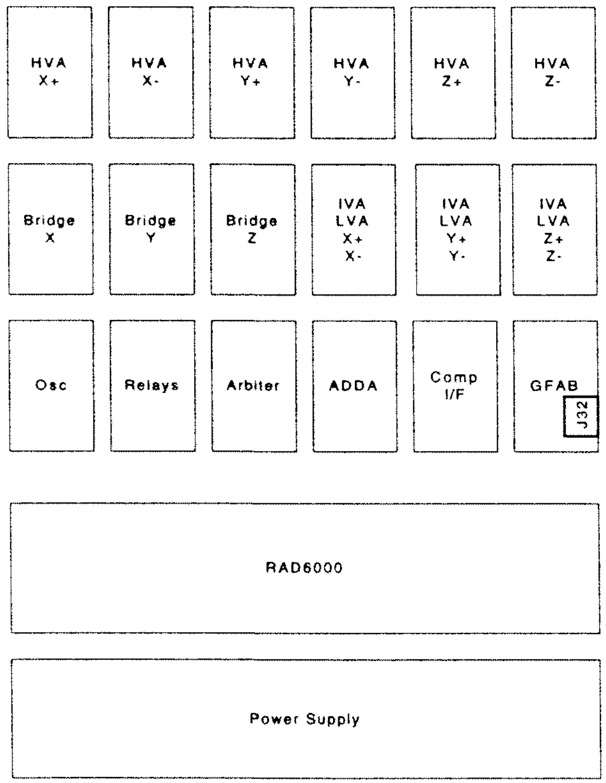


Power System Architecture

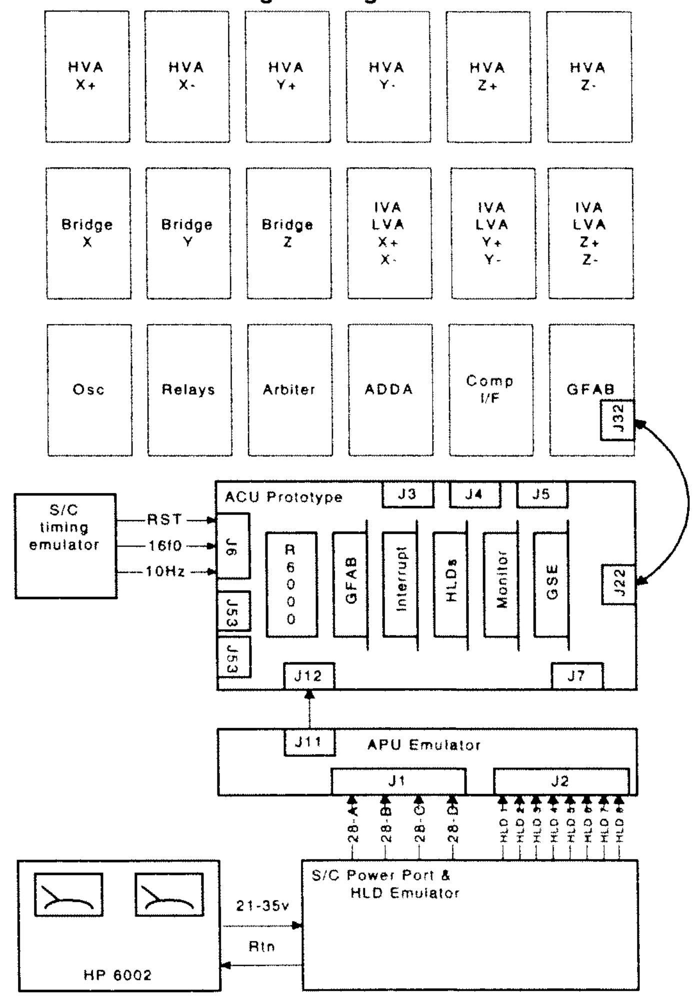


Flight Hardware Transition - 1

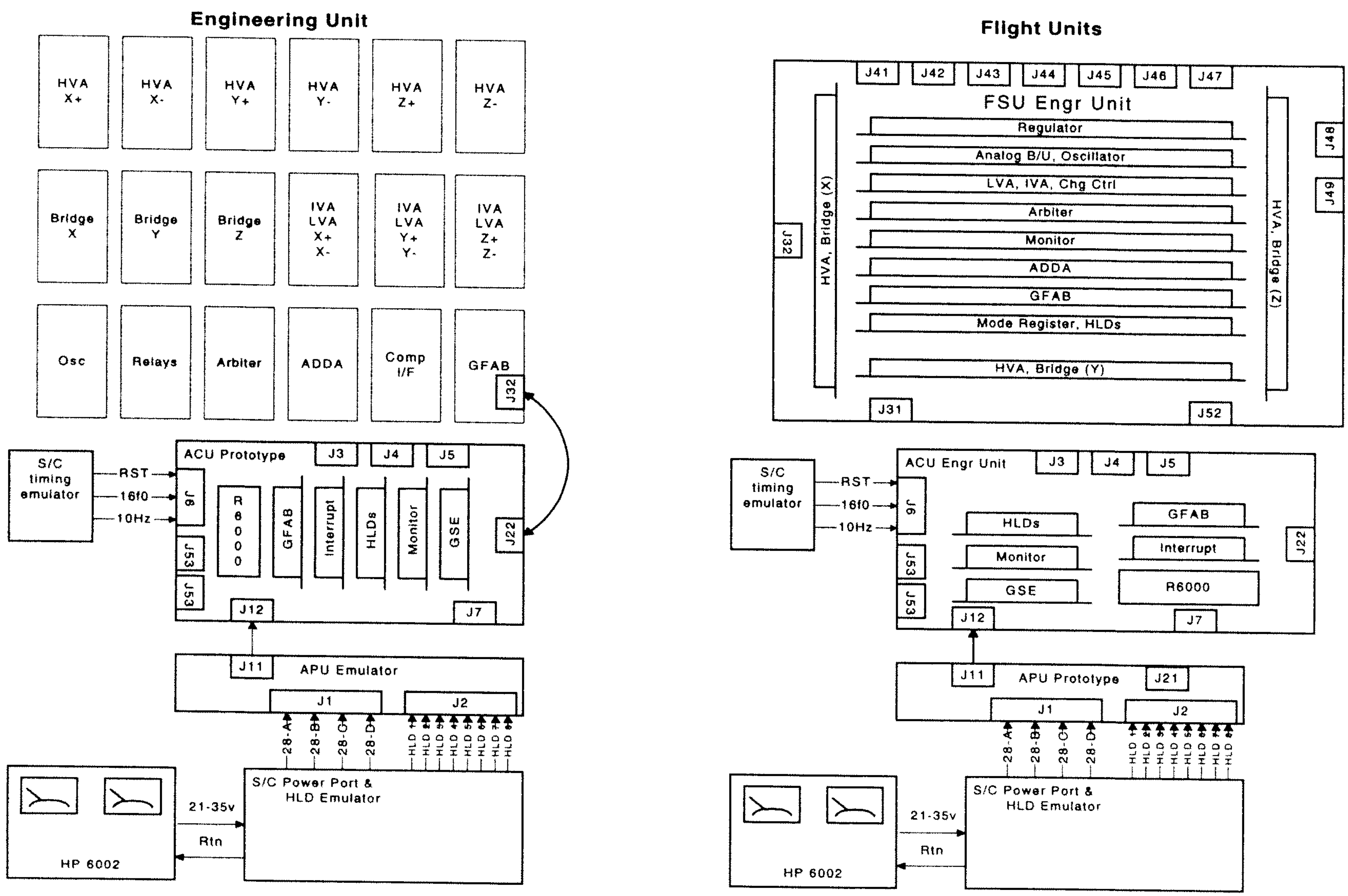
Prototype



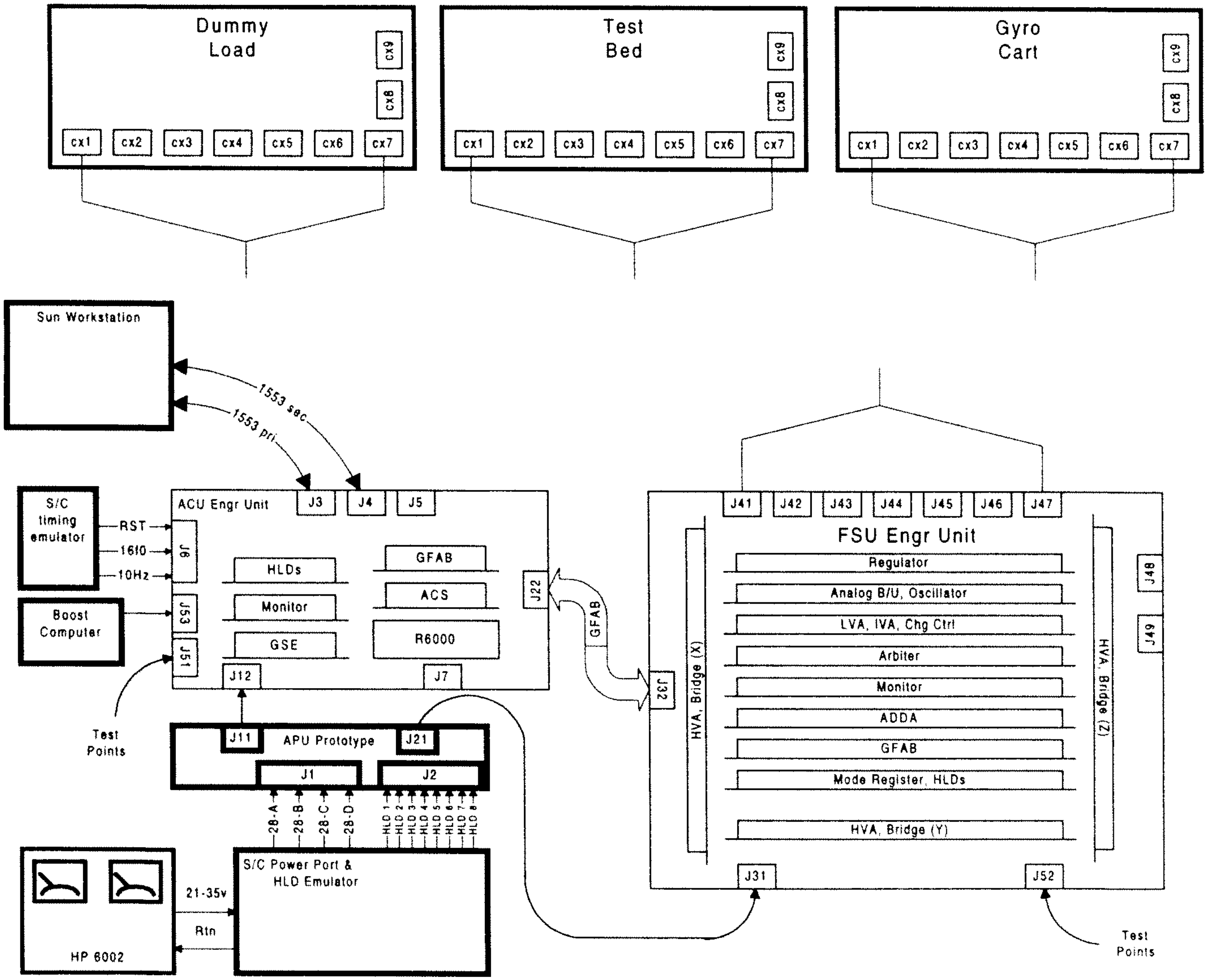
Engineering Unit



Flight Hardware Transition - 2



Ground Support Equipment



Radiation Tolerance Requirements

- SEU - cannot lead to loss of control
- Total Dose tolerance greater than 10Krad
- SEB - LET greater than 80 Mev/mg/cm^2
- Latch Proof - LET greater than 80 Mev/mg/cm^2

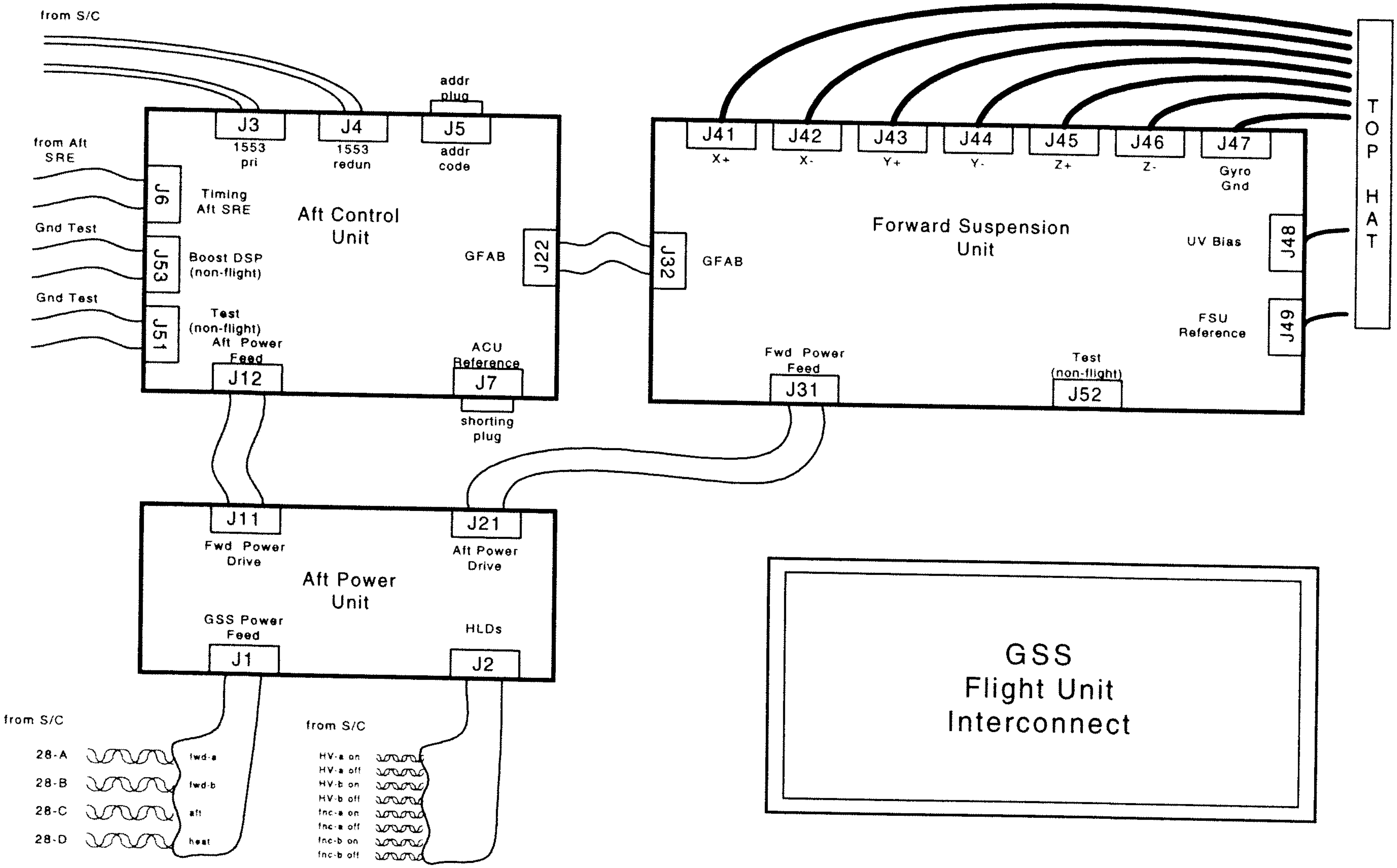
Radiation Tolerance Issues

- **Active Part Types (not including Power Supply) - 42**
  - No Testing Required 14%
  - No Further Testing Required 21%
  - Latch Proof 48%
  - Test Complete, Failure Analysis Underway 5%
  - Testing Underway 5%
  - Need Testing 7%

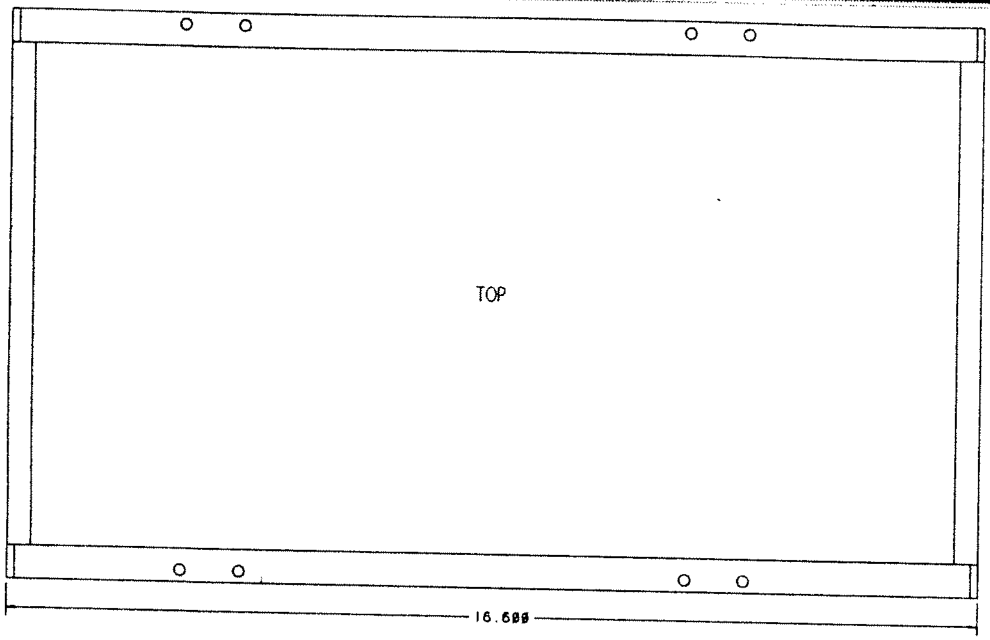
Preferred Parts List

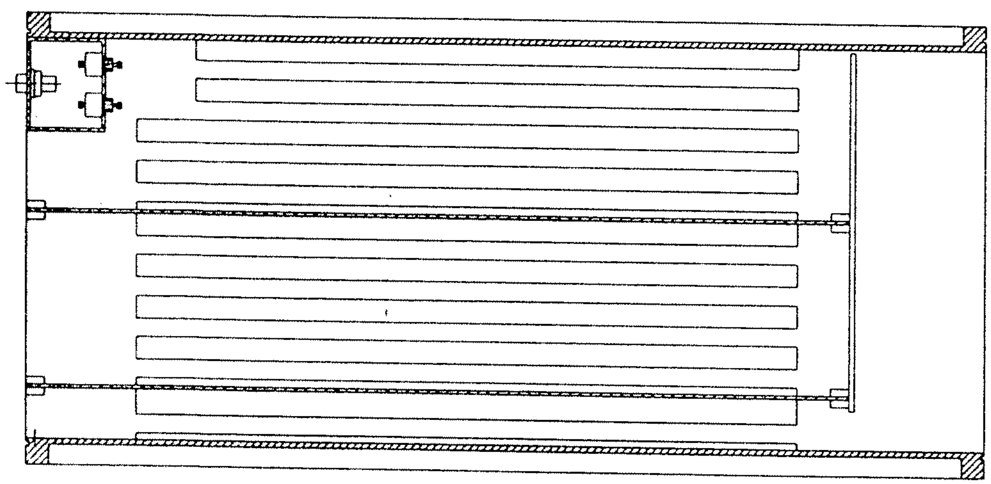
Preferred Parts			
Part Number	**Description**	**Manufacturer**	**Radiation**
AD96685	Voltage Comparator	Analog Devices	Strategic Level*
AD96687	Voltage Comparator	Analog Devices	Strategic Level*
PM139	Quad Voltage Compartor	Analog Devices	Commercial Space Level*
OP420	Quad Voltage Op Amp	Analog Devices	Manned Space Level
OP400	Quad Voltage Op Amp	Analog Devices	Commercial Space Level*
OP290	Dual Op Amp	Analog Devices	
OP200	Dual Op Amp	Analog Devices	Commercial Space Level*
OP27	Low Noise Op Amp	Analog Devices	Strategic Level*
AD847	High Speed Op Amp	Analog Devices	Manned Space Level
AD648	Dual BiFET Op Amp	Analog Devices	
HA-5142	Dual Op Amp	Harris	
HA-2520	High Speed Op Amp	Harris	
2N6782	N-Ch Power FET	Harris	
LM2941	Low Dropout Adj Reg	National Semi	
LM2991	Neg Low Dropout Adj Reg	National Semi	
Note:	Strategic Level	200Krad to 1Mrad	
	Commercial Space Level	50Krad to 200Krad	
	Manned Space Level	< or = 50Krad	
	* = Data Available		

