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Control Structure Interaction/Optimized Design

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CONTROL STRUCTURE INTERACTION/ OPTIMIZED DESIGN

Final Report

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Objective

Under the direction of Dr. Peiman Maghami of NASA Langley Research Center (LaRC), a research computer code (CSI-DESIGN) has been developed to integrate the controller and structural design phases for flexible space structures. The code has been used to optimize the CSI Evolutionary Model (CEM) design which was validated experimentally.

There is a desire to apply the integrated design philosophy in general, and CSI-DESIGN code in particular, to a realistic and mature spacecraft design.

Space Systems/Loral (formerly Ford Aerospace, Space Systems Division), is building the next generation of US weather satellites, the GOES I-M series. These satellites have two main instruments that slew and gather information in an independent manner.

The objective of this study is to apply the integrated design methodology to the mature GOES-I spacecraft design, and to assess the possible advantages to be gained using this approach over the conventional sequential design approach used for the current design. In the process, the development of this technology into a tool that can be utilized for future near-term spacecraft designs should be emphasized.

Objective

- Apply integrated controls-structures design optimization strategy to a realistic, mature, Class II spacecraft design.

- Determine any advantages, with respect to the defined performance objectives, gained using the integrated design process.

- Illustrate this emerging design methodology an appropriate tool for utilization on near-term spacecraft design projects.

Approach

- identify the structural design parameters that are available for modification. Without these candidate structural design variables the problem becomes a controller optimization.
- review the GOES system design to identify past or present controls/structures interaction issues.
- identify the possible controller design variables from the candidate controllers on GOES.
- convert the GOES I NASTRAN model bulk data deck into the equivalent (as near as possible) CSI-DESIGN input deck.
- determine the driving system constraints, such as static loads, open and closed-loop frequencies, dynamic response to disturbances, controller energy, etc.
- determine the driving system performance objectives, such as minimizing mass, minimizing LOS pointing error (jitter) response to disturbances, maximizing controller damping, minimizing controller energy, etc.
- use CSI-DESIGN to optimize the GOES-I design for the chosen objectives and constraints and compare to the baseline design for improvements.
- consider the effect of increasing the actuator and sensor bandwidths, and reducing their noise characteristics, on GOES CSI issues.
- determine the benefits gained by applying the integrated design methodology to GOES-I. Suggest improvements to the CSI-DESIGN code

Approach

- Identify structural design parameters - candidate design variables.
- Review GOES CSI issues.
- Identify controller design parameters from candidate on-board controllers.
- Modify GOES-I structural model from NASTRAN to CSI-DESIGN format.
- Determine important system constraints and performance objectives (mass, LOS pointing error).
- Optimize the designs for the performance objectives using CSI-DESIGN, and compare with baseline system performance.
- Consider improved sensor and actuator impacts on potential GOES CSI issues.
- Make recommendations on possible improvements to CSI-DESIGN code to simplify its use as a design tool.
- Make recommendations on use of integrated design process to future GOES, UARS/EOS, and Space Station classes of platform.

GOES SYSTEM OVERVIEW

GOES-I Spacecraft On Orbit Configuration

The GOES-I spacecraft is shown here in on-orbit configuration. It is approximately 20 m in length and has a total dry mass of about 1000 kg.