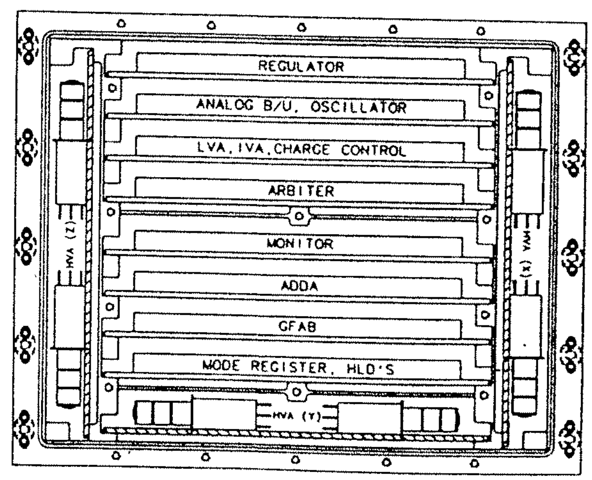
Flight Box Interconnect



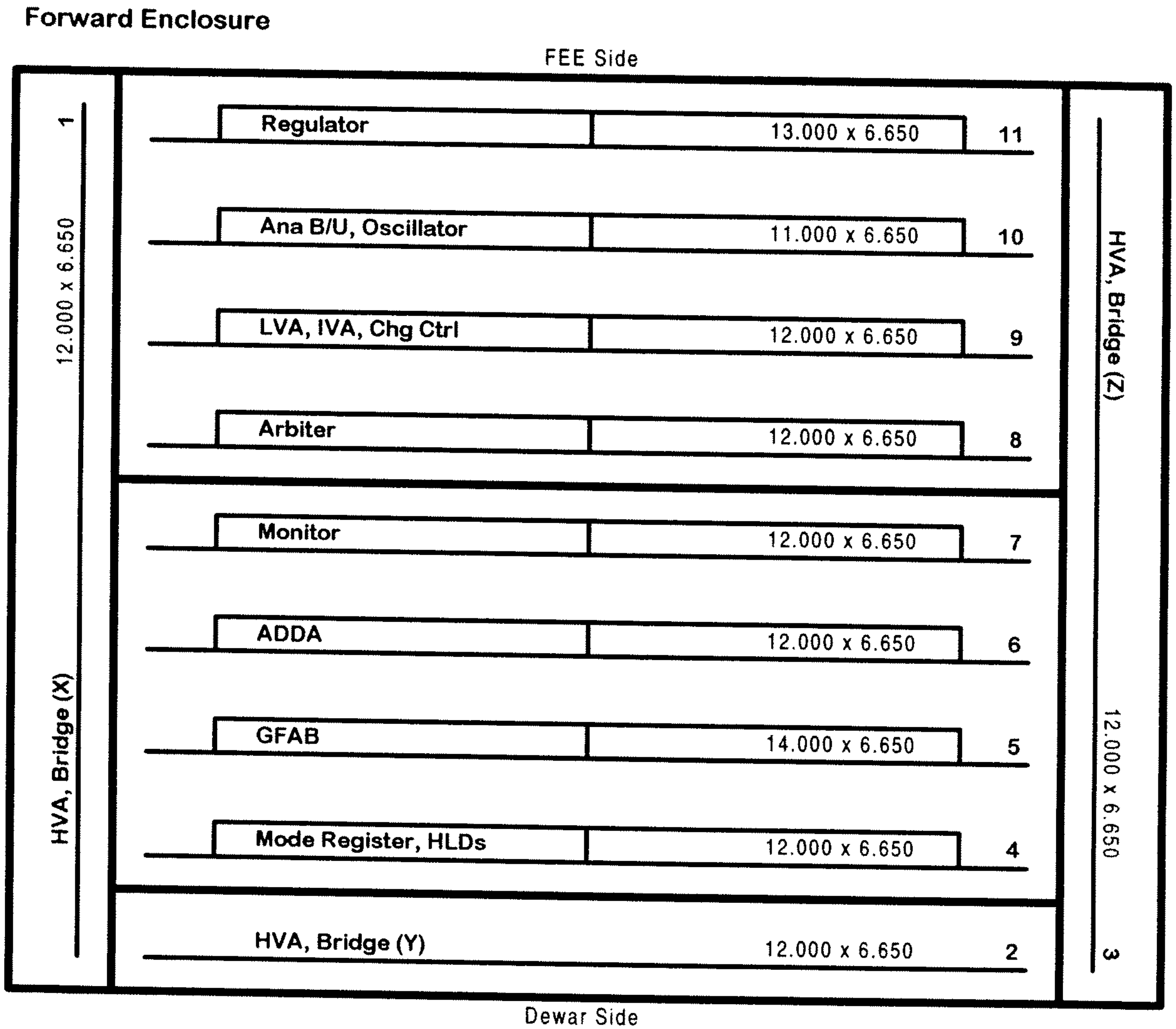
FSU Mechanicals



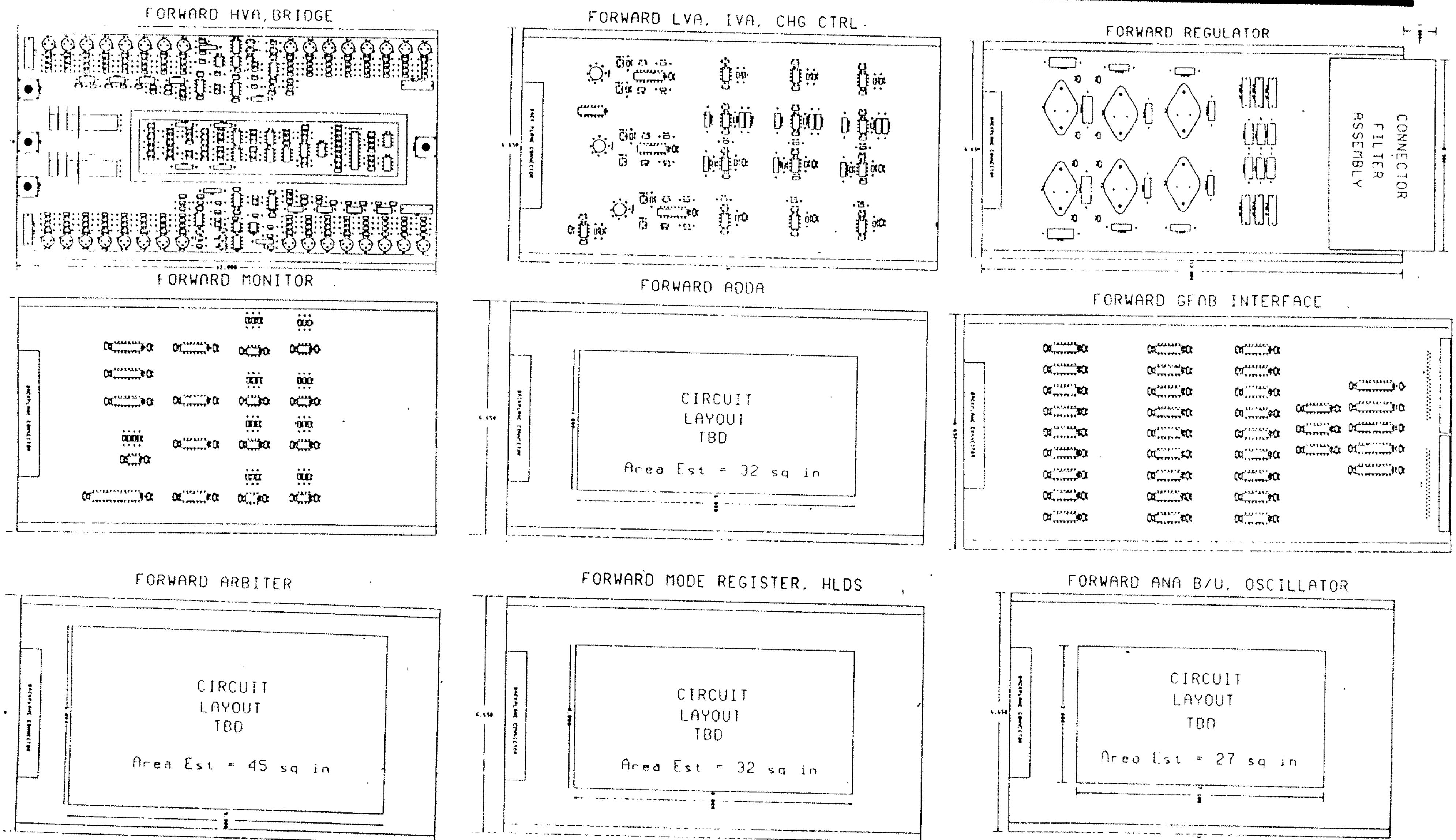




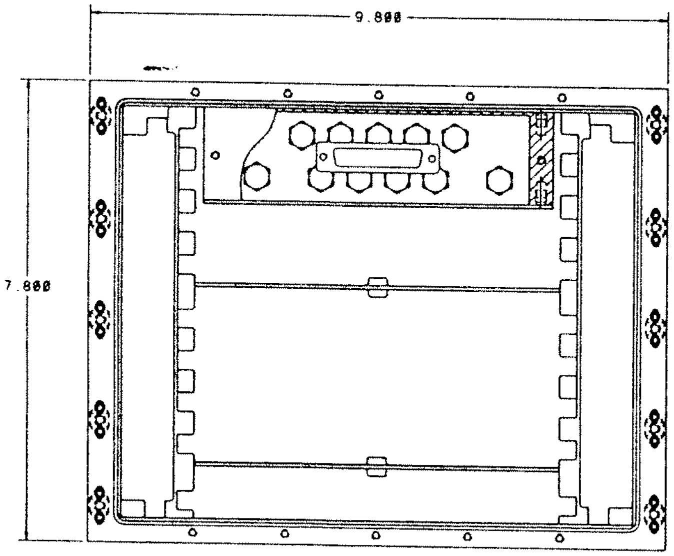
FSU Enclosure, EMI Bulkheads



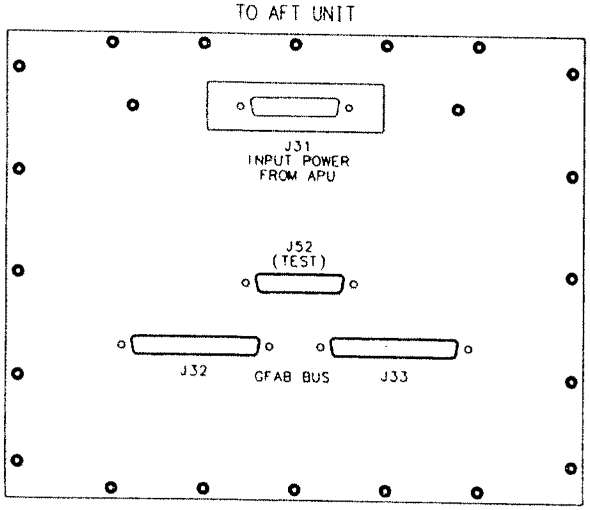
FSU Real Estate Utilization

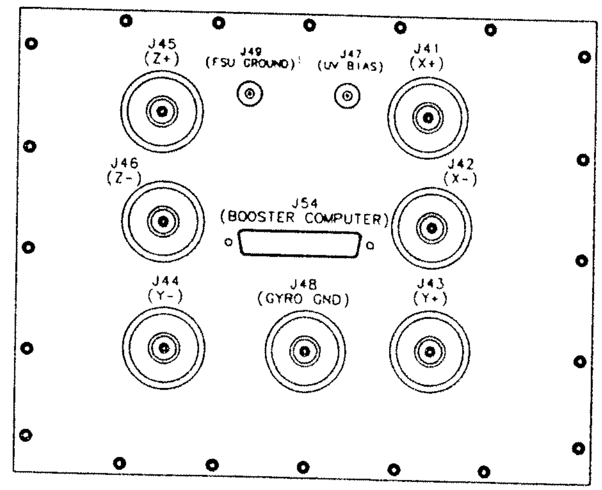


FSU Connector Layout



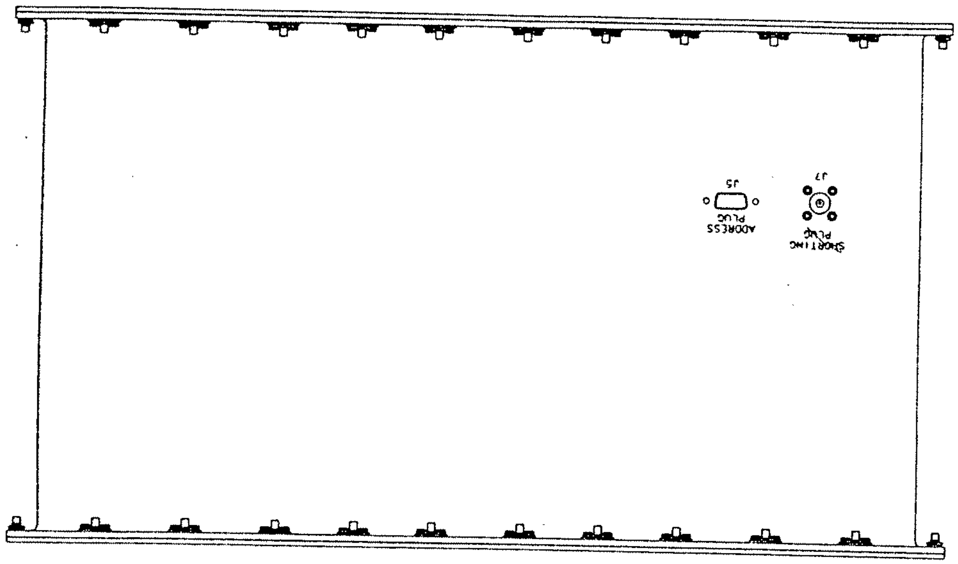
TO AFT UNIT

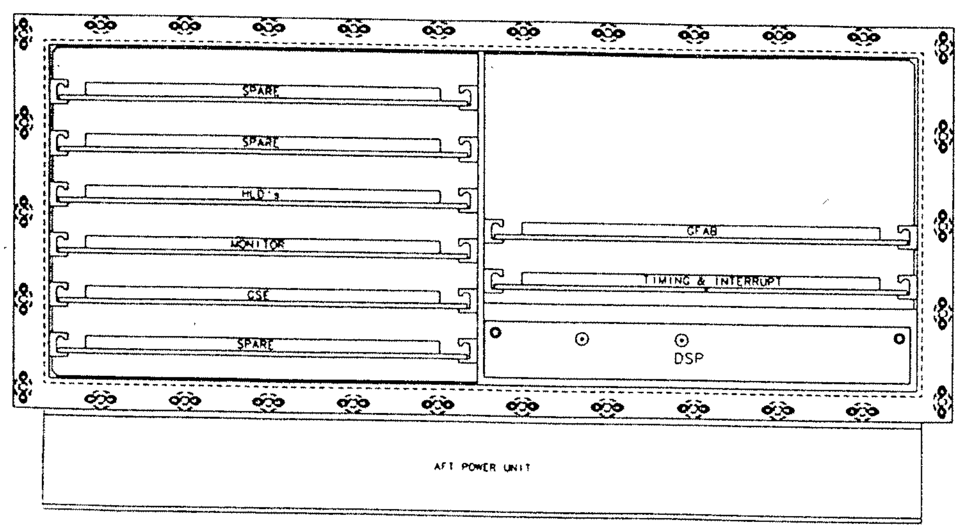


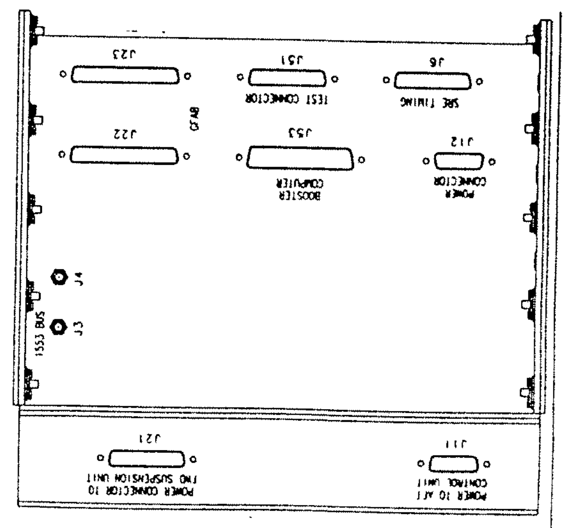


TO TOP HAT

ACU Mechanicals

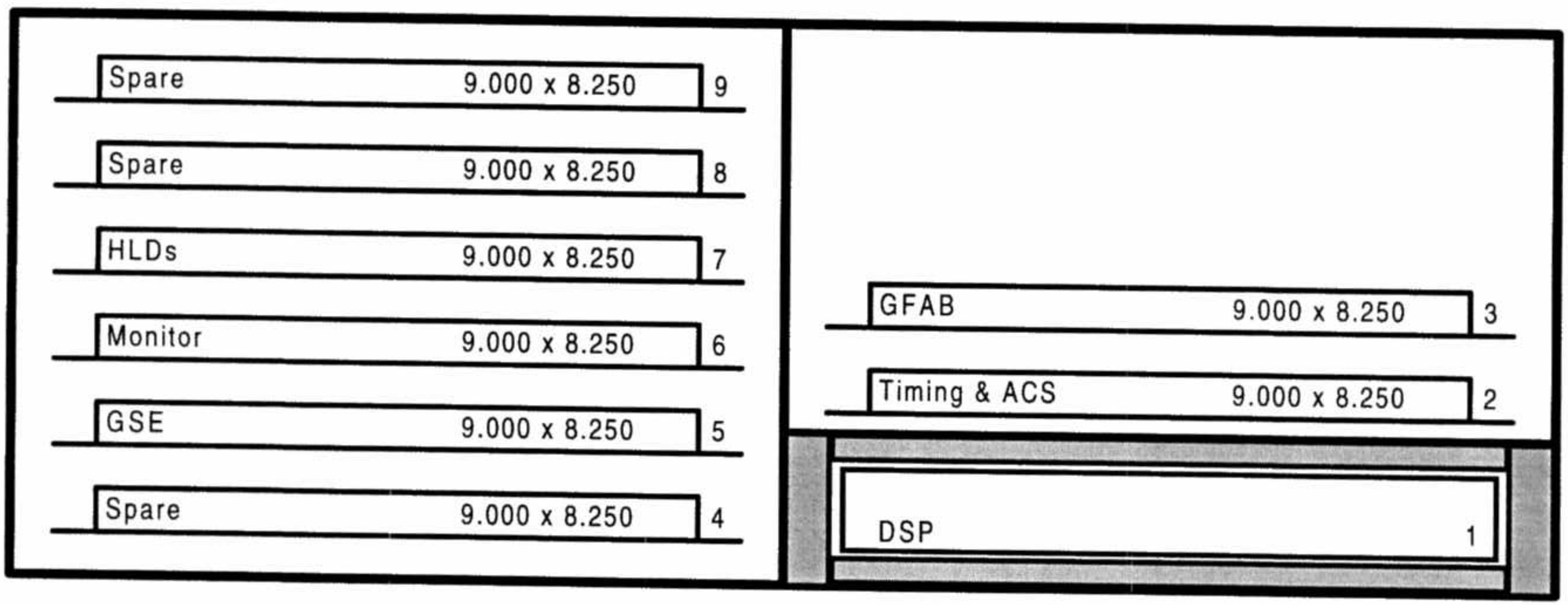






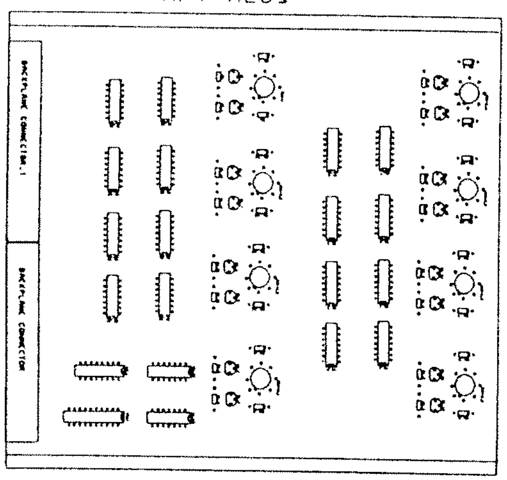
ACU Enclosure, EMI Bulkheads

Aft Computer Unit Enclosure

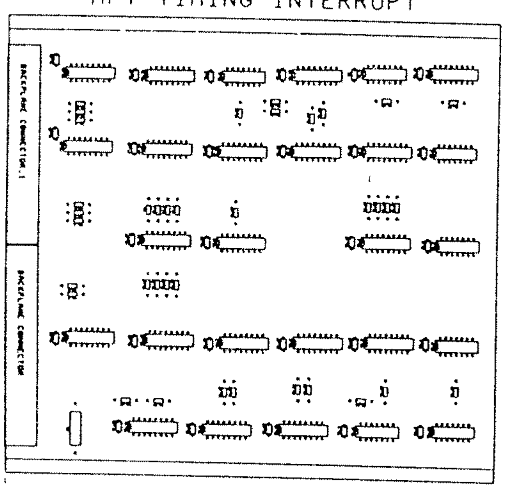


ACU Real Estate Utilization

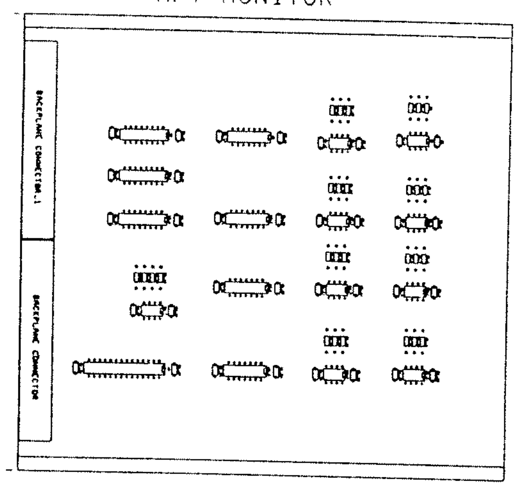
AFT HLDs



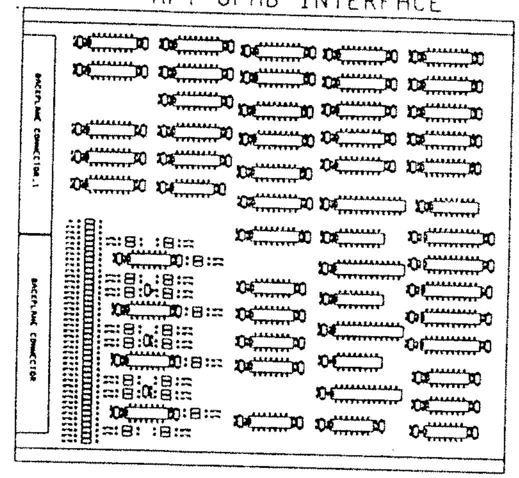
AFT TIMING INTERRUPT



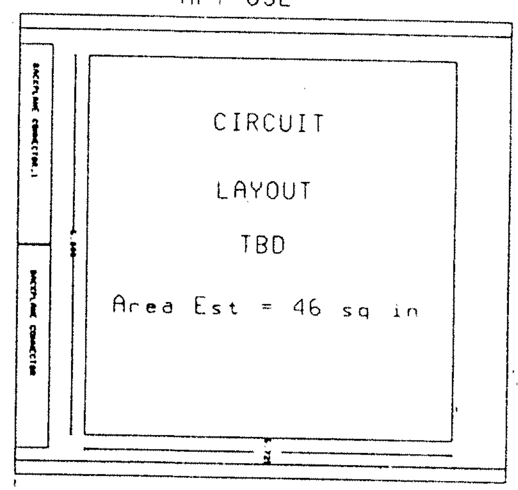
AFT MONITOR



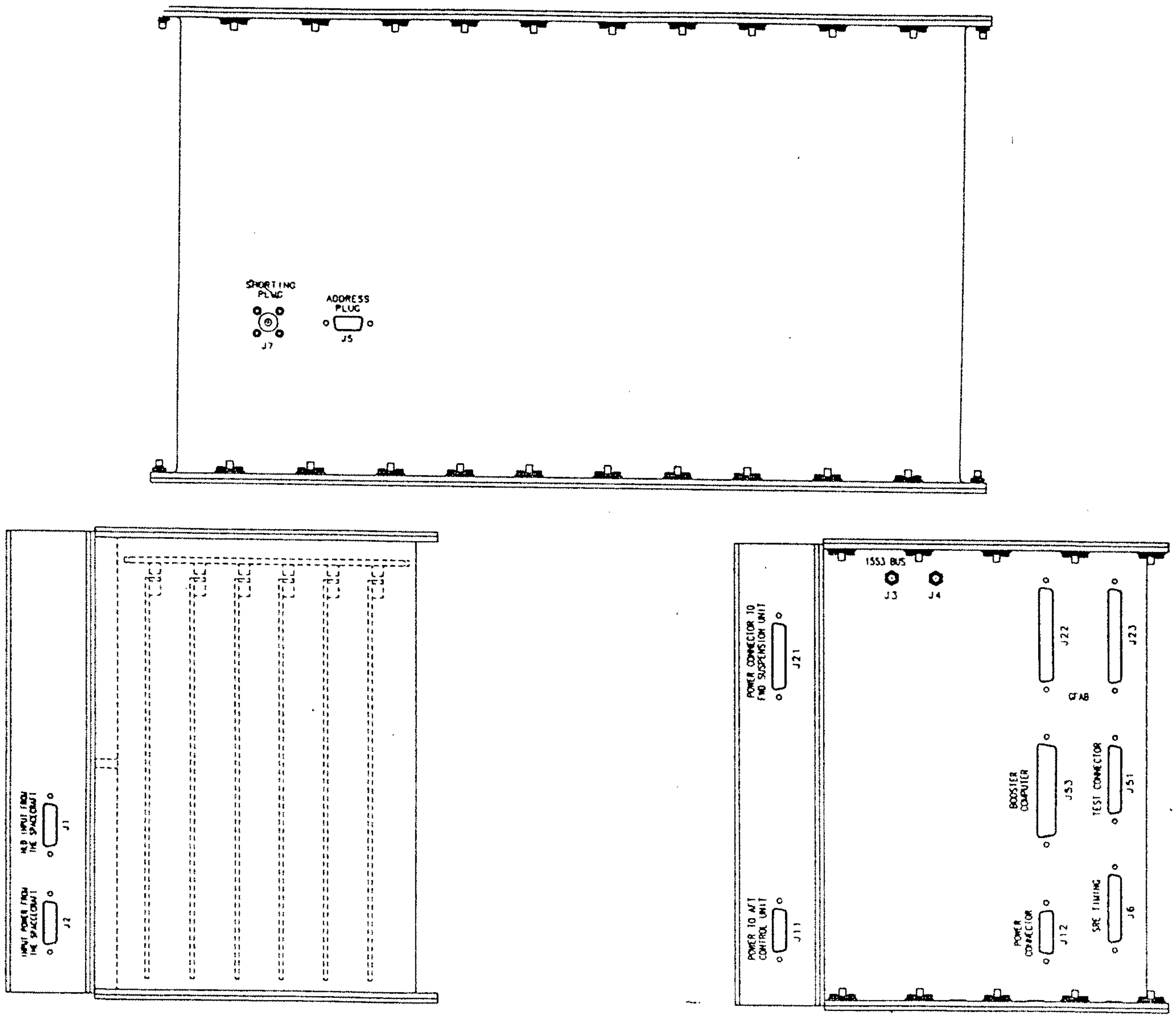
AFT GFAB INTERFACE



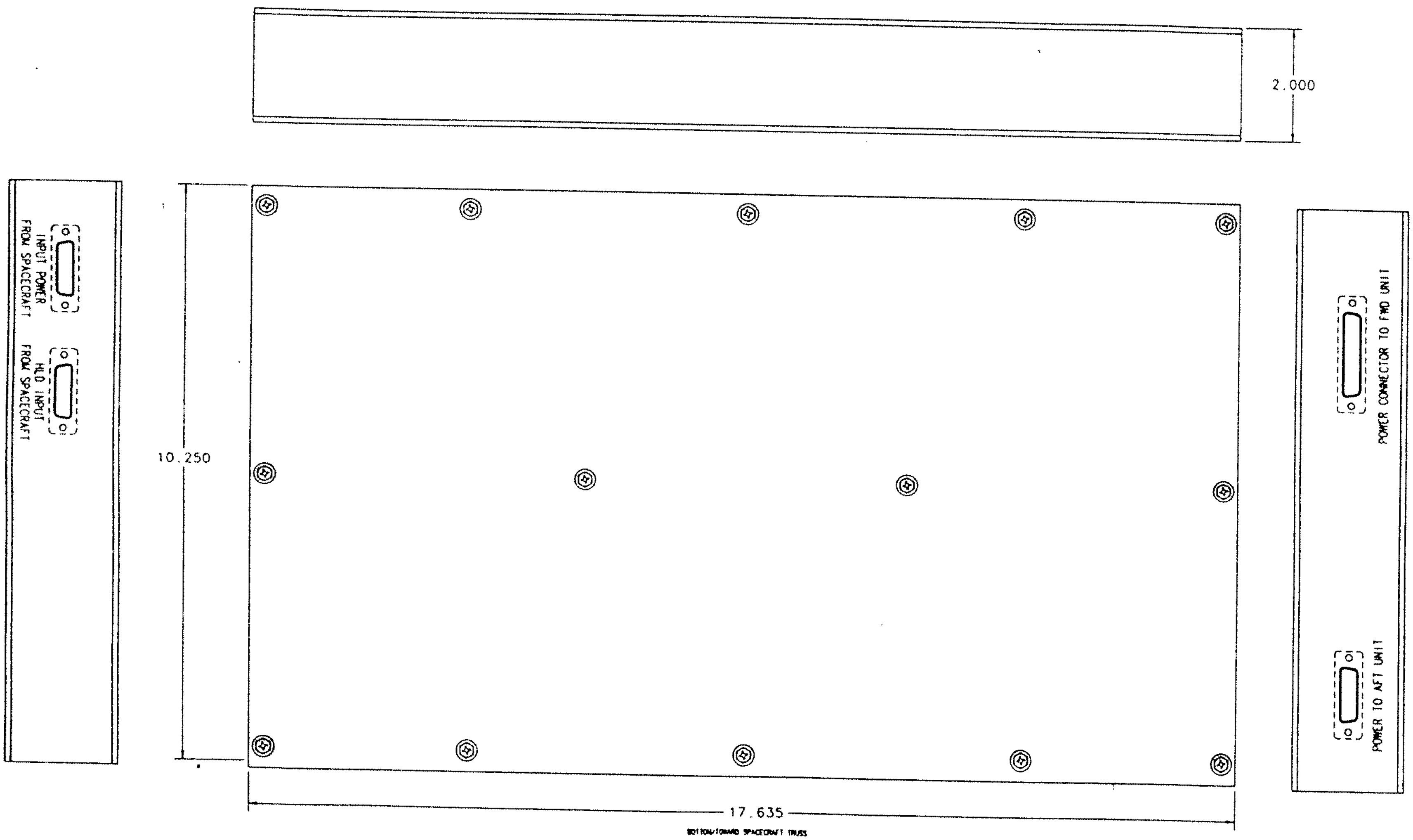
AFT GSE



ACU Connector Layout



APU Mechanicals & Connectors



Mass and Volume Estimates

	FSU internal	FSU external	ACU internal	ACU external	APU	
Length	16.000	16.600	17.435	18.835	17.635	(in)
Width	8.660	9.800	6.450	7.800	2.000	(in)
Height	6.905	7.800	10.400	10.400	10.375	(in)
Volume	956.757	1268.904	1169.540	1527.895	365.926	(in^3)

	FSU	ACU	APU	Cables	Total	
Mass	37.5	37.2	16.1	21.1	111.9	(lb)

Power Estimates

GSS - Flight Enclosure - Power Dissipation Estimates Summary

		A	B	C	A-HV	B-HV
Case 1	Science, Lo Power	ON	OFF	ON	OFF	OFF
Case 2	Science, Redundant	ON	ON	ON	OFF	OFF
Case 3	Spinup	ON	ON	ON	OFF	ON
Case 4	Ground Test (1G)	ON	ON	ON	ON	ON

		FSU	ACU	APU	total	
Case 1	Science, Lo Power	21.19	13.03	16.36	50.58	(W)
Case 2	Science, Redundant	21.19	13.03	20.84	55.05	(W)
Case 3	Spinup	27.10	13.03	25.20	65.34	(W)
Case 4	Ground Test (1G)	33.02	13.03	29.79	75.84	(W)

Thermal Operating Range

GSS - Flight System - Operating Temperature Estimates

		A	B	C	A-HV	B-HV
Case 1	Science, Lo Power	ON	OFF	ON	OFF	OFF
Case 2	Science, Redundant	ON	ON	ON	OFF	OFF
Case 3	Spinup	ON	ON	ON	OFF	ON

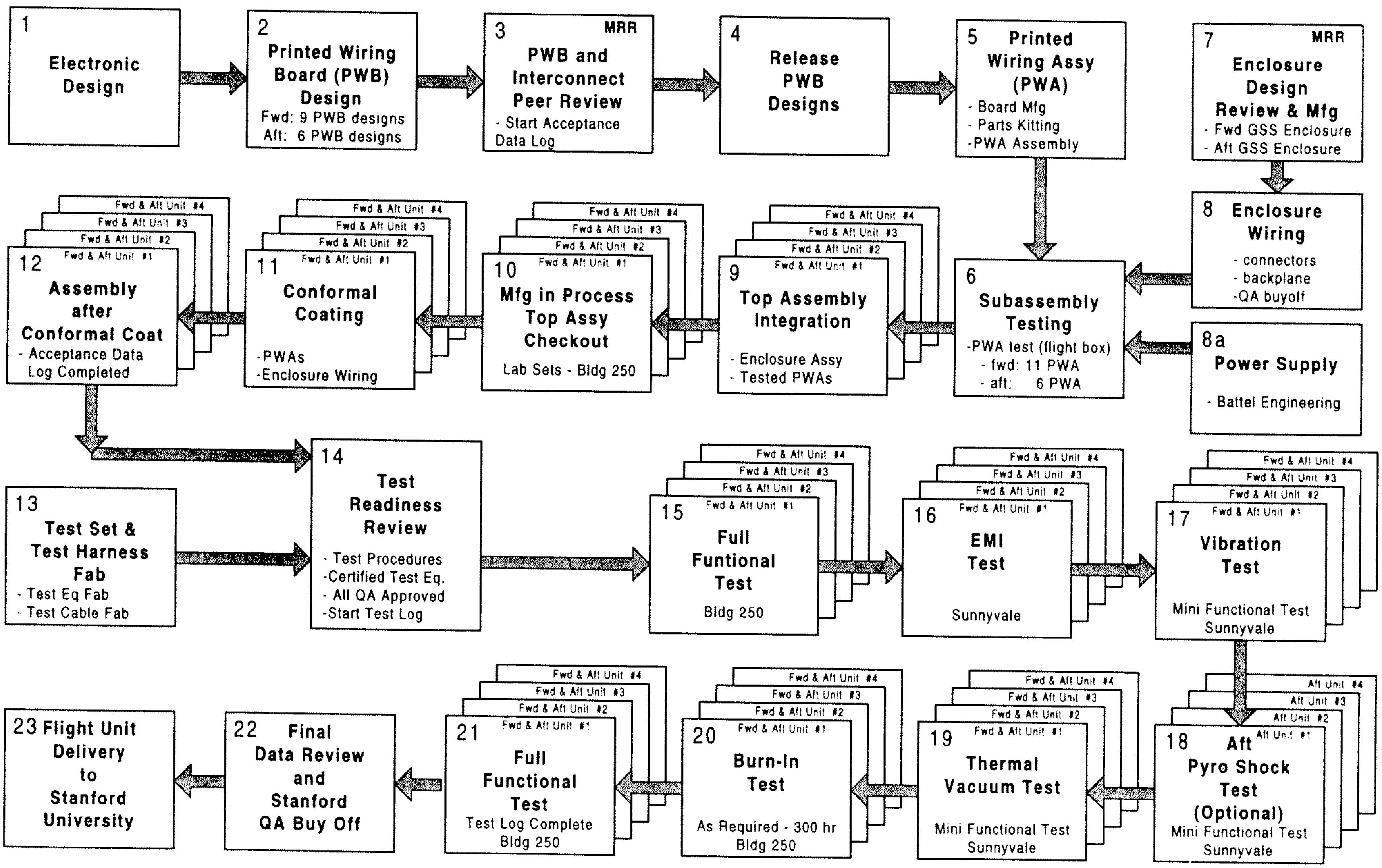
		Fwd	Aft	total	
Case 1	Science, Lo Power	21.19	29.39	50.58	(W)
Case 2	Science, Redundant	21.19	33.87	55.06	(W)
Case 3	Spinup	27.10	38.23	65.33	(W)

		Fwd		Aft	
		max	min	max	min
Case 1	FOSR BOL - Cold		8		-6
Case 2	FOSR EOL - Hot	46		26	
Case 3	FOSR BOL - Hot	62	24	24	-6

Parts Status

- **Parts List is complete**
- **Active Part types - 92**
  - in bonded stores (LMMS) 15%
  - to be delivered 29%
  - purchase request in process 2%
  - quote in process 54%

Manufacturing & Test Flow



7.1 Power System Design

Steve Battel

Battel Engineering

Power System - Overview

- Key Requirements
- Block Diagram
- Load Summary
- Power Estimate
- Breadboard Test Results
- EMC Approach
- High Voltage Engineering
- Packaging Overview
- Manufacturing Plan
- Test Plan
- Schedule
- Issues/Concerns

Key System Requirements 1

1. **Aft Power Unit (APU) to provide all Power for Each of 4 GSS Systems Consisting of an Aft Control Unit (ACU) and Forward Suspension Unit (FSU)**
   - Independent Power Supplies for ACU and FSU
   - FSU Power Supply Warm-Redundant
   - Regulated Make-up Heater Power Also Provided
2. **Divide Power Electronics Between Aft Power Unit (APU) and Forward Regulator Module (FRM) for Four Independent FSU Systems**
   - Minimize Thermal Dissipation (and variation) in FSU
   - Perform all Switching and DC-DC Conversion Aft
   - Perform Linear Power Regulation Forward

Key System Requirements 2

3. Maximum Reliability

- Use Rugged Flight-Proven Technology
- Make FSU Power Supplies Warm-Redundant
- 4 Power Switches from Spacecraft for <u>Each</u> System

4. Low-Noise

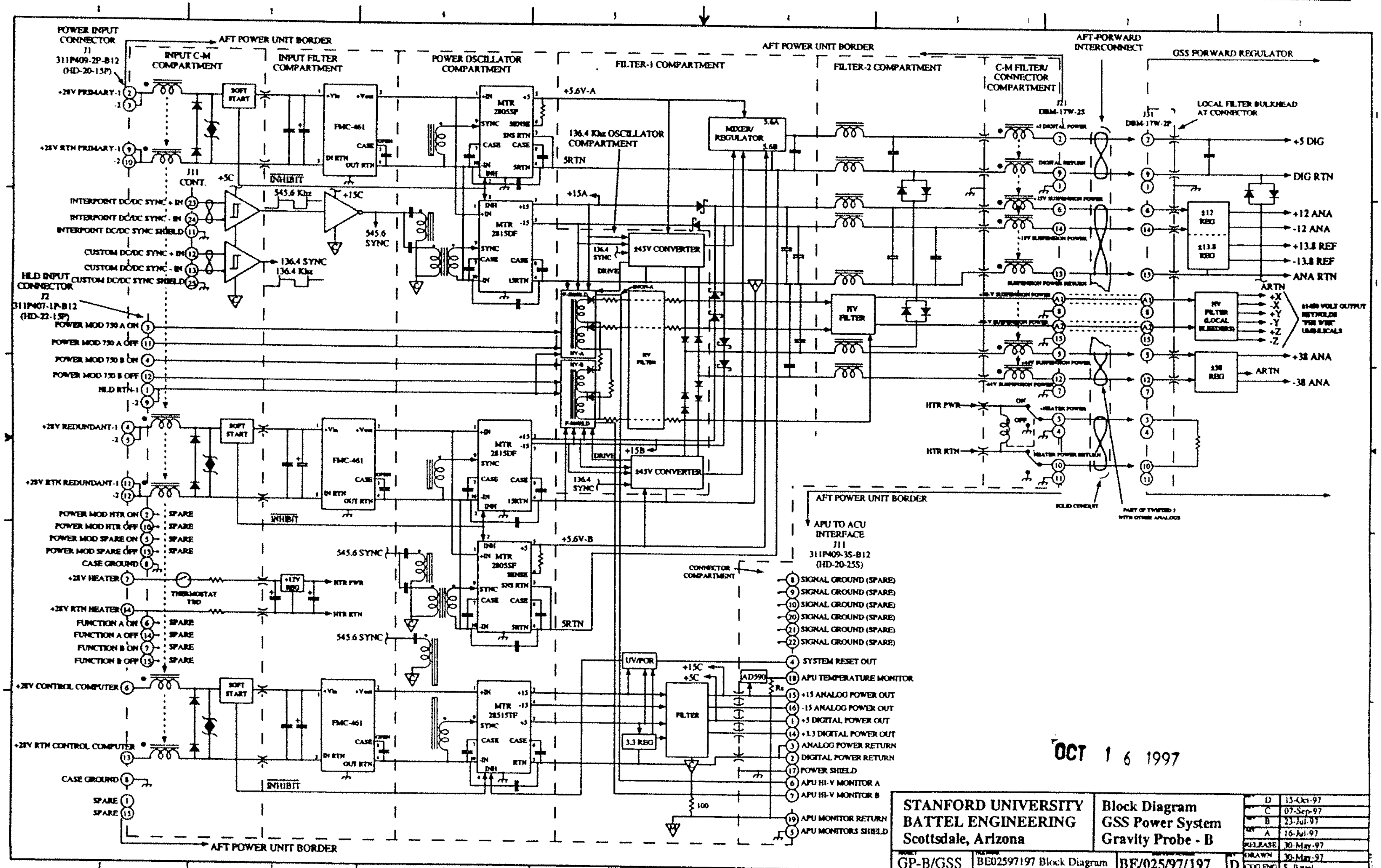
- "SQUID Friendly" System Level Design Approach
- Serially Compartmentalized Electronics
- Isolated Grounds with Input/Output Common-Mode Baluns
- Rise-Time Control and Double Faraday Shield
- Frequency Synchronization of All Converters
- Post-Regulation of Analog Voltages in FRM

Key System Requirements 3

5. Provide Necessary Support Functions

- Radiative Thermal Control for ACU (and APU)
- ACU Voltage Sensing and Reset Functions
- Voltage and Current Monitoring
- High Voltage ON/OFF Control

Power System - Block Diagram



System Load Summary

System Load Specification for the FSU and ACU are Now Fairly Mature. System Design has Margins of More Than 10%. Margins are Limited Solely by 30 W Interpoint Power Supply Output Capability (22.5 W with 75% Derating; 27.0 W with 90% Derating).

V	(real V)	I (mA)	Power
5		683.0	3.42
12	14.20	454.0	6.45
-12	-14.20	-488.0	6.93
13.8	14.20	6.0	0.09
-13.8	-14.20	-6.0	0.09
38	44.00	48.0	2.11
-38	-44.00	-48.0	2.11
1450		4.1	5.95
-1450		-4.1	5.95
		Total (W):	**33.08**

ACU Loads		
V	I (A)	Power
3.3	0.85	2.81
5	1.87	9.33
15	0.03	0.45
-15	-0.03	0.45
	Total (W)	**13.03**

System Power Summary by Mode

Operational MODE	System State Matrix					FSU Power	ACU Power	APU Power	Total Power
	A	B	C	A HV	B HV				
MODE 1:									
Low Power Nominal Operation (non-redundant)	ON	OFF	ON	OFF	OFF	21.19	13.03	16.36	**50.58**
MODE 2:									
Nominal Warm-redundant Operation	ON	ON	ON	OFF	OFF	21.19	13.03	20.84	**55.06**
MODE 3:									
SPIN-UP HV= +/- 725 Volts B side ON.	ON	ON	ON	OFF	ON	27.10	13.03	25.20	**65.33**
MODE 4:									
GROUND TEST HV= +/- 1425 Volts A and B sides ON	ON	ON	ON	ON	ON	33.02	13.03	29.79	**75.84**

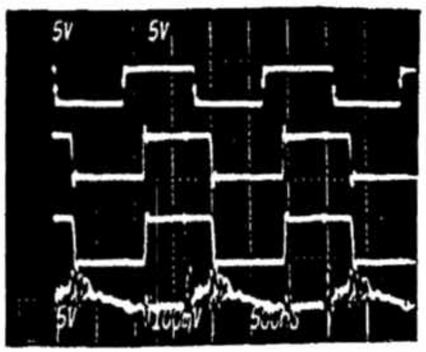
Breadboard Test Results 1

1. Initial Testing of Flight System Breadboard is Complete

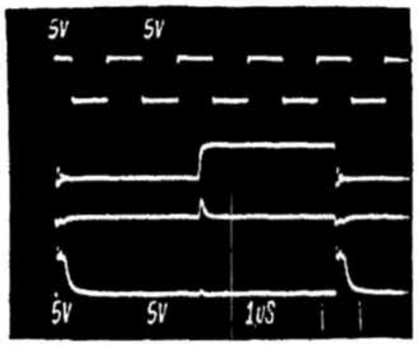
- Results Look Good - No Surprises or Major Issues
- Upgrades and Modifications In Process
- Schematic Diagrams and Parts List Released
- Temperature Testing Planned for November

2. Sync Circuits Look Acceptable Although Some Skew

545.6 kHz SYNC



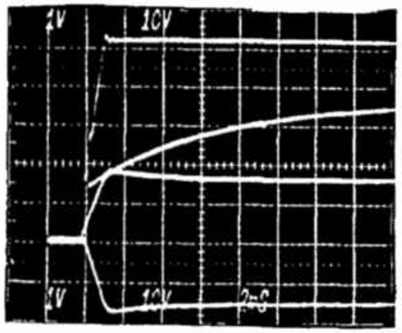
136.4 kHz SYNC



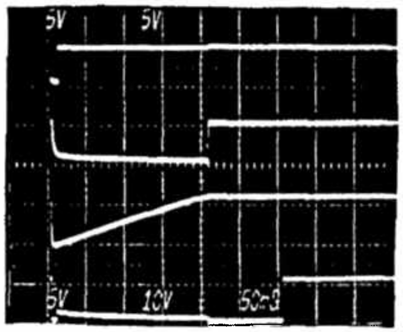
Breadboard Test Results 2

3. Soft Start Works Well - Timing Must Be Considered

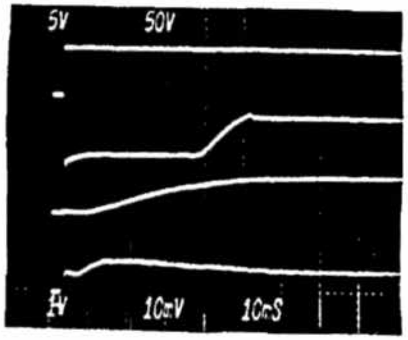
ACU Turn-On



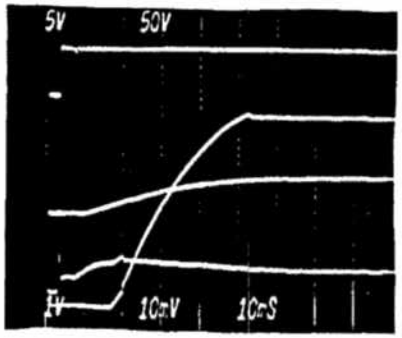
ACU Start/Reset



FSU +5/+45 (Option 1)



FSU +5/+45 (Option 1)



EMC Approach

1. **Design Worked with R. Cliff to Assure Compatibility With System Requirements**
   - Intended to Meet "SQUID Friendly" 50 μV Spectrum Wide Requirement
2. **Cascaded Compartmentalized Noise Control Approach**
   - Similar Approach Used on Noise-Sensitive Cameras
   - 72 dB of Suppression Required; >80 dB Expected
3. **Special Care in Manufacturing Required**
4. **Special EMC Testing Planned to Verify Performance**

High Voltage Engineering

1. **APU Must Generate, Control and Transmit +/-1450 Volts for Use in the FSU**
   - Half-Wave Quadrupler Used to Generate +/-750 Volts
   - Single System (-A or -B) Generates +/-750 Volts; Tandem System Generates +/-1450 Volts

2. **Voltage Level and Other Requirements Do Not Require Specialized Field-Control Approach**
   - Careful Attention to Spacing, Points/Edges, and Coatings

3. **Connectors and Terminations are Important**
   - Special RAM "D" Connector Inserts Baselined
   - Lockheed 1831 HV Termination Blocks Recommended for Connections Internal to FSU
   - Reynolds 10 kV Cable (shielded and unshielded) Planned for Interconnects

APU Packaging Overview 1

1. **Standard Board-In-Frame Construction Used Because of Simplicity and Manufacturing Efficiency**
   - PCB and Frame Can be Processed Separately and Mated Late in Flow
   - Frame Size 17.635 X 10.375 X 2.000

2. **Relatively Heavy Frame Required to Handle Loads and Thermal Conductivity Requirements**
   - Heat Conducted Through 12-15 Bosses
   - Multiple Sealed Compartments for EMI Control
   - Frame to be Gold Plated To Improve Noise Control
   - Top and Bottom Covers to Be Treated as Necessary to Meet Thermal Requirements
   - Thick Walls Simplify Space Radiation Concerns

APU Packaging Overview 2

3. **Venting Toward ACU Via 0.075" Gap**
   - 225 .125" Vent Holes for 4 sq. in.
   - Holes Covered with 325 SS Mesh (1.7 mil; 36% Transmission)
   - Waveguide Cutoff Criteria of 5 Maintained

4. **6-Layer 0.062" Single PCB**
   - 0.093" inch thick PCB Possible if Deemed Necessary for Structural Reasons

5. **All Heat Producing Hardware (> 100 mW) Thermally Attached to Frame**

FRM Packaging Overview

1. **Dedicated PC Card in FSU**
   - Bottom Location Baselined for Best Thermal Performance
   - Enclosed to Minimize Noise
   - Interface Filters Located on Connector Bulkhead That is Not Part of FRM Assembly
2. **6-Layer 0.062" Single PCB**
   - 0.093" PCB Possible if Deemed Necessary for Structural Reasons
3. **All Heat Producing Hardware (> 100 mW) Thermally Attached to Frame**

Manufacturing Plan

1. **5 APU's Built at University of Michigan per Released Battel Engineering Manufacturing Instructions**
   - APU Specification has Details of Plan
   - Quality Assurance Per SPRL Drawing 074-0009 (Based on Cassini Program)

2. **4 FRM's Built at Lockheed or University of Michigan per Released Battel Engineering Manufacturing Instructions**
   - Detailed Plan In Process

3. **Parts Program Per APU Specification**
   - Lockheed Procuring All Parts

4. **S. Battel to Manage Efforts, Supervise All Critical Activities, and Perform All Testing**

Test Plan

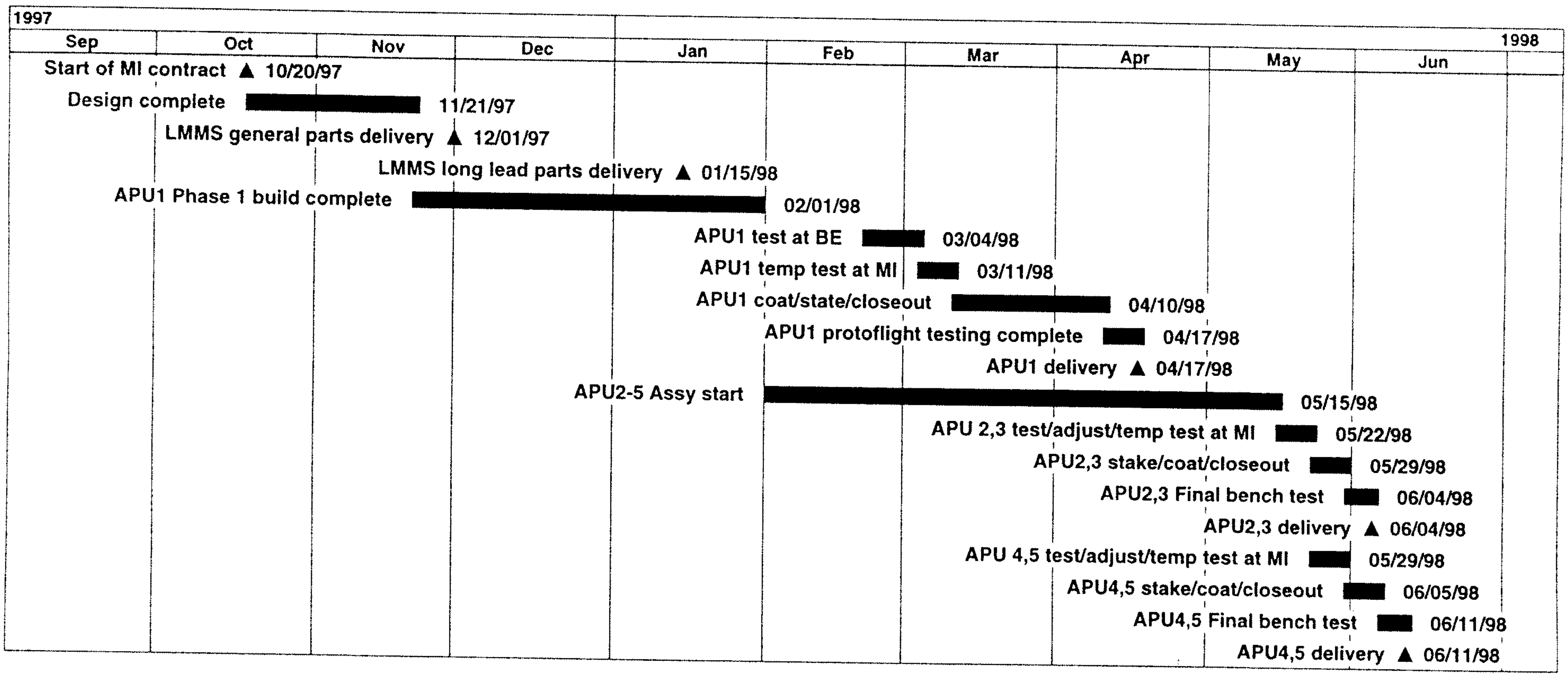
1. **APU Testing Will be Performed by S. Battel as Described in APU Specification**
   - Based on Modified GPB-100727A Program
   - Testing Performed at Battel Engineering, Michigan and at Selected Test Vendors

2. **First APU to be Qualified as a Protoflight Item and Retained as a Program Spare**
   - Vibration, T-V, EMC Tests Performed Plus 300 hour Burn-in

3. **Four Follow-on APU's to be Qualified as Part of Integrated ACU/APU Assembly**
   - Thermal and Bench Testing Planned

4. **FRM Testing Will be Performed at Battel Engineering**
   - Thermal and Bench Testing Only - Qualified as Part of FSU

APU Condensed Schedule



APU Issues/Concerns

1. There are No Major Technical Concerns at This Time

- Electrical Design Complete for APU and Essentially Complete for FRM
- Breadboard Testing in End-Game Phase
- Some Residual Issues Related to Thermal and Mechanical Implementation

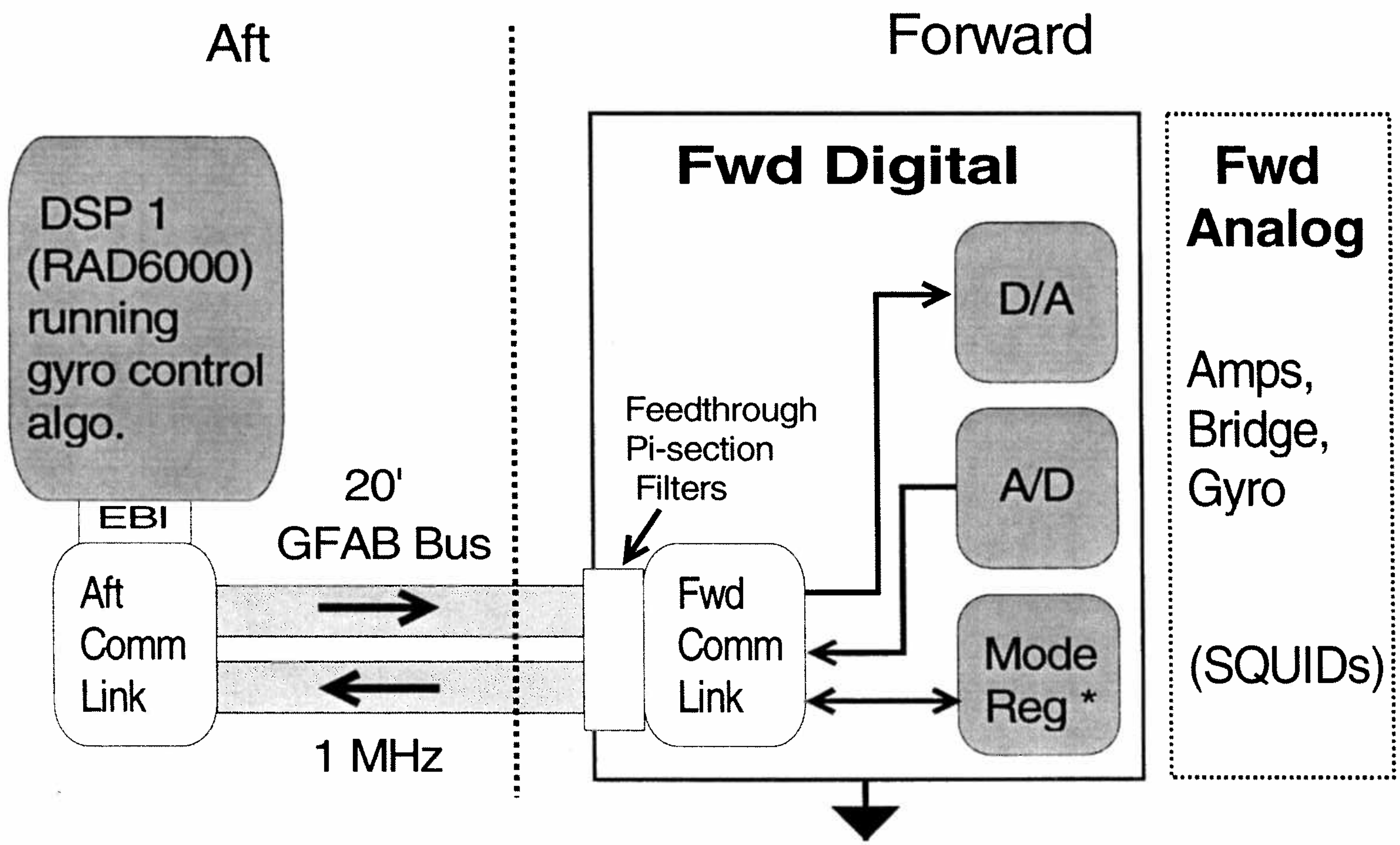
2. Schedule and Cost are Dominant Programmatic Concerns

- Late Start and Design Changes Have Affected Both Areas
- Tight Schedule for First Delivery
- EEE Parts Drive Critical Path
- Effort Will Require Constant Attention
- WE WILL GET IT DONE!