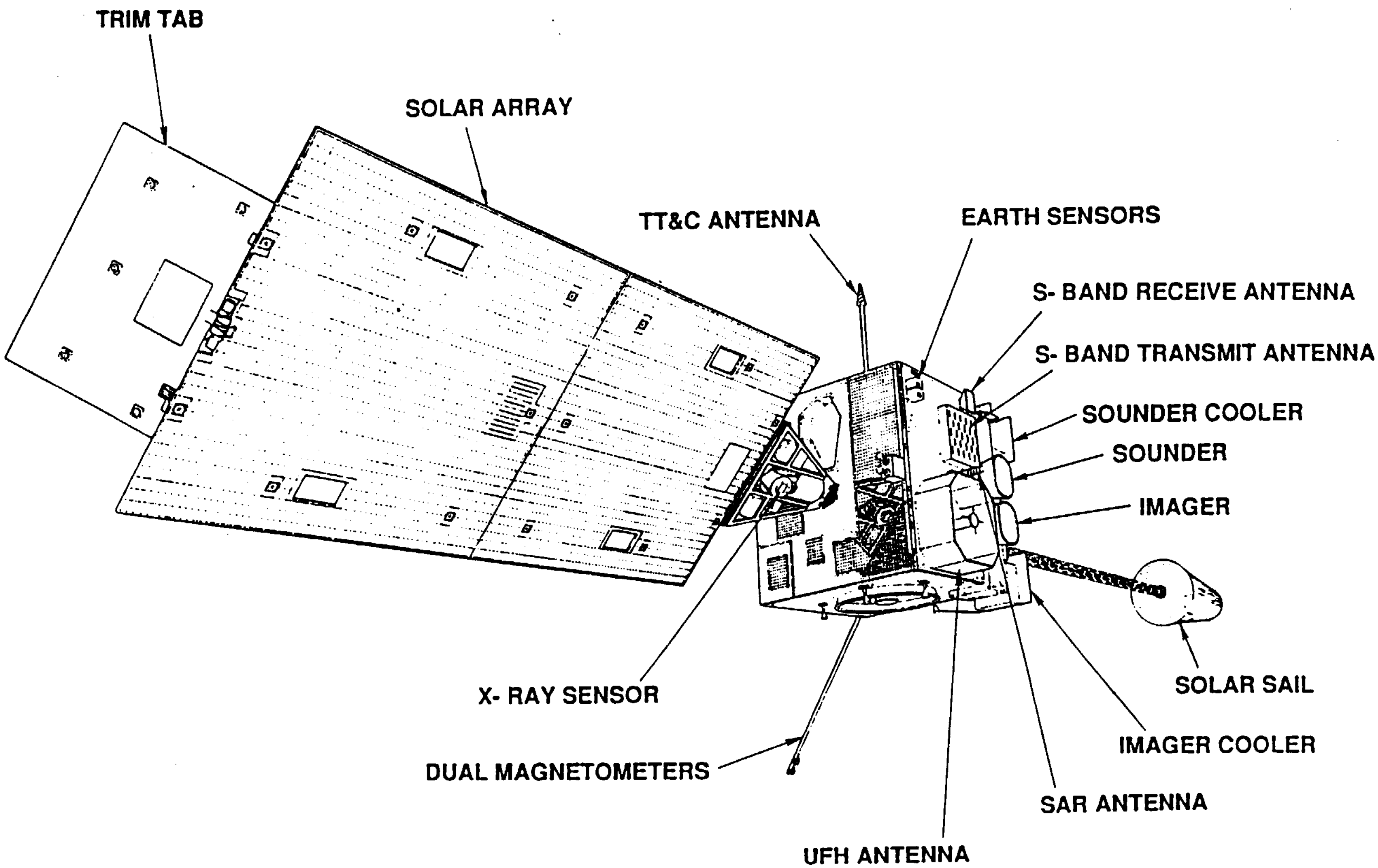
The two main instruments, the imager and sounder, are externally mounted to the main body structure in the north/Earth corner, providing unobstructed continuous visible and IR radiometric imaging and sounding over the entire Earth disk.

The 4.8 m solar array (consisting of two individual panels) attached to the south panel provides electrical power on-orbit, while the 17.7 m solar sail to the north balances to first order the solar toque produced by the solar array while providing unobstructed cooling for the instruments' north facing coolers. A trim tab on the solar array is for fine tuning the solar torque seasonal imbalance.

The GOES-I spacecraft includes a separate, dedicated transponder for search and rescue (SAR) early warning. The magnetometers located on a 3 m deployed boom, and the X-ray sensor and X-ray imager (recently added and not shown on this schematic) located on the solar array yoke, are research experiments only and take no part in the control system operation.

The TT&C antenna is located on a 2 m deployed boom and provides wide band and wide beamwidth telemetry and command performance. The S-band receive and transmit antennae serve as the primary imaging sensor data downlink.

GOES-I Spacecraft On Orbit Configuration



Primary GOES Controls & Structures

There are 3 main closed-loop control systems in GOES-I:

- rigid-body controller, for on-orbit use while instruments are being used
- stationkeeping controller, for orbit maneuvers while instruments are not being used
- instrument servo controllers, to close the loop for the scanning mirrors

There are several key structural components comprising GOES-I:

- a central cylinder, which provides the spacecraft frame and holds the fuel tanks
- 6 equipment panels on faces of the "cube" spacecraft body, holding various spacecraft sensors and actuators
- a solar array to provide spacecraft power, and a solar sail to balance the solar pressure effect on the solar array.
- 2 momentum wheel panels, on which are mounted the main spacecraft on-orbit momentum wheel actuators
- an instrument mounting panel to support the imager and sounder instruments
- the imager and sounder instruments, which are themselves very complicated structural components

Primary GOES Structures

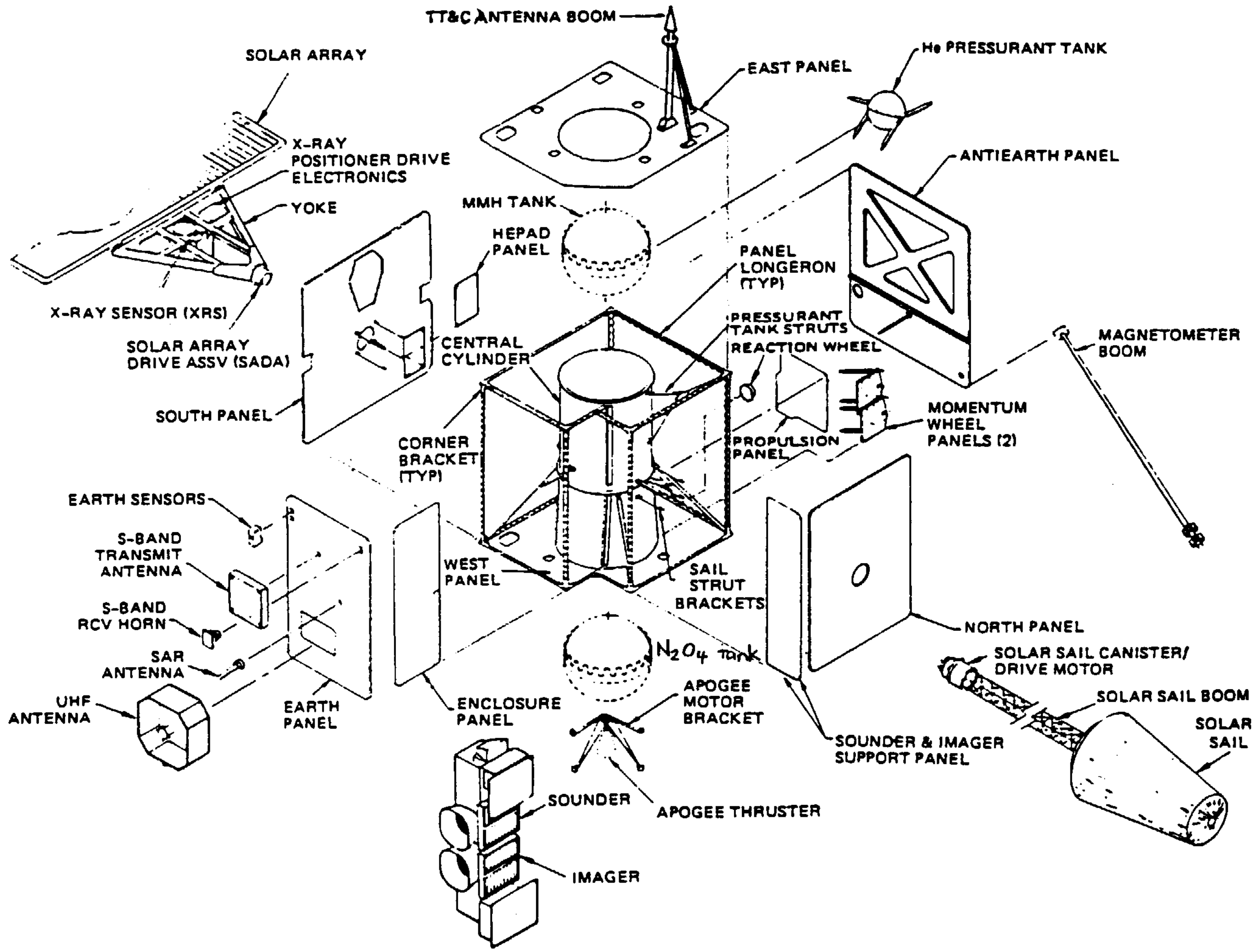
There are several key structural components comprising GOES-I:

- a central cylinder, which provides the spacecraft frame and holds the fuel tanks.
- 6 equipment panels on faces of the "cube" spacecraft body, holding various spacecraft sensors and interfaces to other equipment.
- a solar array to provide spacecraft power, and a solar sail to balance the solar pressure effect on the solar array.
- 2 momentum wheel panels (connected to central cylinder), on which are mounted the main spacecraft momentum wheel actuators.
- instrument mounting panels to support the imager and sounder instruments.
- the imager and sounder instruments, which are themselves very complicated structural components.