7.2.1 GSS Flight Software (GSW) Introduction

Paul Lassa

Simplified Digital Subsystem



GFAB = Gyro Forward-Aft Bus

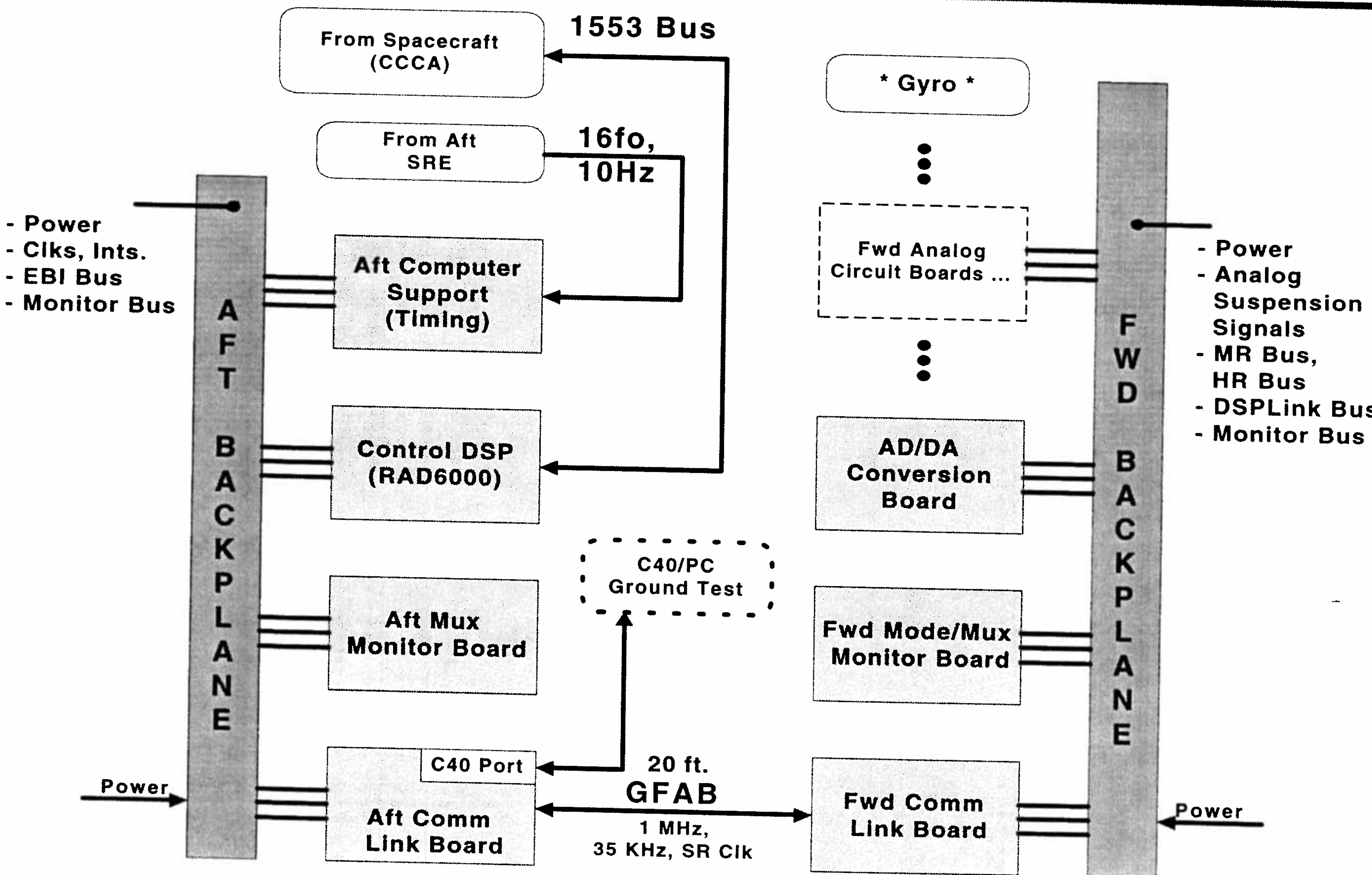
Development Team

1. System and H/W Architecture, Diagnostics:	Paul Lassa
2. System and S/W Architecture:	Steve Larsen
3. Control System Architecture, S/W:	Michael Eglington
4. Cmd/Telemetry & Diagnostics Architecture:	Jen-Nan Lay
5. Flight S/W Development:	Scot Sulak

S/W Development Efforts

1. **Flight O/S and device drivers for RAD6000 (Interrupts, 1553, EBI bus, RAM scrub,...)**
2. **Flight version of Control Alg. performance-tuned to RAD6000.**
3. **S/W Interfaces to the Spacecraft/CCCA (Commands,Telemetry)**
4. **Integrate Science Algorithm S/W (Spin-up,Science Data Filt., ...)**
5. **Support S/W for all Testable Circuit Boards in the GSS system** ☆
   - S/W test fixtures to exercise and diagnose H/W (Coordinate w/ Testbed)
   - Pre-launch Validation/Qualification S/W test suites
   - Pre-lift & Run-time health/diagnostics S/W routines

GSS Digital System



Development Methodology

1. Define Preliminary Requirements.

2. Develop prototype H/W and S/W.

3. Define Full Features/Specifications.

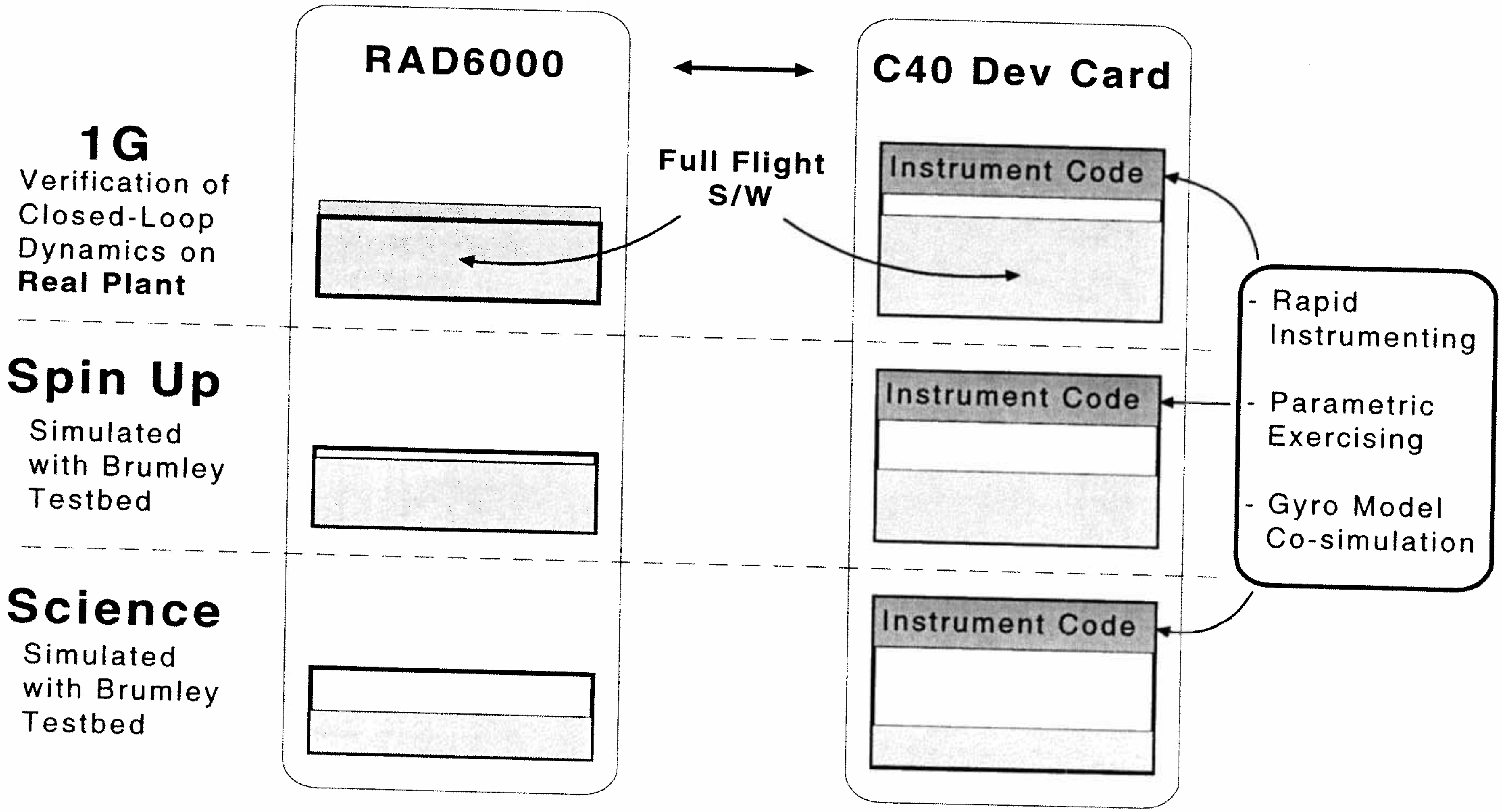
4. Develop Diagnostics / Verification Fixtures, S/W.

5. Maintain Instrumentation capability throughout Development Cycle (accessability & observability). ☆

6. Release.

Co-Development Platform (Fork)

Processor Capacity/Perf. for Flight O/S & Control Algorithm



S/W Development Status

1. Aggressive scrubbing of Control code and O/S tuning to enable 1G B/W operation on RAD6000 platform.

2. High performance features of Control Algorithm enable low modulation suspension (~1900 Hz) for 1g Lift.

3. Several IDD's and Preliminary Specs Completed.

4. Initial Rendezvous (simulated 1g lift) with Testbed Successful.

5. RAD6000 1g Lift imminent. C40 & RAD6000 common code base complete.

7.2.2 GSS Flight Software (GSW) Development

Steve Larsen

Software Requirements

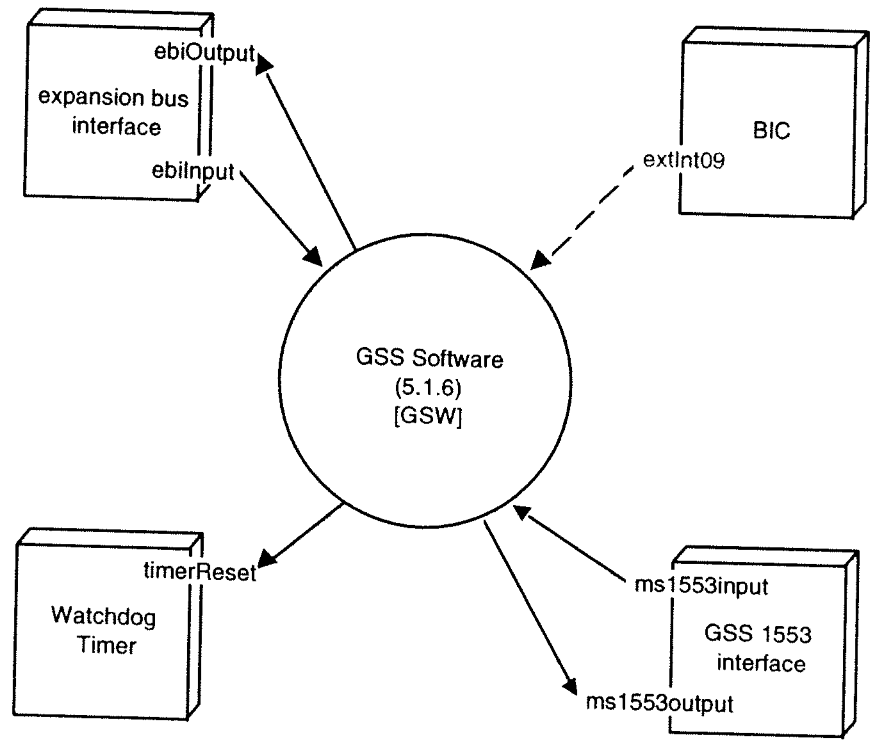
1. No significant changes to requirements.

2. Implementation of some have moved from LMFS-supplied software to in-house developed software to meet performance goals.

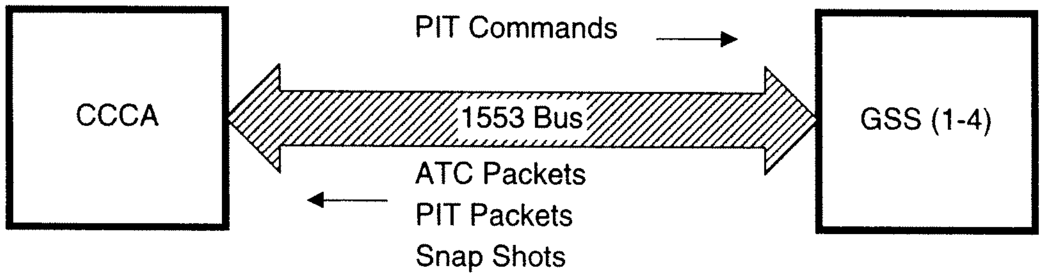
3. GSW requirements excerpt from LMMS document SE-15 in technical appendix.

4. GSW interface definition document excerpt from LMMS document SE-16, section 9 also in technical appendix.

Architecture - GSW Context Diagram



Architecture - CCCA Interface



PIT Command Packet (10 Hz)

- command handler commands
- ATC drag-free gyro commands
- charge control commands
- charge measurement commands

ATC Data Packet (10 Hz)

- command handler status
- ATC drag-free gyro data

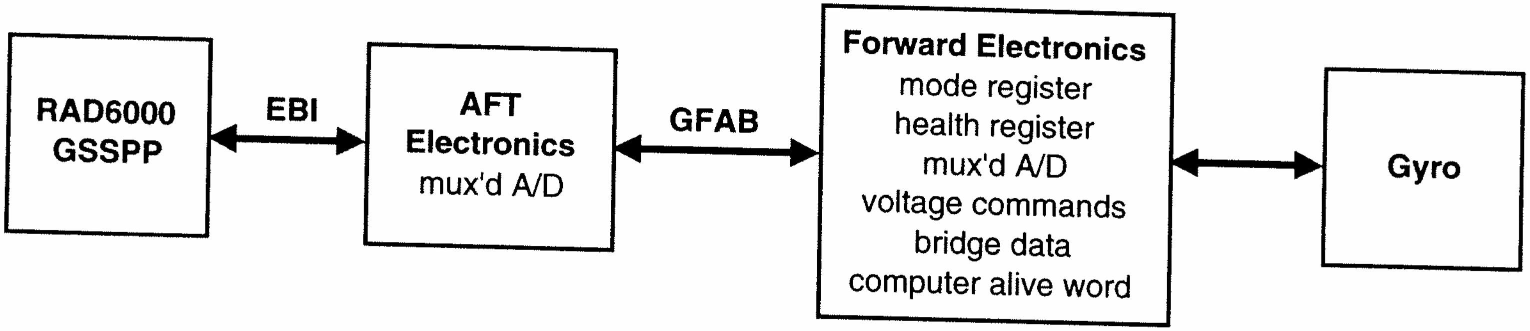
PIT Data Packet (1 Hz)

- Science Data Support
- Charge Measurement Support data
- Engineering Telemetry

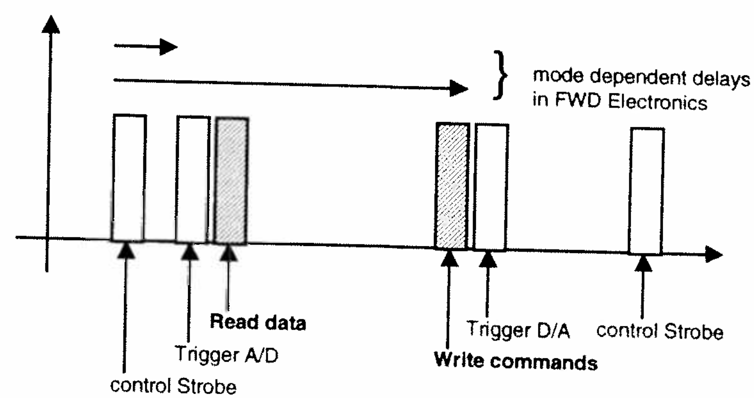
SnapShot Data Packet (1 Hz)

- High rate gyro data
- High rate control law data

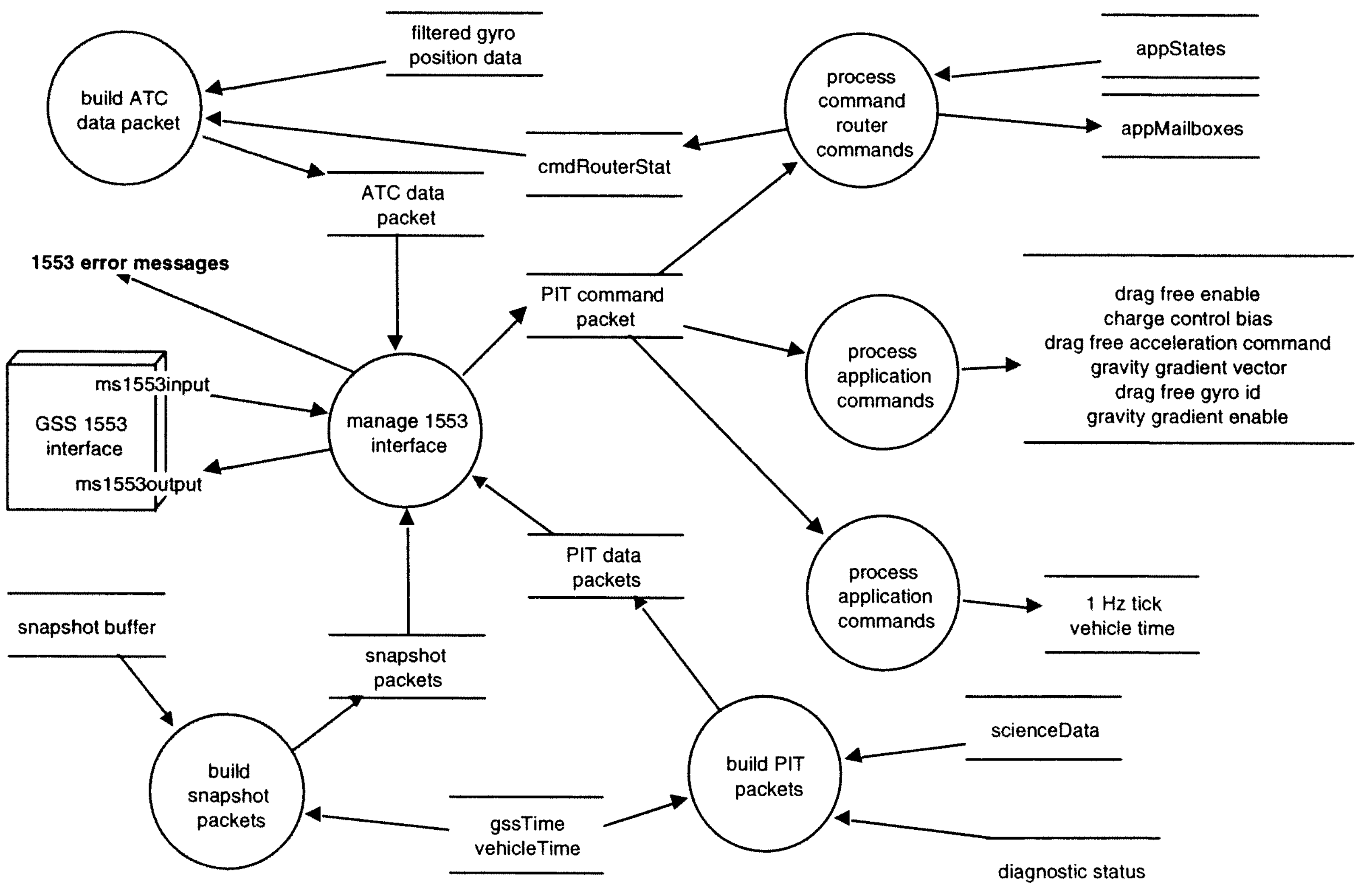
Architecture - GSS Interfaces



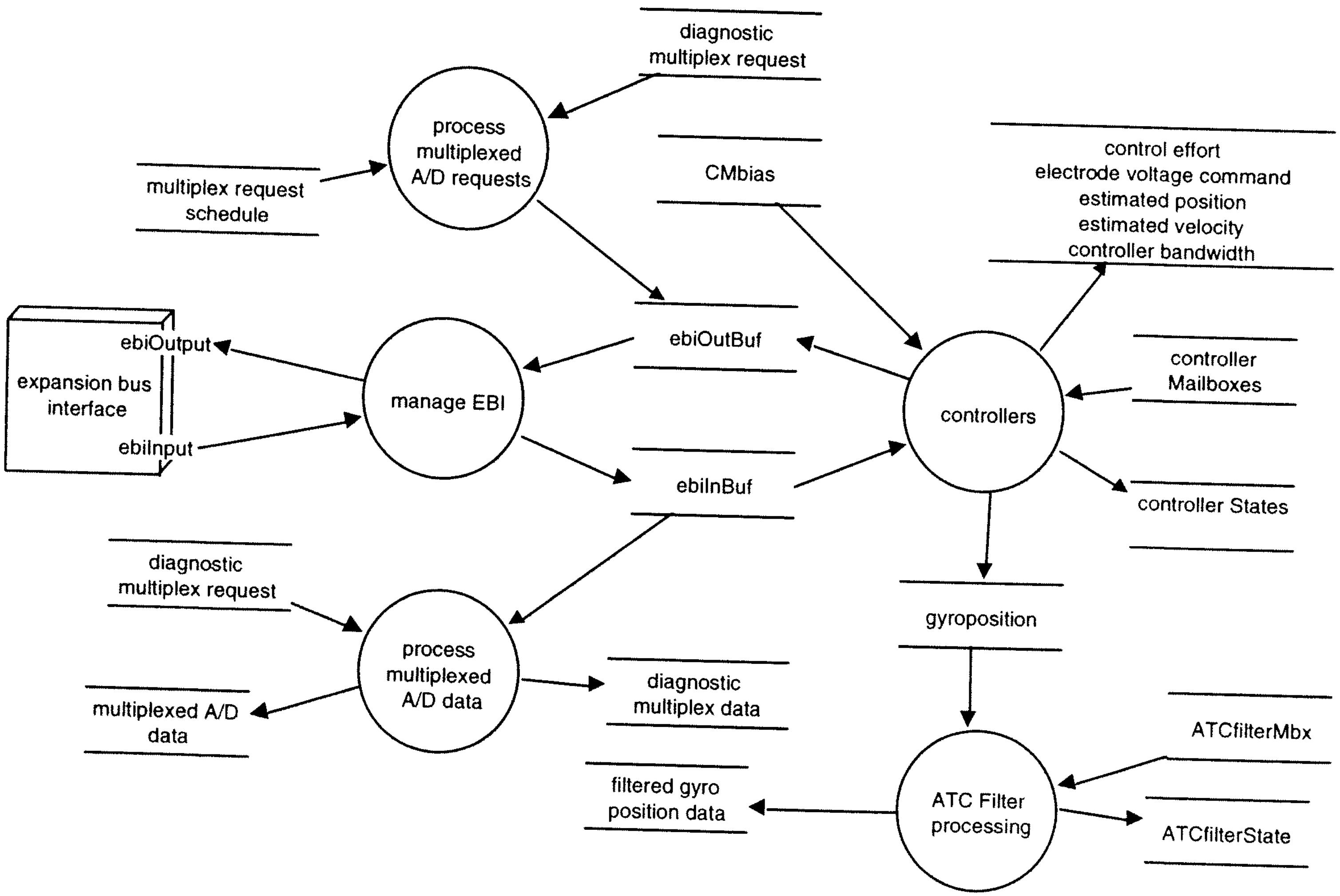
offset	direction	definition
TBD	wo	X1 electrode (16-bit digital to ±10 Volts analog)
TBD	wo	X2 electrode (16-bit digital to ±10 Volts analog)
TBD	wo	Y1 electrode (16-bit digital to ±10 Volts analog)
TBD	wo	Y2 electrode (16-bit digital to ±10 Volts analog)
TBD	wo	Z1 electrode (16-bit digital to ±10 Volts analog)
TBD	wo	Z2 electrode (16-bit digital to ±10 Volts analog)
TBD	ro	X-axis (±10 Volts analog to 16-bit digital)
TBD	ro	Y-axis (±10 Volts analog to 16-bit digital)
TBD	ro	Z-axis (±10 Volts analog to 16-bit digital)
TBD	rw	fwd multiplex channel select (16-bit digital)
TBD	ro	fwd multiplexed A/D data
TBD	wo	mode register (1 of 3 for command voting) (16-bit digital)
TBD	wo	mode register (2 of 3 for command voting) (16-bit digital)
TBD	wo	mode register (3 of 3 for command voting) (16-bit digital)
TBD	ro	mode register (16-bit digital)
TBD	ro	health register (16-bit digital)
TBD	wo	Computer Aliveness Write