GOES-I Structural Configuration

This slide gives the GOES-I structure in an exploded view, showing the major structural components in greater detail and relative position.

GOES-I Structural Configuration



SYSTEM ANALYSIS

Structural Design Drivers

The structural design parameters are the sizes and material properties of the structural model elements. The structural design is driven mainly by the static launch loading and frequency requirements, and for the most part the structure is much stronger than that required to accomodate on-orbit loading.

This slide shows the component design load factors on major structural components due to an STS (Shuttle) or ELV (expendable launch vehicle - Atlas I) launch condition. These g loadings would give equivalent stress or strain conditions which all structural elements must survive, with a margin of safety. Note that these loads are indeed significantly larger than the loads expected on-orbit.

The axial direction refers to the axis of the central cylinder, aligned with the spacecraft X-axis.

Structural Design Drivers

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	Ultimate Load Factor, g			
Component/Launch Vehicle	**Axial**		**Lateral**	
• Panel mounted components	15g		15g	
• Imager/Sounder scanners		$Y_{s/c}$		$Z_{s/c}$
STS - Liftoff	6.0	3.5		8.4
STS - Landing	4.9	4.2		8.4
ELV - Max. lateral	4.9		4.5	
ELV - Max axial	10.0		2.2	
• Propellant tanks				
STS	6.2		8.0	
ELV - Max. lateral	4.2		4.5	
ELV - Max axial	10.0		2.3	
• Solar Array		$Y_{s/c}$		$Z_{s/c}$
STS	7.0	4.2		8.4
ELV - Max. lateral	4.9		6.3	
ELV - Max axial	12.0		2.5	
• Solar Sail boom				
STS	7.0		8.0	
ELV - Max. lateral	4.9		5.6	
ELV - Max axial	12.0		2.2	
• Upper Stage Motor				
STS	6.2		6.0	

Cylinder Element Static Load Margins

This slide gives a summary of the structural components that comprise the central cylinder, and their critical margins of safety with respect to the specified ultimate loading conditions. The minimum factor of safety for the composite material elements is 25%, and for the aluminimum rings is 57%. There is an internal requirement for composite materials of a 25% factor of safety.

Clearly, there are many components whose critical margin of safety exceeds that required, and these components are therefore candiates for change (notwithstanding their necessity to meet the frequency constraints given later). Of course, any structural element could probably get stiffer without problems unless a structural frequency stay-out region is affected.

Cylinder Element Static Load Margins

- This slide gives a summary of the structural components that comprise the central cylinder, and their critical margins of safety with respect to the specified ultimate loading conditions. There is an internal requirement for composite materials of a 25% factor of safety. Note that many components are stronger than required.