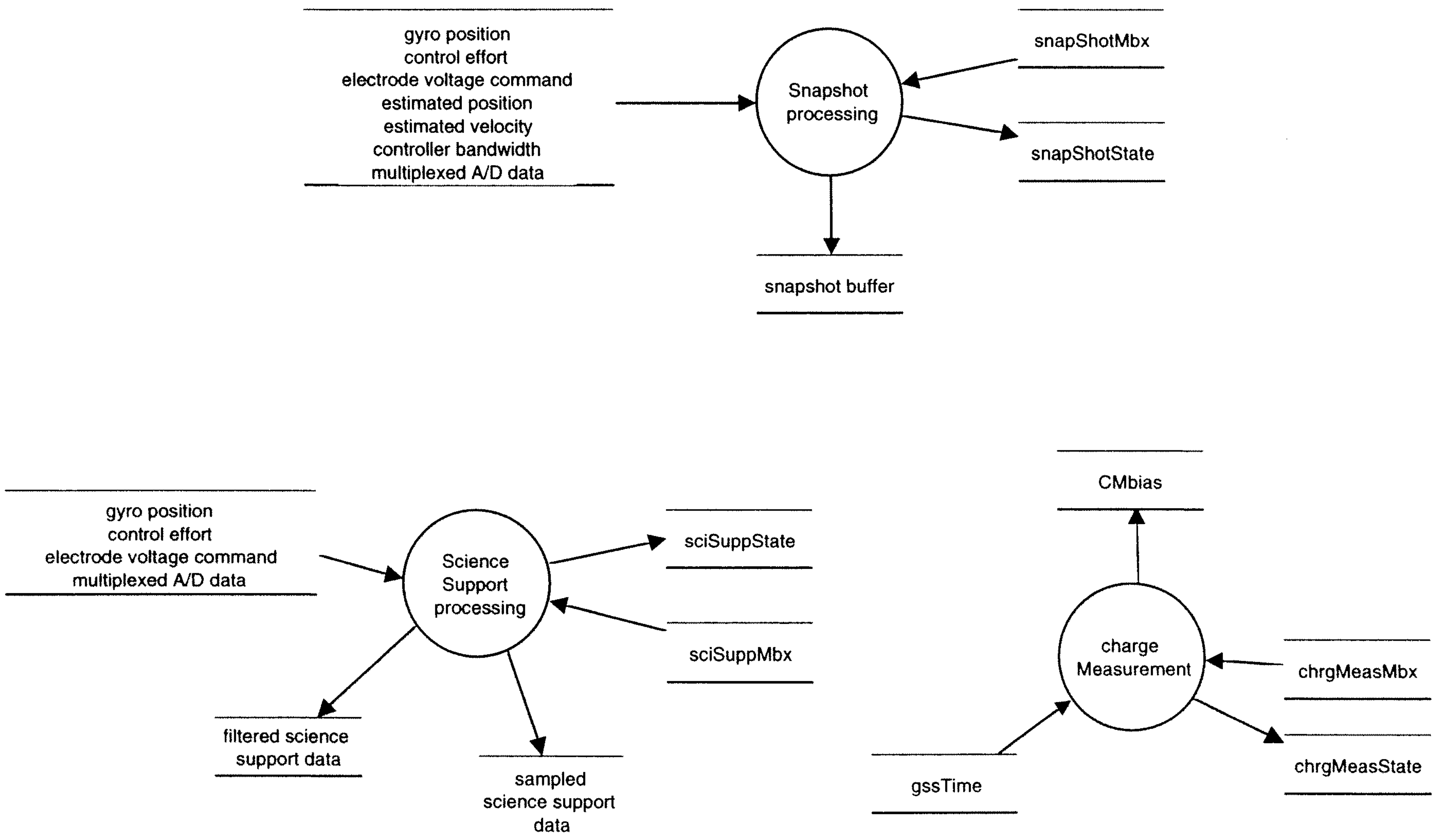
Architecture - level 1 DFD (1553 i/f)



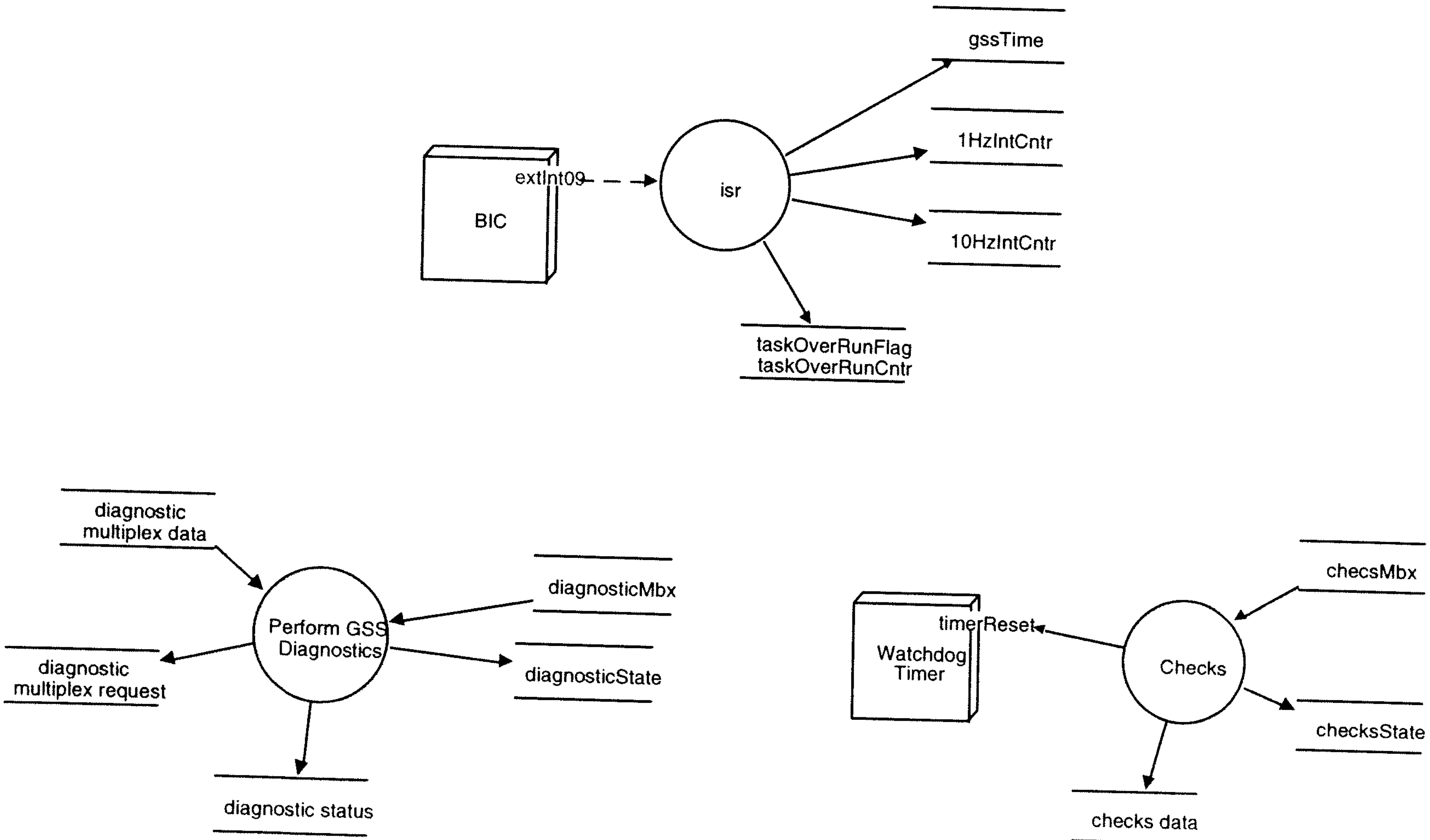
Architecture - level 1 DFD (controller)



Architecture - level 1 DFD (algorithms)



Architecture - level 1 DFD (checks ...)



GSS Diagnostics

Introduction

- A systematic procedure to qualify and diagnose the GSS.
- Qualification Test is a routine check and/or pre-operation test.
- Failure Diagnosis is failure detection and trouble-shooting process.
- Procedures are mode dependent.
- Promotes design with operation in mind.

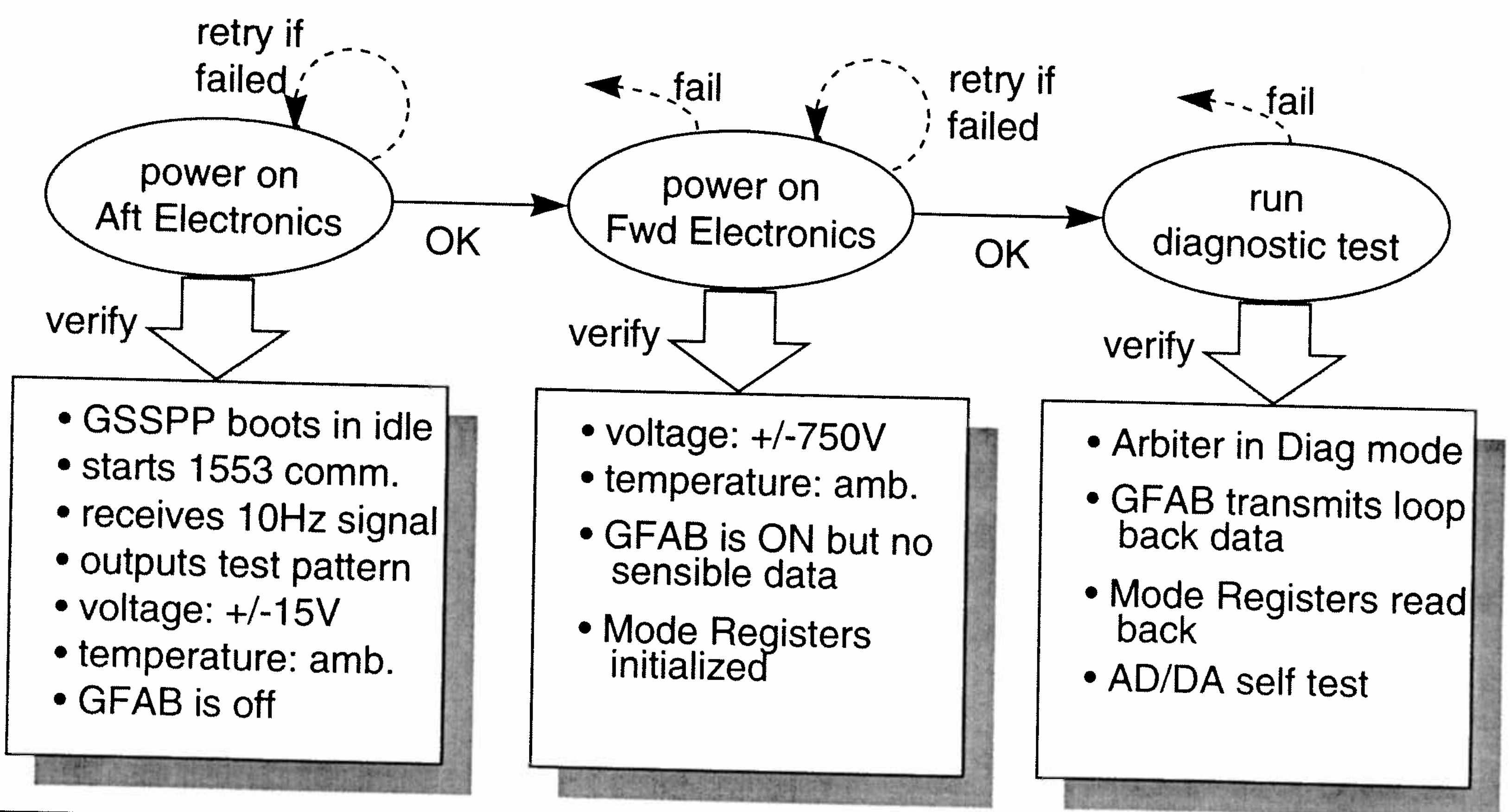
Constraints

- Limited to box-level probing.
- Subjected to Payload Interface Table (PIT) bandwidth limitation.

GSS Diagnostics - Qualification Tests

Qualification Tests

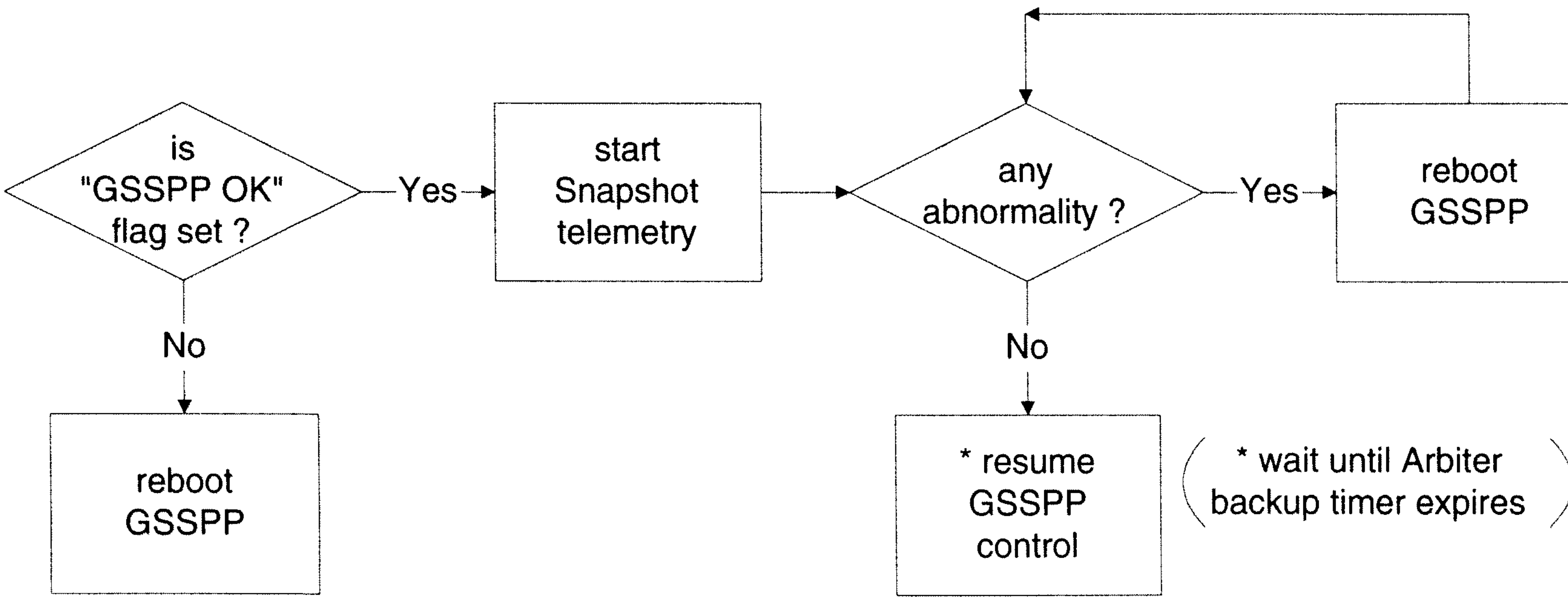
- For each state (mode), a set of parameters are checked
- Example shows transition from power on to diagnostic test:



GSS Diagnostics - Failure Identification

Failure Diagnosis

- Procedure to handle abnormalities or subsystem failures.
- Uses snapshot telemetry to monitor problem area.
- Example shows steps to take when digital control is taken off-line (backup analog in control):



CPU Timing Margin - Science Mission Mode

Application	Time (microsec)	Comment
SCHEDULER		
	60	estimate
1553 I/O		
	150	estimate
EBI		
	170	estimate
APPLICATIONS		
	1160	estimate
COMMAND & TELEMETRY		
	290	estimate
CHECKS		
	300	estimate
DIAGNOSTICS		
	60	estimate
Total Time	2190	(4545 us = period of 220 Hz)
Percentage Use	48.2%	

- Condensed timing table
- Complete table in technical appendix

CPU Timing Margin - Spin Up Mode

Application	Time (microsec)	Comment
SCHEDULER		
	60	estimate
1553 I/O		
	140	estimate
EBI		
	170	estimate
APPLICATIONS		
	640	estimate
COMMAND & TELEMETRY		
	290	estimate
CHECKS		
	130	estimate
DIAGNOSTICS		
	60	estimate
Total Time	1490	1515 us = period of 660 Hz
Percentage Use	98.3%	

- Condensed timing table
- Complete table in technical appendix

CPU Timing Margin - Ground Test Mode

Application	Time (microsec)	Comment
SCHEDULER		
	50	measured on GSSPP
1553 I/O		
	0	not applicable in Ground Test Mode
EBI		
	80	measured on GSSPP
APPLICATIONS		
	380	measured on GSSPP
COMMAND & TELEMETRY		
	0	not applicable in Ground Test Mode
CHECKS		
	0	not applicable in Ground Test Mode
DIAGNOSTICS		
	0	not applicable in Ground Test Mode
Total Time	510	526 us = period of 1.9 kHz
Percentage Use	97.0%	

- Condensed timing table
- Complete table in technical appendix

CPU Memory Margin

Requirements Paragraph Number	Level 1 CSC	Level 2 CSC	Level 3 CSC	Reqid	Estimated Memory Size	Actual Memory Size
5.1.4	Operating System Software			OSS	150,000	
5.1.6	GSS Support Software			GSW		
5.1.6.1		Scheduler		SHG	1,000	
5.1.6.2		GSSPP Initialization		GIN	1,000	
5.1.6.3		Data Management		GDM	15,000	
5.1.6.4		GPBPP I/O Processing		GIO	6,000	
5.1.6.5		Checks		GCK	11,000	
5.1.6.6		GSS Support Processing		GPP	120,000	
5.1.6.7		Science Support Processing		SCS	310,000	
	Low memory					
	Stack/Heap				200,000	
Subtotal					814,000	0
Total						814,000
% Usage						77.63%

- Condensed memory table
- Complete table in technical appendix

Status & Issues

1. Ground Test Mode ready for testing

2. GSW 1.0 will be delivered to Norm Bennett 12/1/97 (supports interfaces in comm test mode - no control necessary)

3. Schedule is Aggressive - rigorous design & code reviews & testing to eliminate errors prior to launch

4. Spin Up Mode timing margins are extremely tight - estimates are conservative, continue benchmarking as actual flight code is developed

5. Algorithms & hardware interfaces still appearing and changing - need to be responsive to this but it can impact schedule

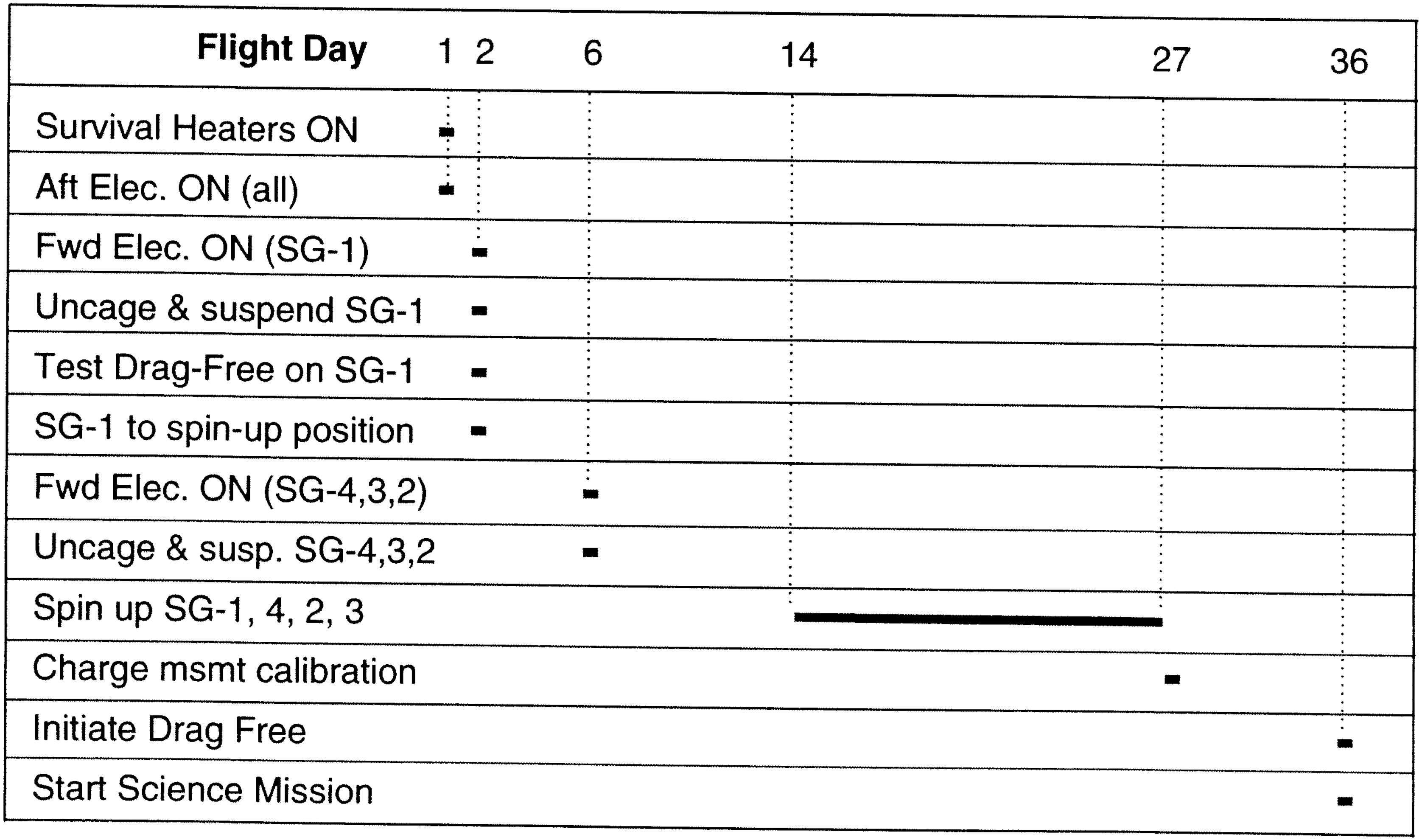
Mission Timeline - GSS Operations

GSS Operation Timeline

- GSS operation team
  - Lead - Dave Manner
  - will meet regularly to refine the operation timeline
- Preliminary timeline has been defined
  - Day 1 - power on survival heaters
  - Day 1 - power on Aft Electronics on all four GSS's
  - Day 14 - spin up four Gyros sequentially
  - Day 27 - gyro spin-up complete
  - Day 36 - ready for Science Mission

Mission Timeline - GSS Operations

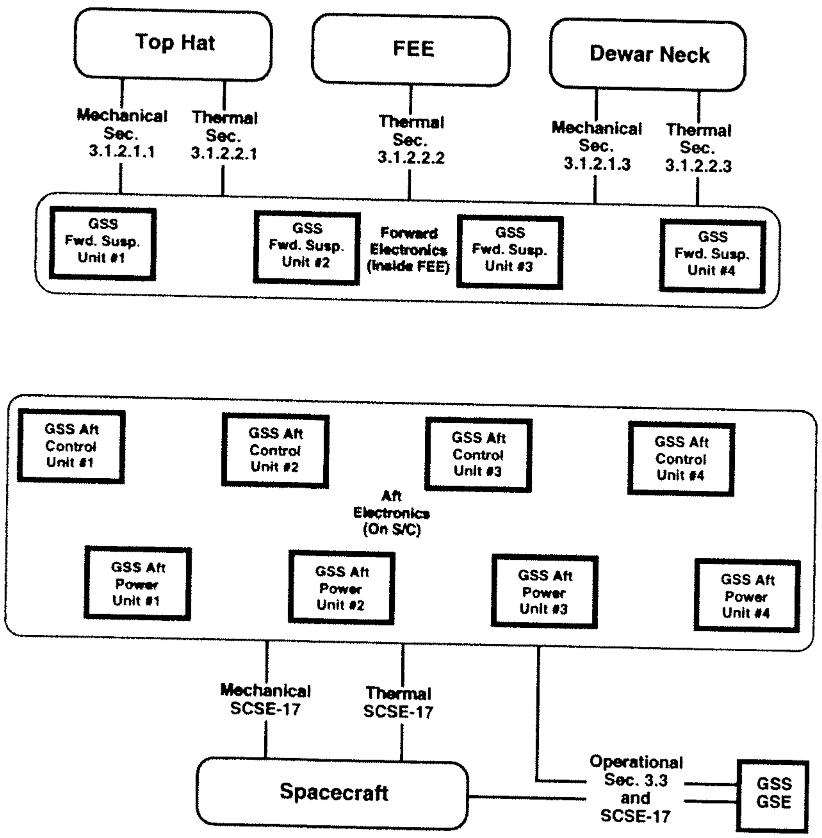
Preliminary GSS Operation Timeline

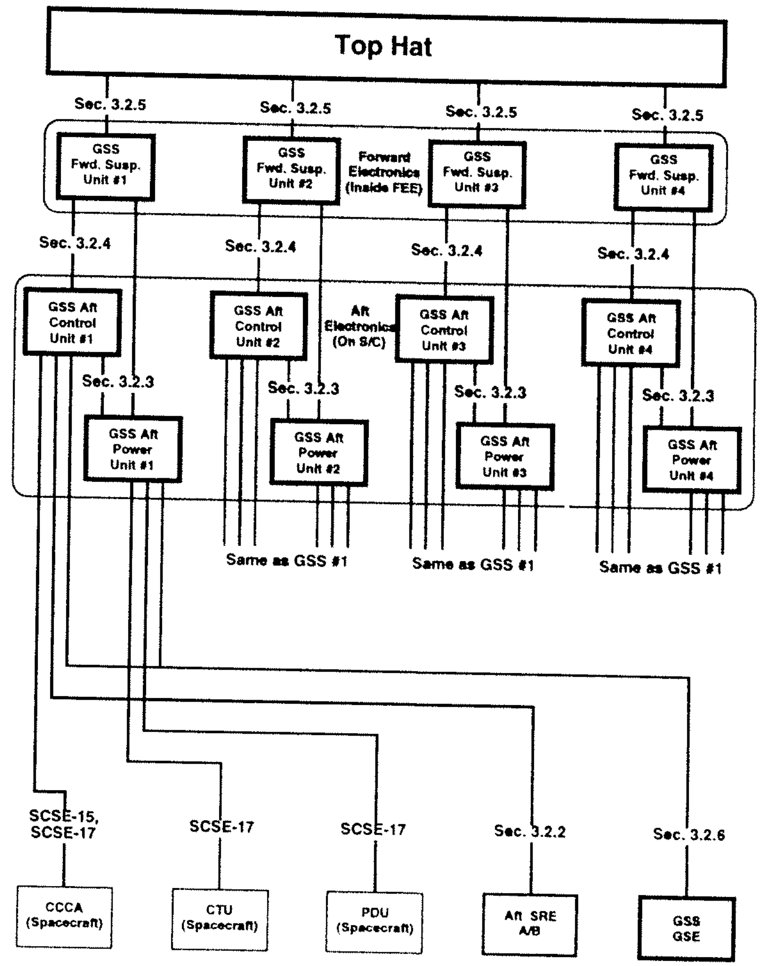


8. Interfaces

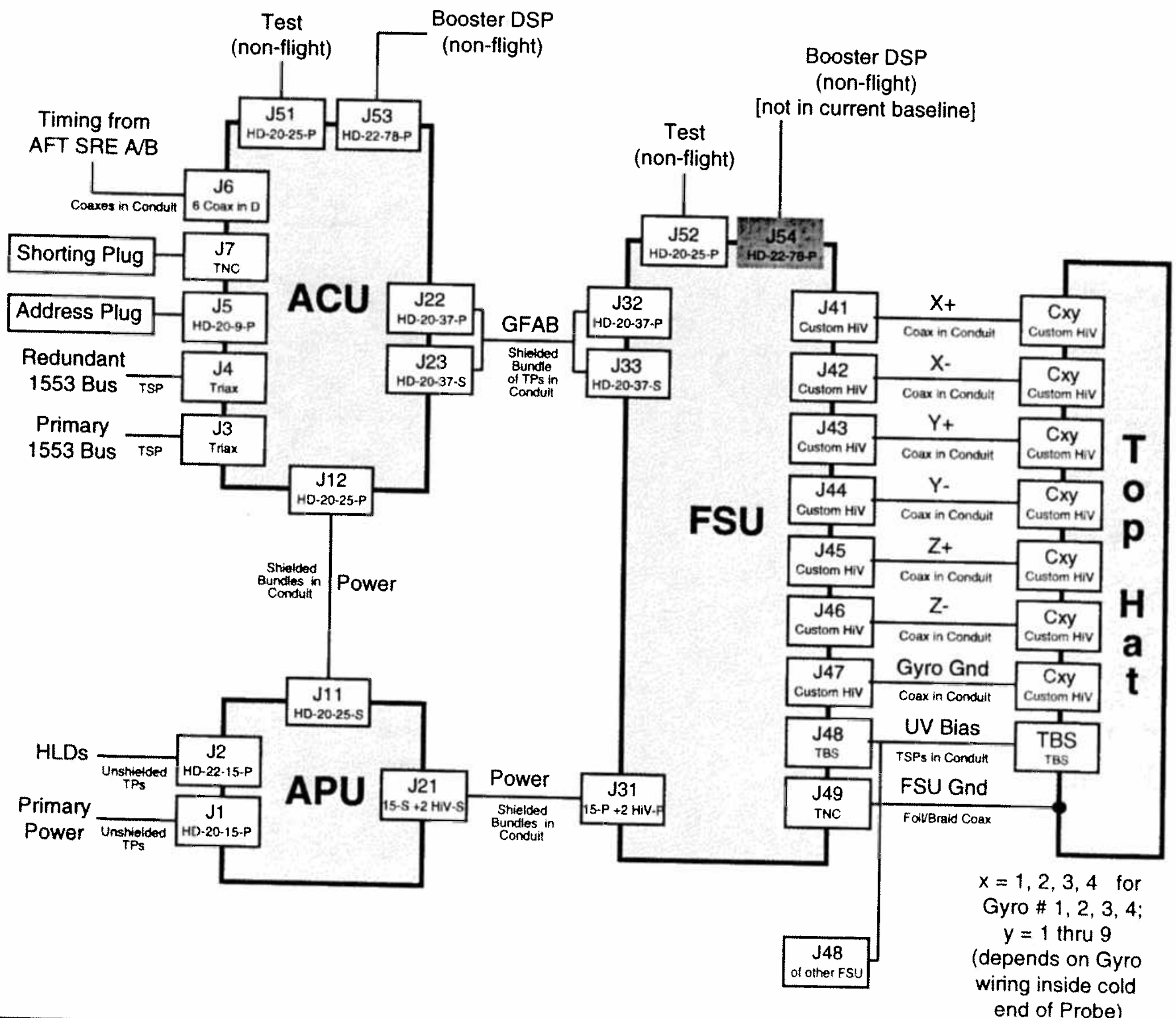
Rodger Cliff

Interface Road Map

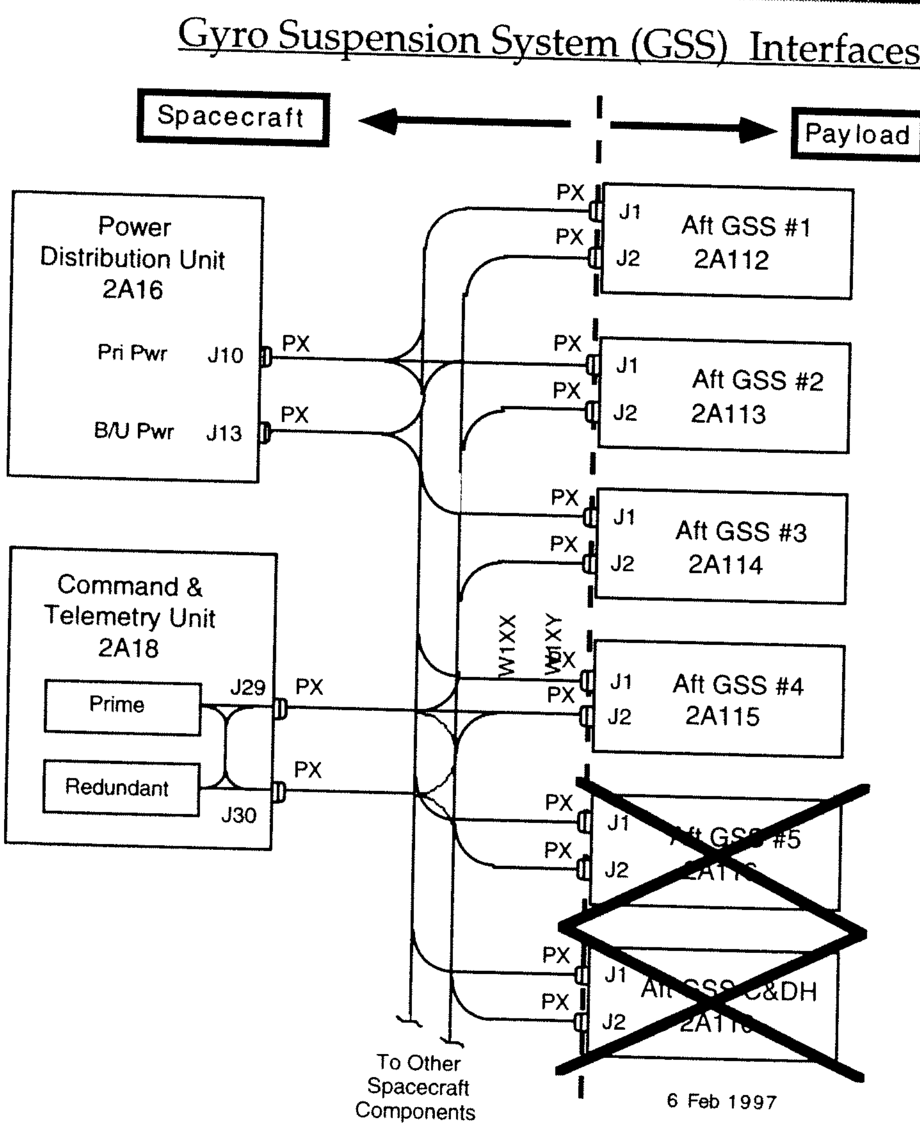




GSS Connectors and Cables



Electrical Interface to Spacecraft



Power Interface

Four Power Ports Per GSS (16 total)

- 1) Primary Power for the Forward Suspension Unit (7 A)
- 2) Redundant Power for the Forward Suspension Unit (7 A)
- 3) Power For the Aft Control Unit (5 A)
- 4) Power for the Forward and Aft Heaters (5 A)

Power is Fused and Switched in the Spacecraft PDU

All Power from the Spacecraft Feeds the Aft Power Units (APUs)

- APUs Distribute Power to Aft Control Unit and Forward Suspension Unit
- APUs Contains all DC/DC Converters

High Voltage for Spin-Up and 1g Lifts is Generated in APU

- Redundant +/- 725 V DC/DC Converters in Each APU Controlled by HLDs
- Both Hi-Voltage Converters ON at Once Gives +/- 1450 V for 1g Lift

Power Estimate

Specified Maximum GSS Power in Science Mode: **218 W**

Estimated GSS Power in Science Mode (no contingency): **217 W**

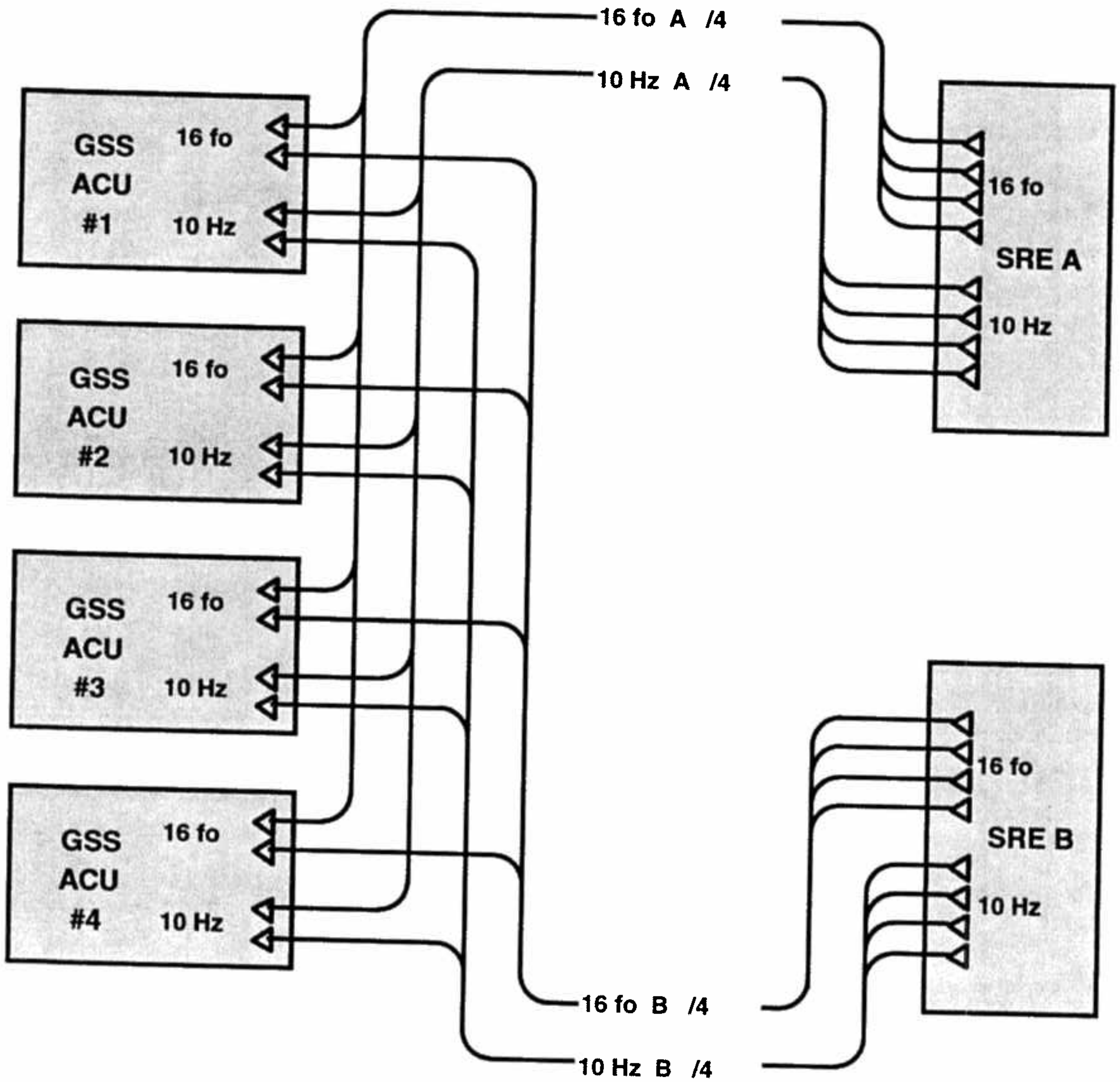
- Assumes Individual DC/DC Converters are 80% Efficient

Estimated GSS Power in Spinup Mode (no contingency) : **263 W**

Estimated GSS Power in Science Mode (w/ full contingency): **304 W**

Estimated GSS Power in Spinup Mode (w/ full contingency): **383 W**

Timing Interface



9. GSS Performance Verification and Test

Rob Brumley and Leo DiCarlo

Verification of GSS Requirements

Task: Verify GSS on-orbit performance meets science requirements.

REQUIREMENT AREAS

1. Basic Functionality (Gyroscope stays levitated)
2. Survival in Space Environment
3. Science Mission Drift Requirement
4. Compatibility with other systems (Readout, ATC)

TESTING CATEGORIES

1. Simulated Mission (Flowdown Verification)
2. Acceptance Test Plan (Space Qualification)
3. Stanford Checkout
4. Integrated Testing

Verification Tools: Overview

- **Ground Levitation of Gyroscopes**
  - Most hardware will be checked with ground levitation
  - All control algorithms scaled to 1-G for verification
- **Board-Level Simulation**
- **Environmental Testing (e.g. Thermal Vac, Vibration)**
- **Software Simulation**
- **Analysis**
  - Analysis and Verification results should agree
  - On-orbit disturbance mode (S285)
  - Gyroscope Model (S284)
- **GSS Testbed**
  - Allows verification of on-orbit closed-loop GSS performance
  - Integrated GSS Testing
  - Verification of "Tough" Torque Requirements

High-Level Test Flow

Flowdown Verification (Stanford Dev. Testing)

- Prototype and Engineering Unit
- Design Verification
- Verifies flow of T003 Reqs to GSS Box Specs

↓

GSS Acceptance Testing (Lockheed)

- Flight GSS, Board and Dummy Load Testing
- Verify GSS Box Level Specifications
- Fundamental space qualification process

↓

Stanford Checkout (Stanford University)

- Flight GSS and Gyroscope, Testbed
- Closed-Loop control system verification
- Completes verification of GSS Reqs document

↓

Payload Functional (Stanford University)

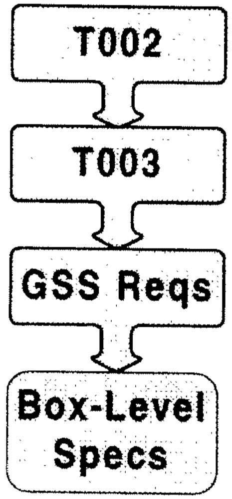
- Flight GSS and Payload
- Check Integration of GSS
- Final confirmation of SQUID compatibility/EMI

↓

Space Vehicle Functional (Lockheed)

- Flight GSS in Space Vehicle
- Testing of integration into spacecraft
- Ensure qualification of S/V does not damage GSS

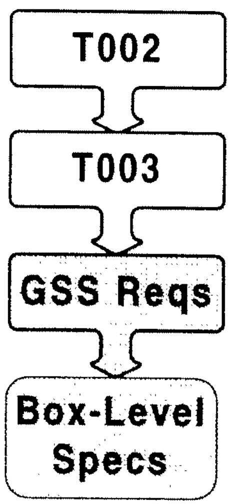
The Two Types of Verification



Flowdown Verification Plan

- Accomplished using prototype and engineering units (not flight)
- Time-intensive investigation
- Extensive testing of various in-flight parameters (e.g. drift added due to micrometerorite empacts)
- This work will also contribute to the overall GSS development effort

<u>Goal</u>: Show that ATP reliably verifies SM-level performance

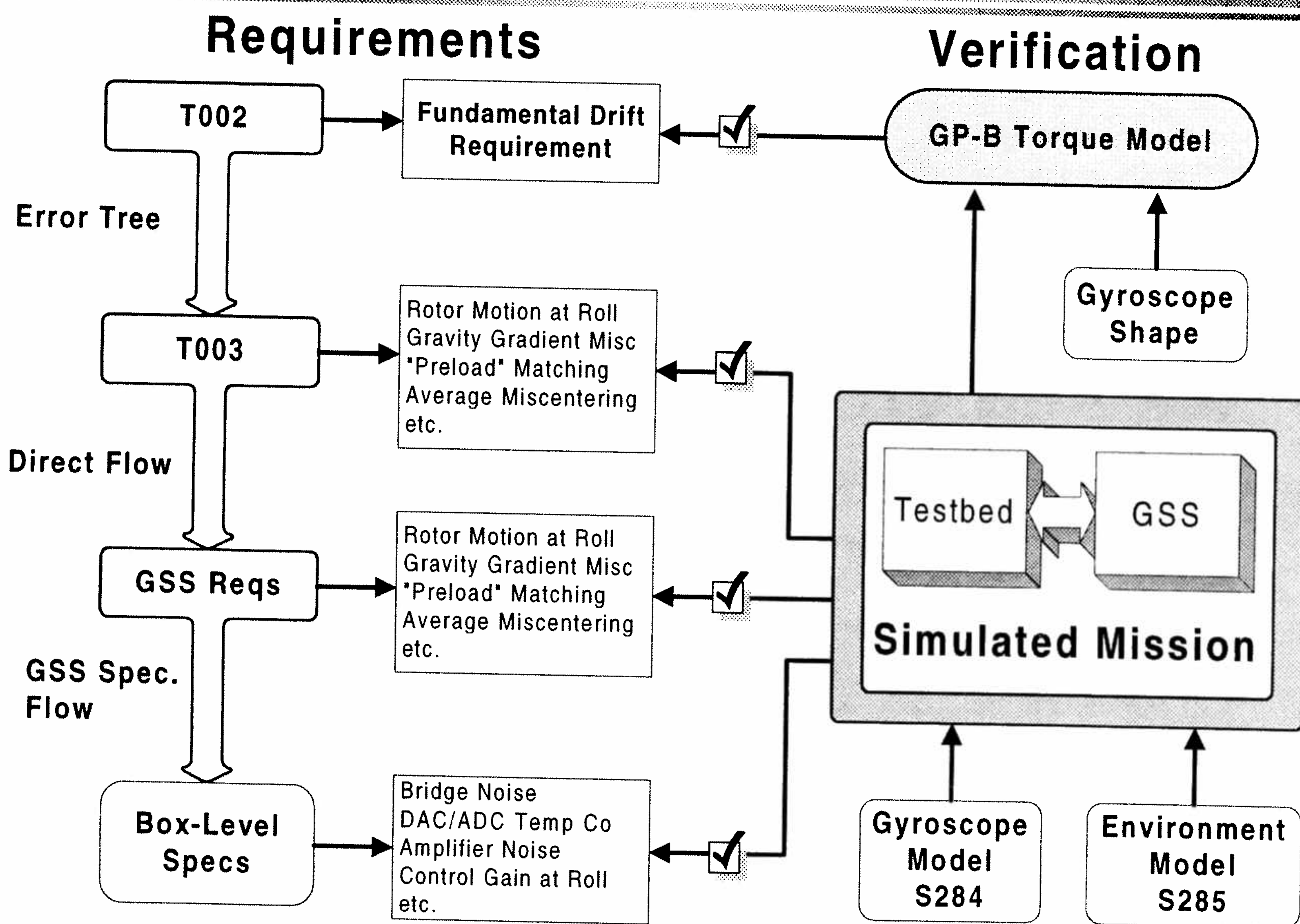


Acceptance Test Plan

- Easily measurable quantities
- Concentration on space qualification (vibration, thermal vac, etc.)
- Composed of Lockheed ATP and Stanford Checkout
- Testbed WILL test all mission modes and basic roll-frequency variations (limited duration test)

<u>Goal</u>: Verify flight systems are reliable and ready to ship

Simulated Mission Verifies Key Science Requirements



GSS Requirements Flowdown

1. **All GSS-related requirements in T003 are traced to appropriate places in GSS requirements document and verification strategy (see doc. packet)**

2. **A test strategy exists for all GSS Requirements (see doc. packet)**

3. **All GSS requirements are flowed up to parent requirements to trace drivers (in doc. packet also)**

4. **Test Plan unites Requirements and Verification Matrix**
   - "Requirements Interpretation" section provides mathematical equations used for verification.
   - Flows science requirements given design-specific assumptions to board-level requirements that are easy to check.

5. **The verification of flowdown process ends in the commissioning of the GSS Acceptance Test Plan**

Verification of Quantities Averaged over a Year

Most torque-related requirements are of the form:
("The variation at roll averaged over a year....")

$$\frac{2}{1\,year}\int x(t)e^{-j2\pi ft}dt\Big\|_{f=f_{roll}} < \varepsilon$$

There are 3 valid ways to check this requirement:

1. Show x(t) never exceeds ε
2. Divide the year into smaller pieces (e.g. 1 day) and show that the integral over the *worst* such piece is less than ε
3. Couple Method 2 approach with statistical analysis on the frequency and severity of disturbances (e.g. micrometeoroids)

☆ The specific method used and the appropriate time interval for averages are at the discretion of the GSS group.

☆ The testbed allows the measurement of the GSS closed-loop response to expected on-orbit disturbances, allowing the direct verification of tough science mission requirements.

Verification of Compatibility Requirements

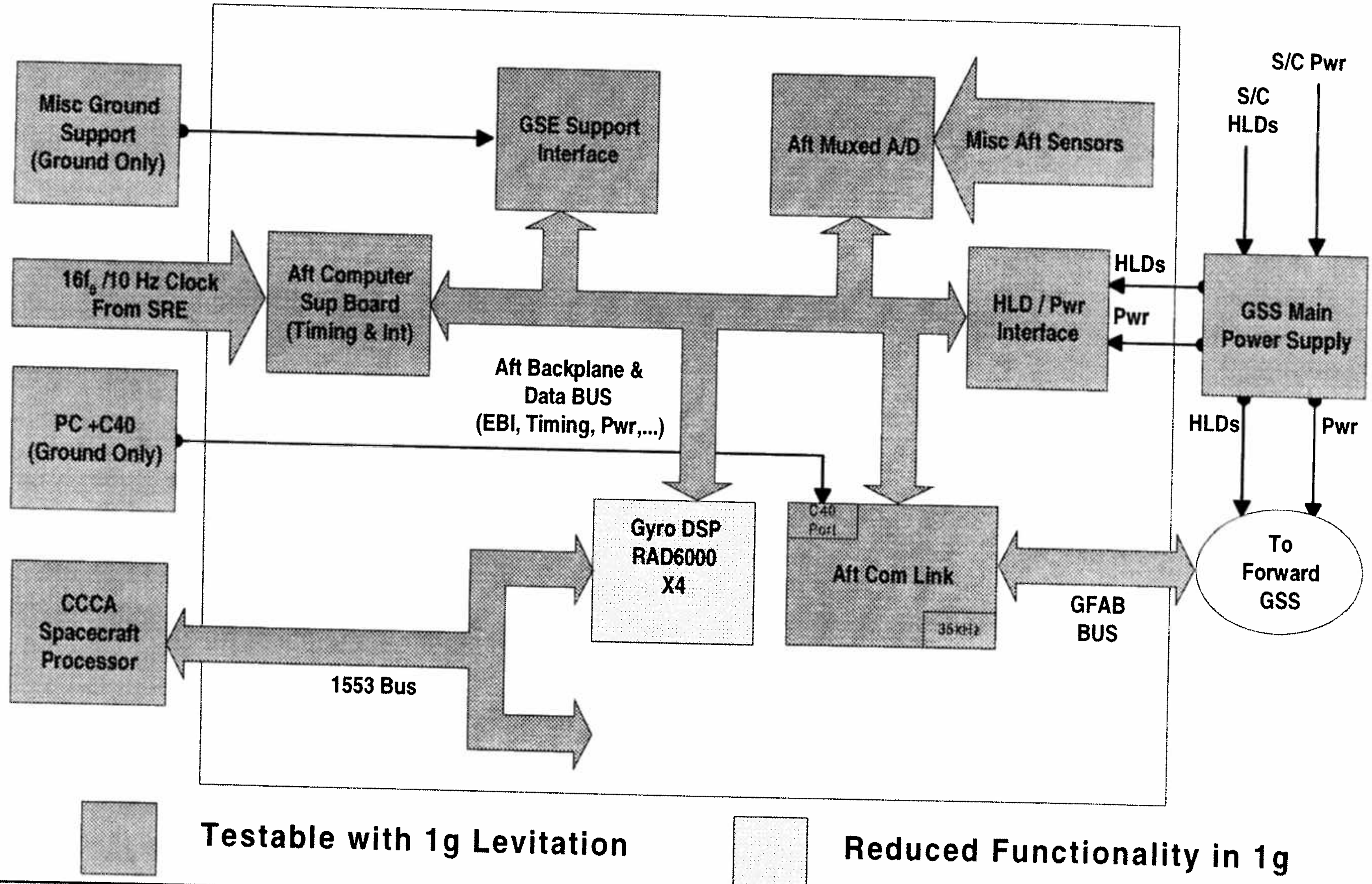
SQUID INTERACTION

- GTU-2 TESTS VERIFIED FUNDAMENTAL GSS/SQUID COMPATIBILITY (T003) TO THE LIMITS OF THE GTU-2 TESTS.
- GSS Requirements flow compatibility to measurable currents at electrode (these are used to commission the GSS and will be measured at Stanford Checkout).
- Final Confirmation of SQUID compatibility will occur in payload integration.

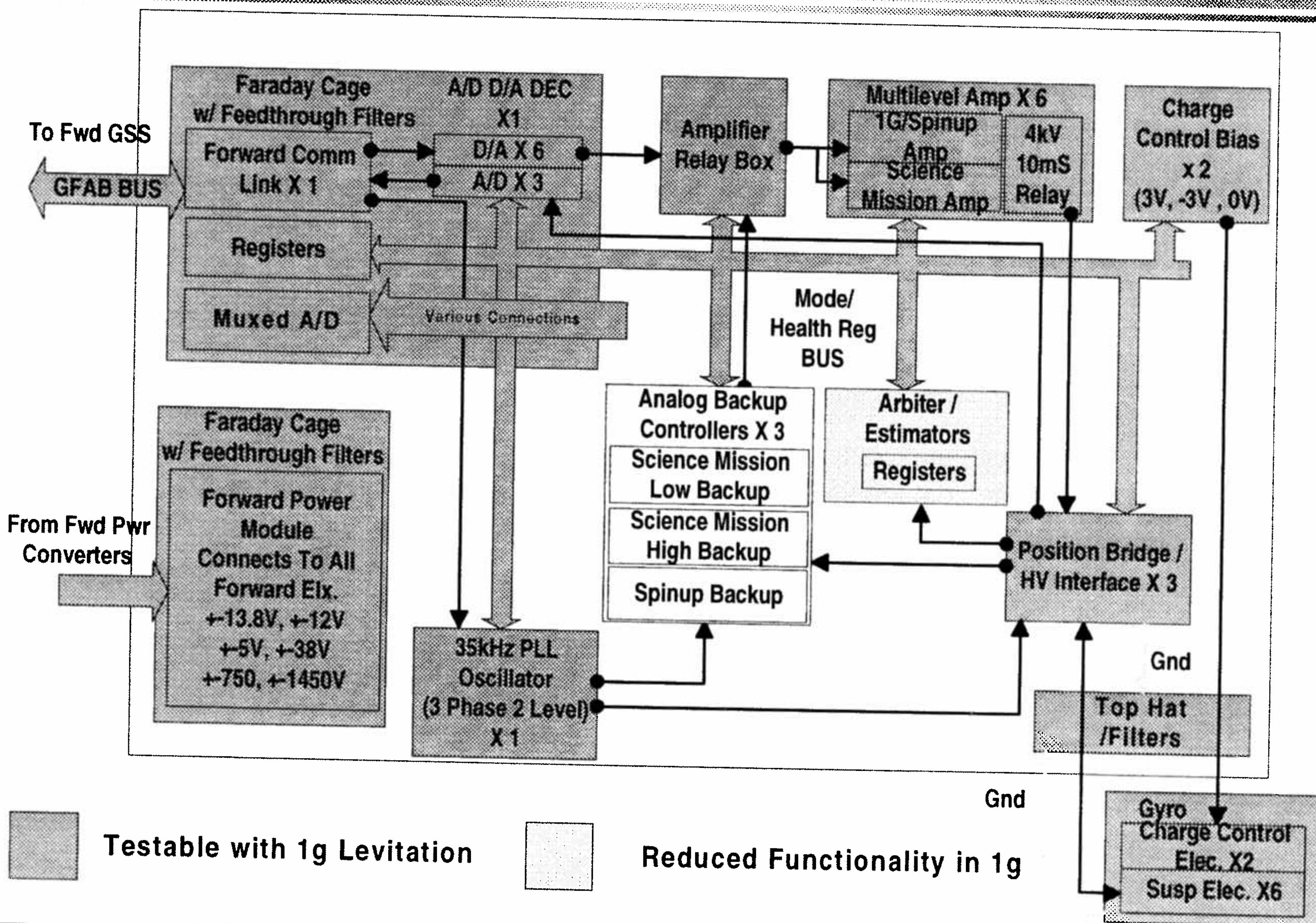
ATC COMPATIBILITY

- Most requirements can be verified by design.
- Position measurement signals requirements verified in GSS Testbed.
- GSS Testbed used to verify GSS-Drag Free Control Transfer.

Aft Architecture Testable with 1g Lift



Forward Architecture Testable with 1g Lift

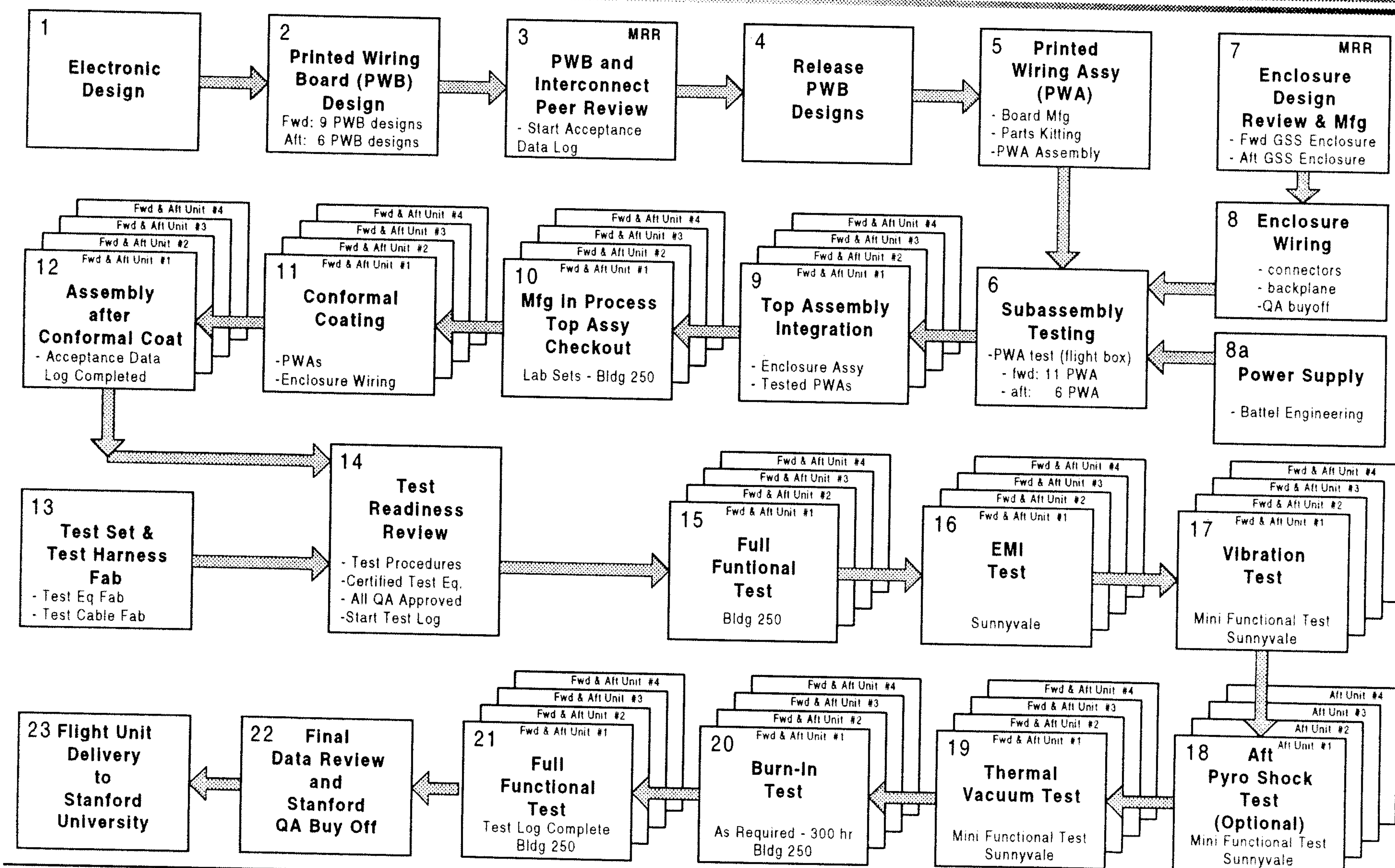


Verification Matrix

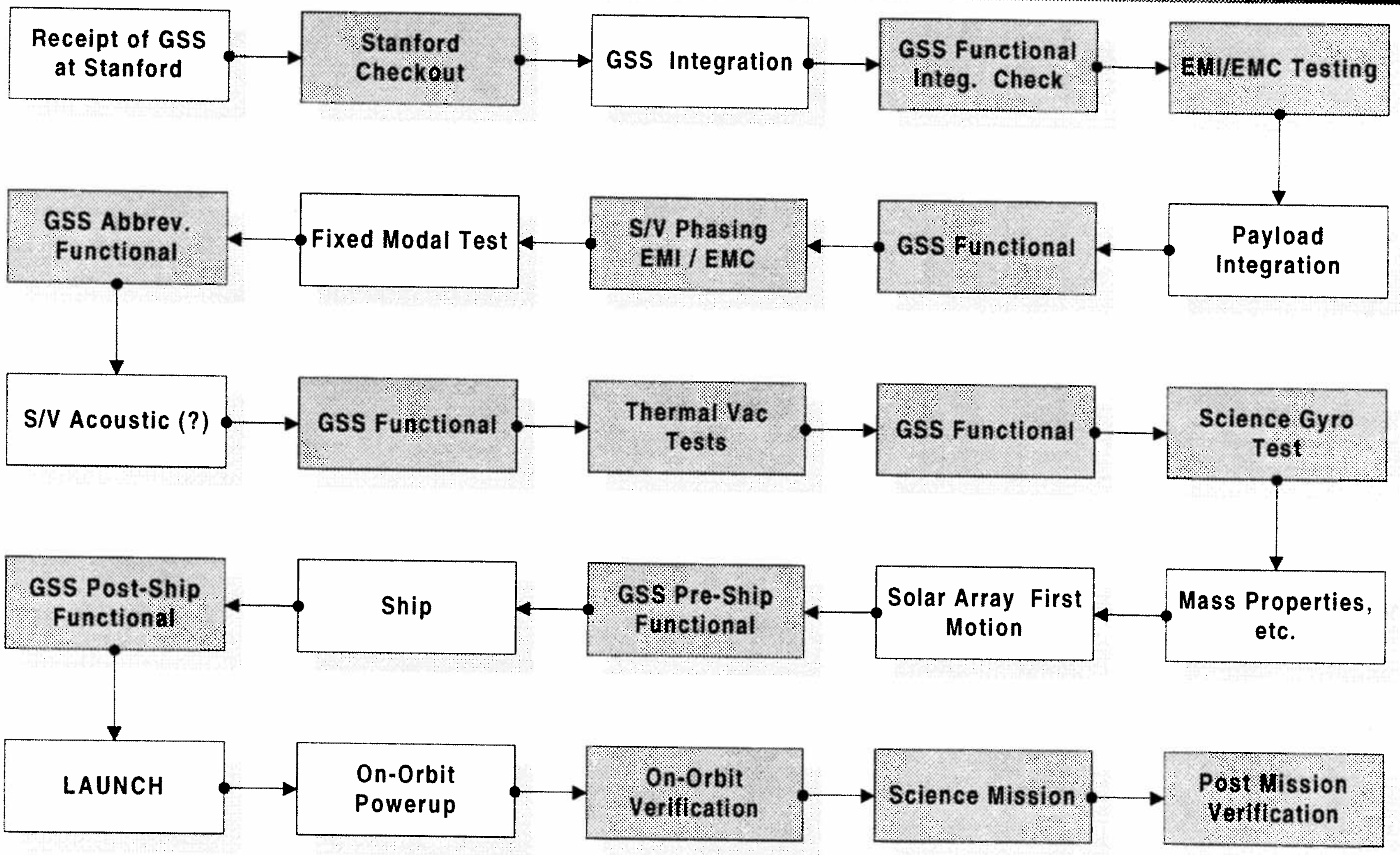
(One page of many -- See Technical Appendix for complete matrix)

Section	Parameter	Requirement	Flowup	Test Flow
3.2.2	**GSU Science Performance Requirements, <u>Suspended Gyro</u>**		T003 2.	N/A
3.2.2.1	**Gyro Rotor Miscentering, All specs in <u>body coordinates</u> measured from capacitive center**		T003 2.3	N/A
3.2.2.1.1	Average miscentering parallel to each electrode axis averaged over any 1 month period.	$<M_{a,b,c}> \leq 0.6\ \mu m$ ($\leq$ 2% of gap)	T003 2.3.2	Flowdown, Simulated Mission (Stanford Checkout)
3.2.2.1.2	Random miscentering near S/V roll rate parallel to each electrode axis:	$ASD(M_{a,b,c})\|_{any\ f,\ roll \pm 1/(0.5\ year)}$ $\leq 1.0\ \mu m / \sqrt{Hz}$	T003 2.3.1	Flowdown, Simulated Mission (Stanford Checkout)
3.2.2.1.3	Average miscentering parallel to S/V roll axis averaged over 1 year	$<M_z> \leq 0.6\ \mu m$	T003 2.3.2	Flowdown, Simulated Mission (Stanford Checkout)
3.2.2.1.4	Average miscentering at S/V roll rate perpendicular to S/V roll axis averaged over 1 year	$<M_{xy}>$ inertial $\leq$ 0.3 nm	T003 2.3.3.1	Flowdown, Simulated Mission (Stanford Checkout)
3.2.2.1.5	Average miscentering, at S/V roll rate + annual rate, perpendicular to S/V roll axis averaged over 1 year	$<M_{xy}>$ inertial+annual $\leq$ 1.0 nm	T003 2.3.3.2	Flowdown, Simulated Mission (Stanford Checkout)
3.2.2.1.6	Average miscentering, at S/V roll rate - annual rate, perpendicular to S/V roll axis averaged over 1 year:	$<M_{xy}>$ inertial-annual $\leq$ 1.0 nm	T003 2.3.3.2	Flowdown, Simulated Mission (Stanford Checkout)
3.2.2.1.7	Zero to Peak Gravity Gradient Miscentering parallel to S/V roll axis:	A <= 25 nm	T003 2.3.3.3	Flowdown, Simulated Mission (Stanford Checkout)

Pre-GSS Integration Test Flow



Test Flow After GSS Delivery to Stanford



Summary of GSS Testbed Capabilities

1. **The Testbed provides verification of the closed-loop GSS performance ("testing in space without going into space"):**
   - Testing of the integrated GSS (no connections are broken)
   - Physical motion ("moves" just like a real gyroscope)
   - Desired disturbance environment controlled by user (gravity gradient, micrometeoroids, centrifugal force, etc.)

2. **The functionality of the GSS *in all modes of the science mission* can be verified using the GSS Testbed:**
   - Rotor Spinup
   - Science Data Collection
   - Post-mission calibration

3. **Ability to test experimentally the response of the GSS to various failure modes (verified in Stanford Checkout of Flight GSS Units):**
   - FULL CHECKOUT of analog arbiter functionality
   - FULL CHECKOUT of transitions between modes (e.g. Spinup --> Science)
   - FULL CHECKOUT of backup controller performance

4. **Performance is consistent with measurement of "tough" science requirements**

Validation of GSS Testbed

Since the GSS Testbed will be used to validate fundamental GSS requirements, it must undergo its own validation process.

Key elements to validate:

(1) Accuracy of gyroscope and disturbance models

(2) Conformance of closed-loop testbed to the desired dynamics

Main Vehicles for this verification:

(1) **Analysis:**

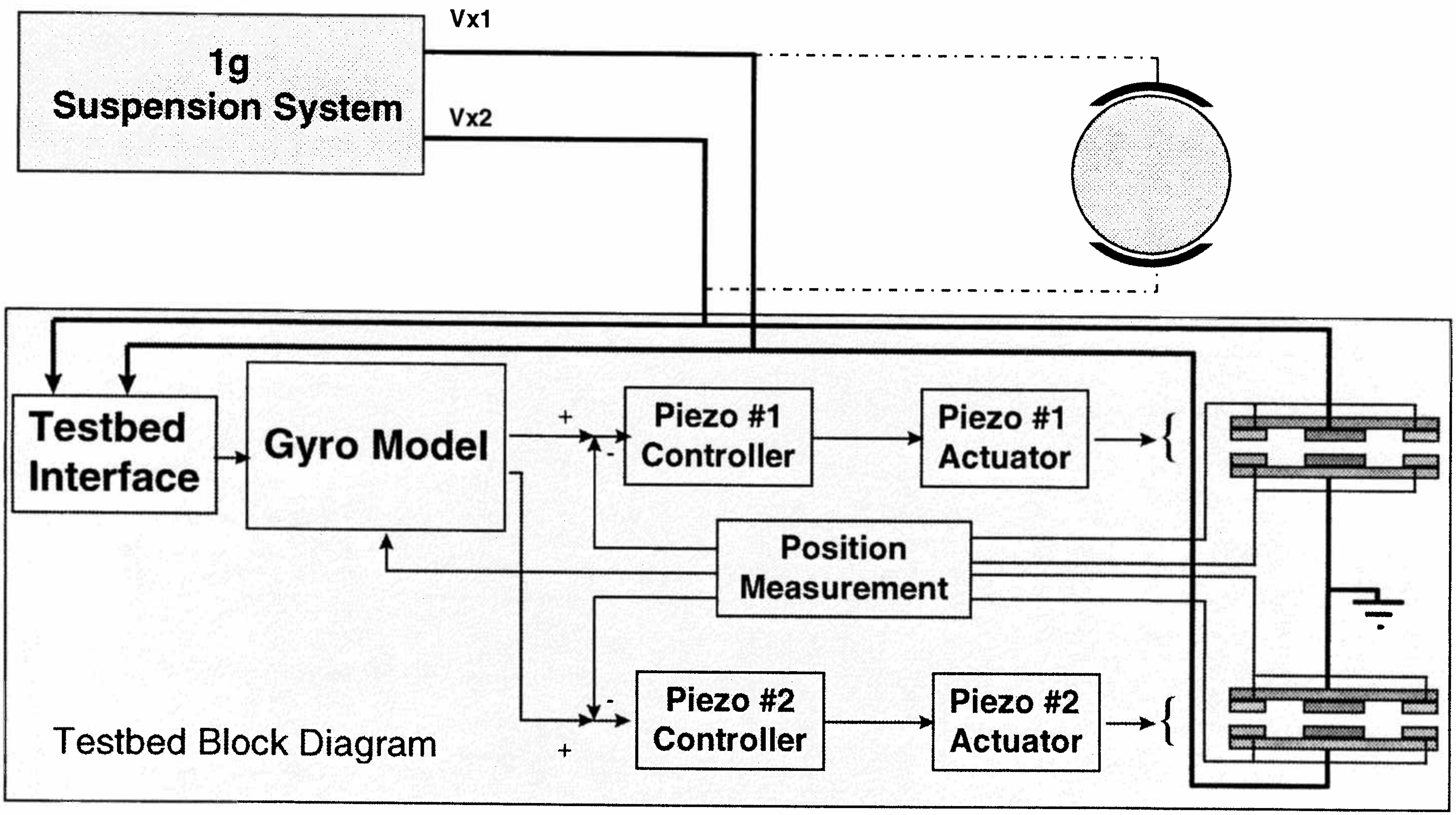
Electrostatic force law (cross coupling, effect of nonzero rotor potential...)
On-orbit environment (gravity gradient, micro-meteoroid impacts…)

(2) **1g Levitation:**

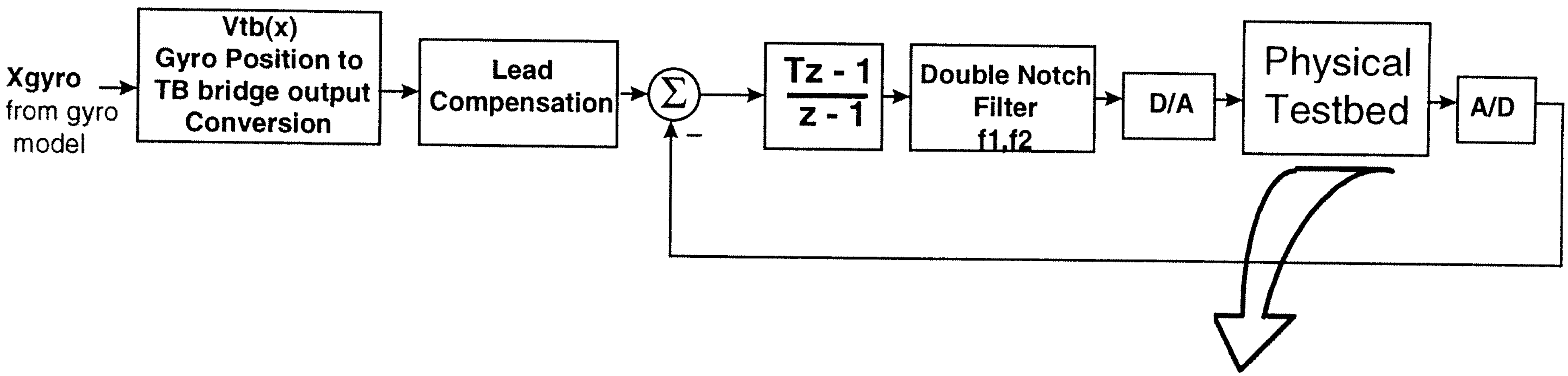
Most difficult test of the testbed hardware, due to:

a. mechanical piezo resonances and considerable phase loss of open loop testbed within the suspension system bandwidth (not so in any Science Mission mode).
b. Piezo slew rate limitation
c. Limited computational power

1g Validation of Testbed

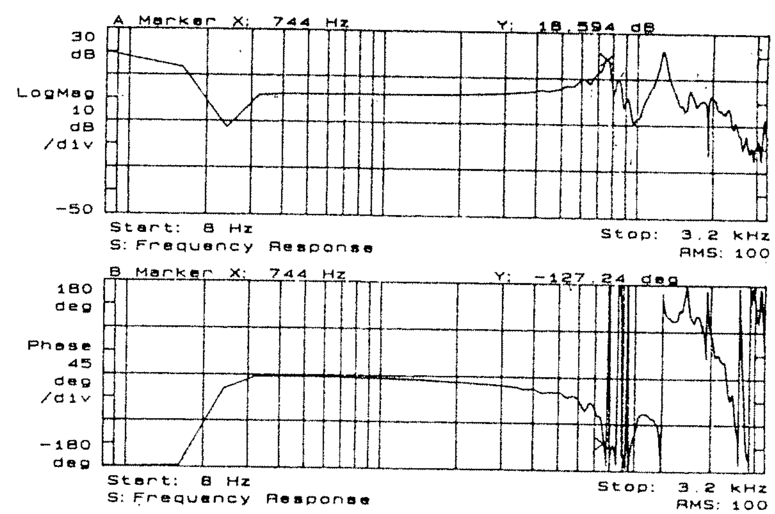


Testbed Piezo Controller



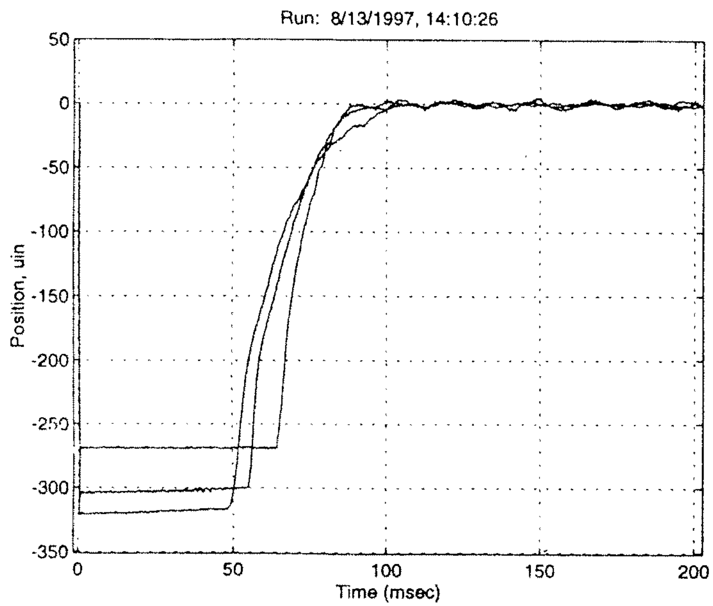
Inner Loop Controller Design:

- MSE optimization of complete suspension system step response w.r.t. step response with ideal gyro.
- 900Hz BW with 4KHz DSP sampling rate
- Testbed resonances are very stable with system under vacuum, requiring limited controller fine tuning.

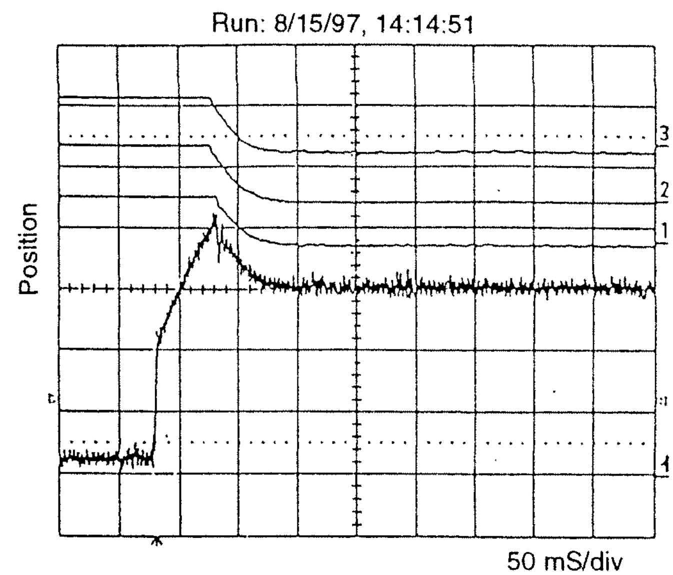


1g Testbed Suspension Results

Lift Trajectories of Testbed with DDC and Prototype GSS Systems



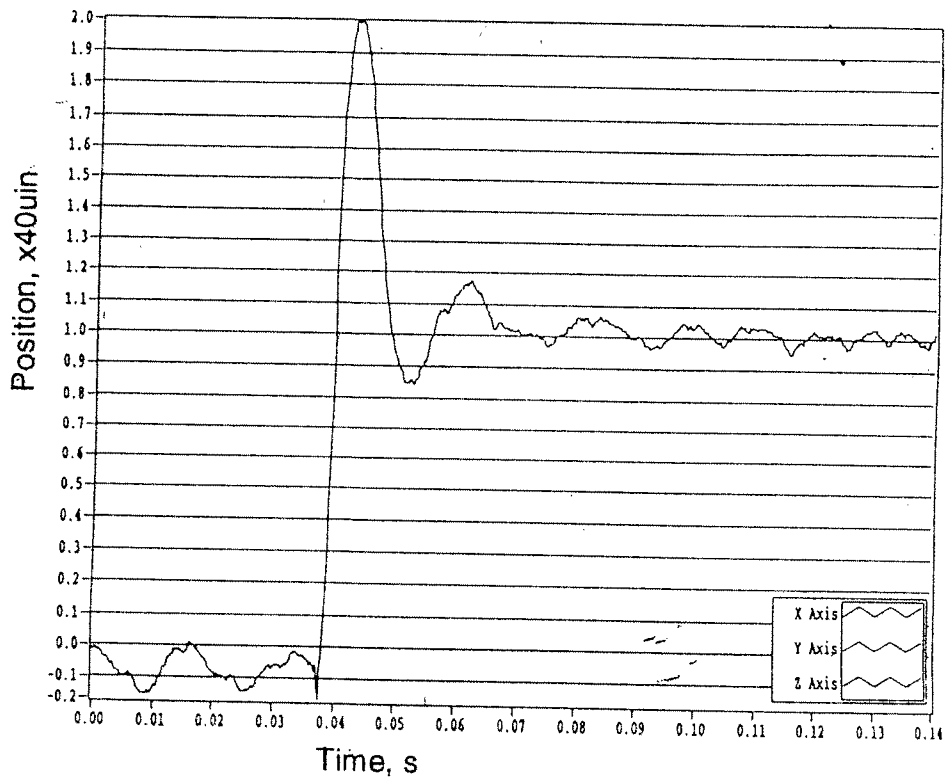
DDC Lift



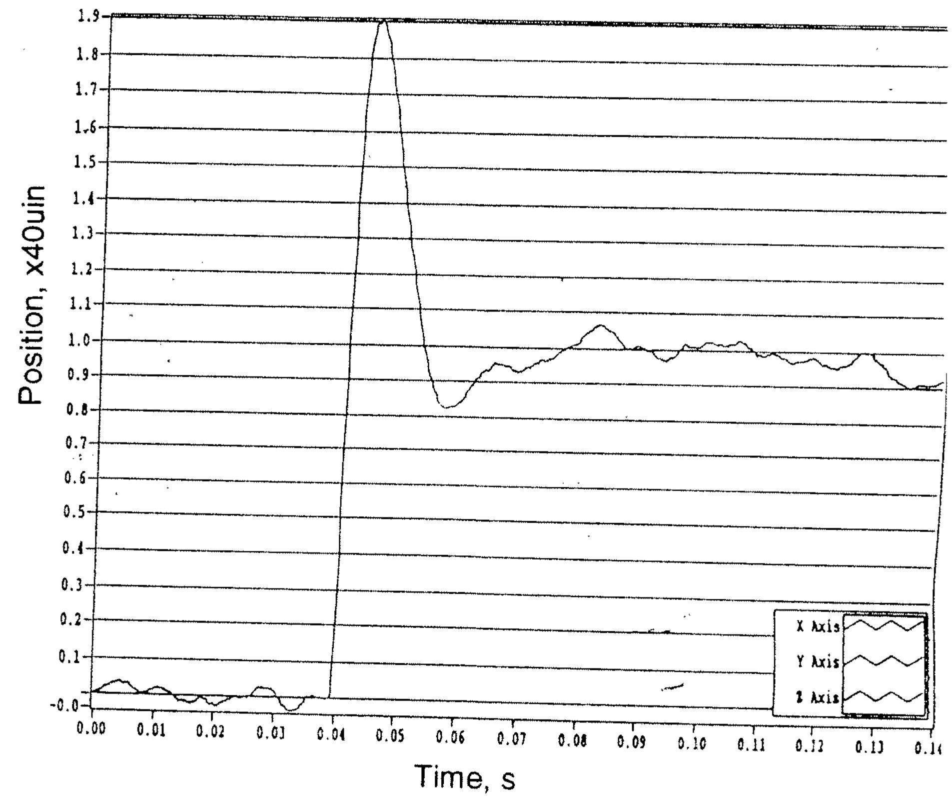
Prototype GSS Lift

1G Testbed Suspension Results

Comparison of Small Signal Step Responses of DDC System with Testbed and Gyro



Testbed



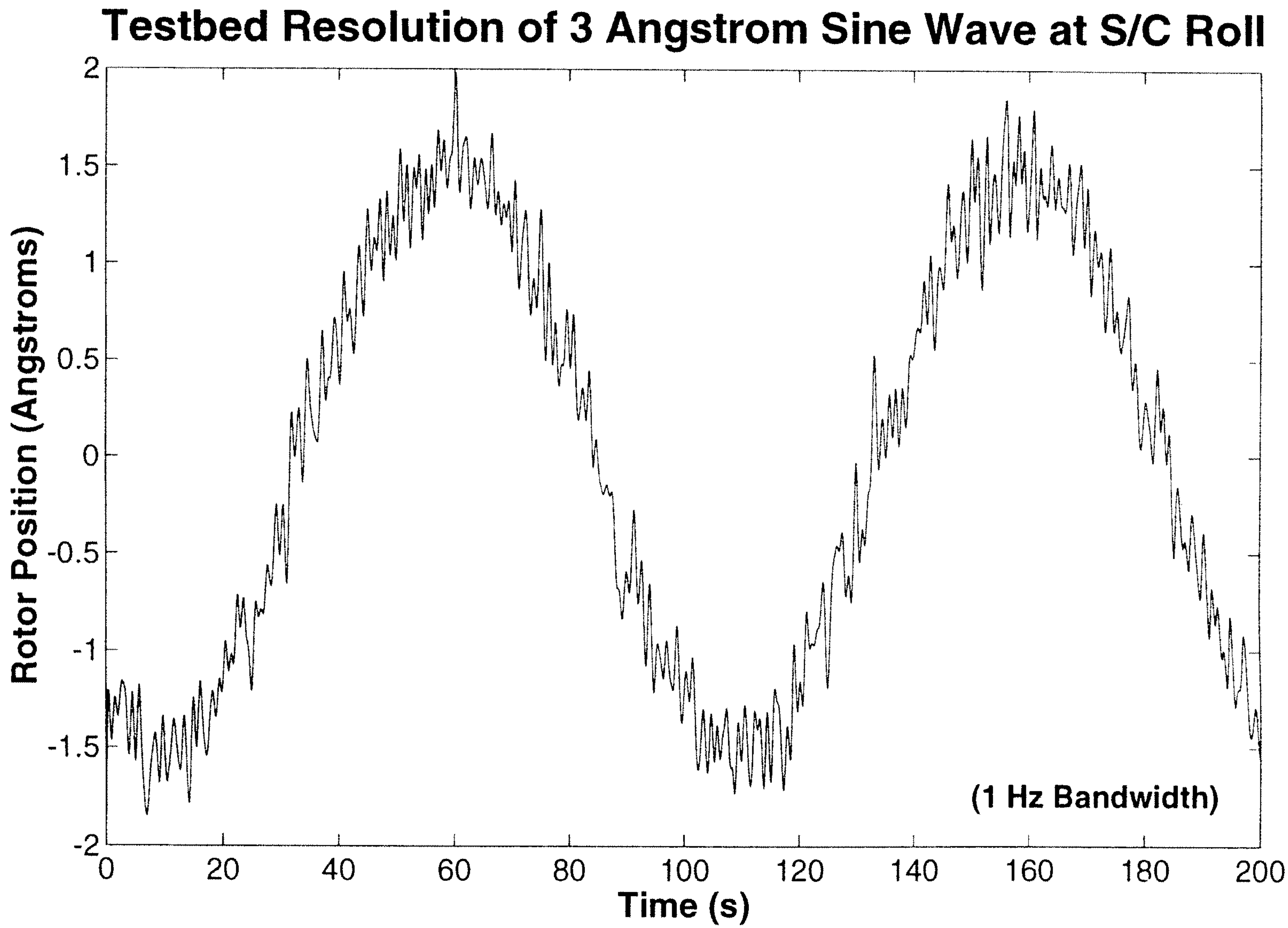
Gyroscope

Same DC Loop Gain!

Testbed: Deltas Since PDR

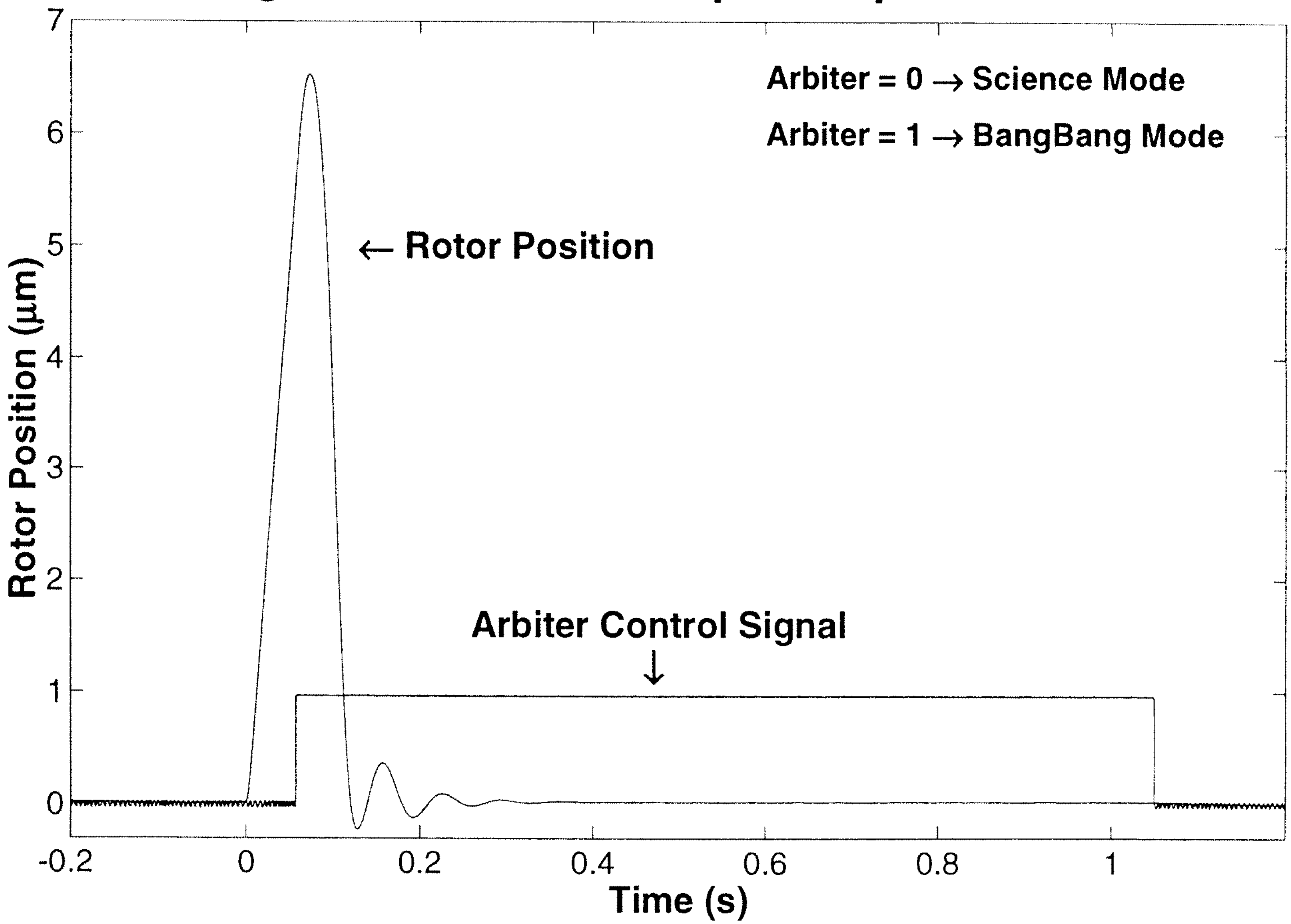
- Testbed Commissioned for GSS Testing purposes (some work on interfaces still needed)
- Three-axis levitation in simulated on-orbit conditions (10^{-6} g)
- Three-axis 1g Levitation with DDC
- Three-axis 1g Levitation with GSS Prototype
- Reduction in closed-loop positioning noise by 10x yields resolution at spacecraft roll of ~10 picometers.
- Demonstration of micrometeoroid survival using arbiter-controlled transition to a digital bangbang mode.
- New implementation of testbed software on a higher power DSP platform begun.

Testbed Checks "Tough" SM Requirements



Testbed Verification of Backup Controller and Arbiter

A Large Micrometeorite Impacts Spacecraft at T=0



Needed Testbed Development

- Spinup mode GSS to Testbed interface electronics
- Reduction of noise in current low-voltage interface for floating shields (EU Interface).
- Build mechanical interface for flight cables (use flight-qualified coffin boxes)
- Include torque models in post-mission processing
- Upgrade gyroscope dynamics / on-orbit disturbances models
- Upgrade computational facility (in progress)

10. FMECA Review

Sam Pullen

FMECA Objectives

1. **Fulfill requirements of MIL-STD-1629A**

2. **Identify GSS subsystem failure modes**
   - include failures due to hardware, design, and interface problems
   - focus on components and functional roles (e.g., analog control devices)

3. **Evaluate *criticality* (Cr) of each failure mode based on:**
   - probability of failure event — P(M)
   - conditional probability of worst-case result — β
   - severity of worst-case result — Sev

4. **Determine relative acceptability of failure risks**
   - high-criticality (low Cr number) modes require further mitigation
     - further analysis, testing, and/or design changes
   - low-criticality modes can be accepted "as is"

FMECA Evaluation Definitions

P(M) = Occurrence Probability

A	frequent	(Pr ~ 0.2)
B	probable	(Pr ~ 0.1)
C	occasional	(Pr ~ 0.05)
D	remote	(Pr ~ 0.005)
E	improbable	(Pr ~ 0.001)

β = Conditional Probability (worst event)

1	actual loss	(Pr ~ 1.0)
2	probable loss	(Pr ~ 0.5)
3	possible loss	(Pr ~ 0.05)
4	no effect	(Pr ~ 0.00)

Sev = Severity (worst event)

1	catastrophic	(loss of mission)
2	critical	(major degradation)
3	minor	(minor damage)
4	other	(unsched. repair)

classifications for failures which lead to gyro crash

FMECA Criticality Determination

Risk	P(M)	β	Sev 1	Sev 2	Sev 3	Sev 4
UA	A	1	1	5	9	13
	A	2	2	6	10	14
	B	1	2	6	10	14
	B	2	3	7	11	15
	C	1	3	7	11	15
	C	2	4	8	12	16
	A	3	6	10	14	17
	B	3	7	11	15	18
	D	1	7	11	15	18
UD	D	2	8	12	16	19
	C	3	8	12	16	19
	E	1	10	14	17	20
	E	2	11	15	18	21
	D	3	12	16	19	22
AR	E	3	15	18	21	23
AW	A	4	24	24	24	24
	B	4	24	24	24	24
	C	4	24	24	24	24
	D	4	24	24	24	24
	E	4	24	24	24	24

UA - unacceptable

UD - undesirable

AR - acceptable with review

AW - acceptable without review

GSS Failure Modes (1)

Aft Section

FAILURE MODE & CAUSES	EFFECTS:	ASSESSMENT:	Sev.	P(M)	ß	Cr
a) GSU control computer (DSP) failure	a) Loss of digital control	a)	3	D	1	15
b) Fwd. science power computer failure	b) Loss of redundancy	b)	3	D	1	15
c) High-voltage power converter failure	c) Reduced voltage available	c)	3	D	2	16
d) Aft computer power converter failure	d) Loss of digital control	d)	3	D	1	15
e) 1553 serial GSU bus failure	e) Loss of science data	e)	3	E	1	17
f) timing regulation failure	f) Loss of science data	f)	3	E	2	18
g) heating regulation failure	g) Loss of science data	g)	3	E	2	18
h) software design failure	h) Loss of digital control	h)	2	D	3	16
i) radiation-induced failure (SEU, SEL)	i) Loss of digital control	i)	3	C	3	16

GSS Failure Modes (2)

Forward Section

FAILURE MODE & CAUSES	EFFECTS:	ASSESSMENT:	Sev.	P(M)	ß	Cr
j) D/A converter/filter failure (1 of 6)	j) Loss of digital control	j)	3	D	1	15
k) A/D converter/filter failure (1 of 3)	k) Loss of digital control	k)	3	D	1	15
l) analog backup control failure (1 of 3)	l) Loss of mission	l)	1	E	3	15
m) analog arbiter failure (1)	m) Loss of mission	m)	1	D	3	12
n) actuator amplifier failure (1 of 6)	n) Loss of mission	n)	1	E	3	15
o) high-voltage interface failure (1 of 3)	o) Loss of mission	o)	2	D	3	16
p) position bridge filter failure (1 of 3)	p) Loss of mission	p)	1	E	3	15
q) 3-phase oscillator failure (1)	q) Loss of mission	q)	1	E	3	15
r)UV bias control failure (1 of 2)	r) Loss of science data	r)	3	E	2	18

GSS Failure Modes (3)

External Modes

FAILURE MODE & CAUSES	EFFECTS:	ASSESSMENT:	Sev.	P(M)	ß	Cr
s) forward-aft power interface failure	s) Loss of mission	p)	1	E	3	15
t) forward-aft data interface failure	t) Loss of mission	q)	3	E	1	17
u) electrode interface failure	u) Loss of mission	r)	1	E	3	15

***Note*:** **gyro and ground-plane electrodes are included in gyroscope subsystem FMECA.**

Failure Criticality Ranking

COMPONENT/ASSY.	FAILURE MODE	CRITICALITY	STATUS
Analog arbiter	m	12	I
GSU control computer	a	15	I
Fwd science power converter	b	15	I
Aft GSU power converter	d	15	I
Analog backup	l	15	I
Actuator amplifier	n	15	I
Position bridge/filter	p	15	I
3-phase oscillator	q	15	I
forward-aft power interface	s	15	I
Electrode interface	u	15	I
High-voltage power converter	c	16	I
Software design	h	16	I
radiation problem (SEU, SEL)	i	16	I
D/A converter/filter	j	16	I
A/D converter/filter	k	16	I
HV interface	o	16	I
1553 serial bus	e	17	I
Forward-aft data interface	t	17	I
Timing regulation	f	18	I
Heating regulation	g	18	I
UV bias control	r	18	I

» **Only analog arbiter is not in "acceptable" (AR) category**
- arbiter issue is difficulty of complete verification

Conclusions

1. **All but one subsystem failure mode have "acceptable" criticality (15 or better)**
   - overall risk appears acceptable

2. **Several failure modes would likely lead to gyro crash**
   - possible, but presumed unlikely, loss of mission
   - loss of affected gyro (only) is most probable result

3. **Assessments are sensitive to unknown occurrence probabilities**
   - particularly true for single-string components (forward electronics)

4. **More detailed examination of single-string electronics to be done in reliability analysis**

11. Quality Assurance

Sam Pullen/Ben Taller

Quality Assurance Controls

1. Design, per Stanford Quality Plans

- Quality Provisions per SU's "Science Mission Quality Plan" P0108.
- Configuration Control per "Science Mission Configuration Management Plan" P0098
- Drawings Release through Drawing Release Review
- Changes of requirements through Program Change Board (PCB)
- Changes of Drawings, Drawings Trees and P-Documents through Engineering Change Board (ECB)

2. Fabrication Control, per LMMS Plans

- Per LMMS "Safety, Reliability, Maintainability & Product Assurance Plan" LMSC-F428533.
- Identification, Operation Order, As-Built Configuration.

Quality Assurance Controls 2

2. Fabrication Control: (continued)

- Special Processes: Per written procedures.
- ESD Control per MIL-STD-1686A

3. Tests

- Test plan, Test Module.
- Test Equipment Calibration per MIL STD 45662.

4. Records

- Design, and Testing at the Box level records will be kept in SU GP-B Configuration & Test Database.
- This includes Drawings Configuration, P-Documents, PCBs, ECOs, DRs, Dwgs/Parts Tree, Components, Tests Plans, Tests Results and Calibration.
- Fabrication records- at LMMS.

Quality Assurance Controls 3

5. Parts

- EEE Parts List and Non-Standard Parts List by December 1, 1997.

6. Nonconformance Control

- Design and Testing- in Stanford Database, Fabrication- LMMS system.
- Discrepancy Reports including Analysis and Corrective Action. Disposition by Material Review Board (MRB).
- Use-As-Is and Repair disposition at LMMS require DEPRO concurrence.

7. Reliability (Sam Pullen)

- Per SU Reliability Plan, P0146 (Revised)
- FMECA completed.

8. Software Quality Assurance and Configuration Control

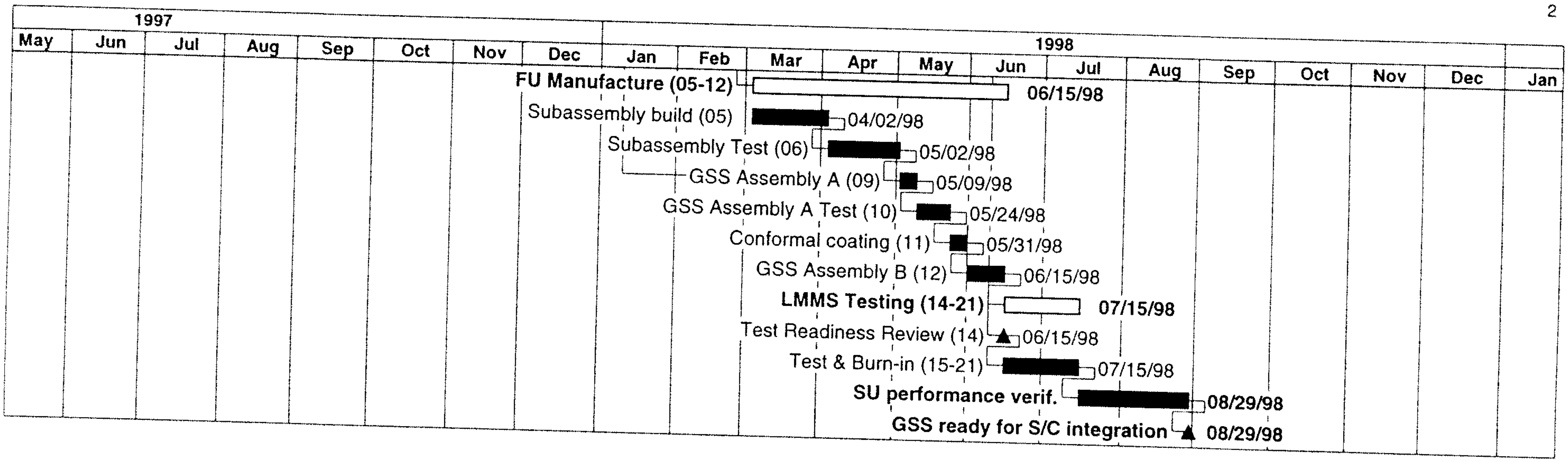
- Per LMMS Plan

12. Schedule and Resources

William Bencze

GSS Master Schedule 2

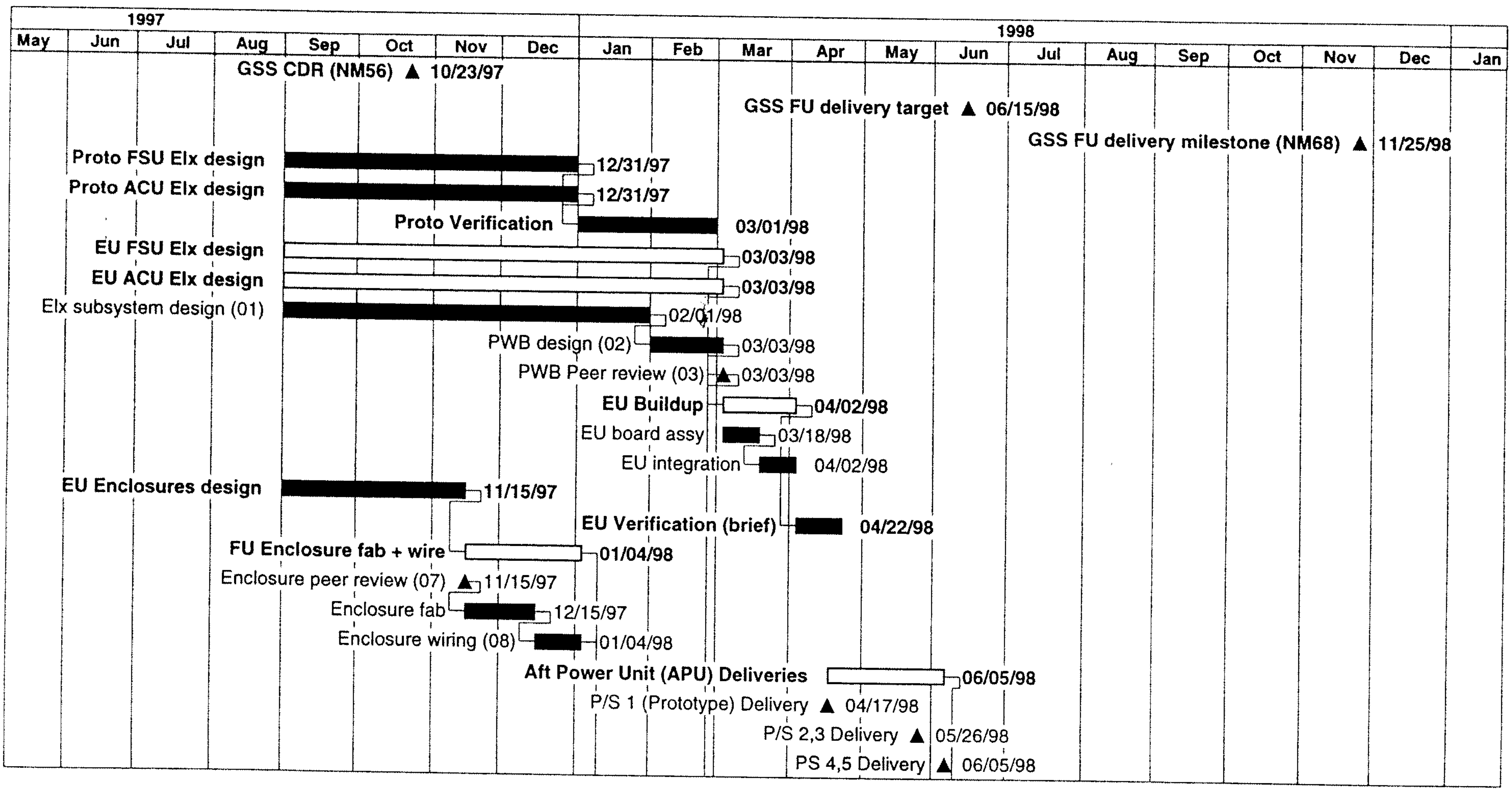
GSS Top-level schedule (overview)



GSS Master Schedule 1

GSS Top-level schedule (overview)

1



Issues and Risks

1. **This is a *success-oriented* schedule.**
   - Mandates an efficient design completion, build, and test process.
2. **<u>Largest risk area:</u> Integration of prototype designs into an EU/FU system.**
   - Risk increased by the time-efficient overlapped development process.

   This risk is mitigated through:
   - Prototype/EU handoff criteria; Prototype designs are scrubbed in detail before EU designs commence.
   - The bulk of the integration effort will be done by the Prototype design team.
3. **Schedule predicated on full staffing of GSS personnel billets.**
   - Digital design engineer postion still open; actively searching for a person.