Drawing No.	Part Description	Material	Material ID	Load Case	Failure Criteria	Stress or Load		Margin of Safety*
						Allowable	Predicted	
570801	Cylinder Assembly							
	doubler, separation ring to cone	T300/934		STS	Max. strain	8900 us	570 us	High
	doubler & lower cone	P75/934	20002	STS	Max. strain	-1240 us	-590 us	1.1
	cone	P75/934	20002, 20003	STS	Max. strain	-1240 us	-680 us	0.82
	edge of lower propulsion cut-out	P75/934	20020	STS	Max. strain	-1240 us	-990 us	0.25
	edge of lower 1" diameter holes	P75/934		STS	Max. strain	-1240 us	-810 us	0.53
	cylinder/cone transition region	P75/934	20004, 20003	STS	Max. strain	-1240 us	-750 us	0.65
	core in cylinder/cone transition region	3.1 pcf Al	20004, 20003	STS	Core shear	110 psi	76 psi	0.45
	lower tank insert area	P75/934		STS	Max. strain	-1240 us	-750 us	0.65
	cylinder between upper & lower tanks	P75/934	20004	STS	Max. strain	-1240 us	-465 us	1.7
	edge of upper propulsion cut-out	P75/934	20020	STS	Max. strain	-1240 us	-780 us	0.59
	edge of upper 1" diameter holes	P75/934		STS	Max. strain	-1240 us	-600 us	1
	upper tank insert area	P75/934		STS	Max. strain	-1240 us	-530 us	1.3
	cylinder near east panel ring	P75/934	20004	STS	Max. strain	-1240 us	-250 us	3.9
570755	ring, east panel	2219-T852	20300	STS	Bearing	89.0 ksi	56.8 ksi	0.57
570756	ring, cylinder/cone transition	2219-T852	20200, 21950, 22050	STS	Stress	45.0 ksi	20.0 ksi	1.2
570757	ring, west panel	2219-T852	20100	STS	Bearing	89.0 ksi	42.7 ksi	1.1
570758	ring, satellite separation	2219-T852	20000, 20001	STS	Stress	46.0 ksi	15.2 ksi	2
570867	splice, ring, flat	2219-T852	20000, 20001	STS	Stress	46.0 ksi	10.1 ksi	3.6
570868	splice, ring, angle	2219-T852	20000, 20001	STS	Stress	46.0 ksi	15.5 ksi	1.9
570708	longeron, upper cylinder	2024-T81	31401	ELV	Bearing	94.0 ksi	55.9 ksi	0.68
570709	longeron, lower cylinder	2024-T81	31401	ELV	Bearing	94.0 ksi	55.9 ksi	0.68

* margin of safety = (Allowable-Predicted)/Predicted

Equipment Panel & Strut Element Static Load Margins

This slide is similar to the previous slide, but summarizes the structural components that comprise the equipment panels and the struts. Their respective critial margins of safety with respect to the specified ultimate loading conditions are shown in the tables.

Again, there are many components whose critical margin of safety exceeds that required, and are therefore candiates for structural design variables.

Equipment Panel & Strut Element Static Load Margins

- This slide gives a summary of the structural components that comprise the equipment panels and primary struts, and their critial margins of safety with respect to the specified ultimate loading conditions. Again, many components are stronger than required.

Drawing No.	Part Description	Material	Material ID	Load Case	Failure Criteria	Stress or Load Allowable	Stress or Load Predicted	Margin of Safety
	Equipment Panels							
570712-01	Earth panel	2024-T81	14001	15g lateral	core shear	50 psi	28 psi	0.79
570712-02	anti-Earth panel, lower (-X)	faceskins	12001	ELV	faceskin normal	58.0 ksi	24.5 ksi	1.4
570712-03	north panel	&	11001	15g lateral	core shear	50 psi	28 psi	0.22
570712-04	south panel	5056 Al	13001, 13002, 13501	15g lateral	core shear	50 psi	28 psi	0.47
570712-05	imager/sounder enclosure panel	core	15001	15g lateral	core shear	50 psi	28 psi	2.6
570712-06	imager/sounder mounting panel		16001	15g lateral	core shear	110 psi	64 psi	0.72
570713-01	anti-Earth panel, upper (+X)	graphite/	12002	15g lateral	faceskin normal	10.5 ksi	3.4 ksi	2.1
570713-02	east panel	epoxy	17001	STS	faceskin normal	10.5 ksi	3.4 ksi	0.64
570713-02	west panel	faceskins	18001	ELV	faceskin normal	10.5 ksi	3.4 ksi	0.39
570713-03	propulsion panel	& 5056 Al		ELV	faceskin normal	10.5 ksi	3.4 ksi	14.8
570716-01	momentum wheel panel	core	25090. 25091	STS	core shear	200 psi	168 psi	0.19
	Primary Struts							
570718	tube, strut, graphinte 2.0" diameter	P-75/T-300	99910	ELV	buckling	8555 lbs	3606 lbs	1.4
570858	fitting, end strut, 2.0" diameter	2024-T81		ELV	yield	6400 lbs	4400 lbs	0.45
570810	collar strut, 2.0" dia	6061-T6		ELV	yield	35.0 ksi	11.3 ksi	2.1
	Secondary Struts							
570864	tube, strut, graphite, 0.75" diameter			STS				
(-01)	earth/cylinder strut	P-75/T-300			buckling	1287 lbs	211 lbs	5.1
(-02)	anti-Earth/cylinder strut				buckling	1821 lbs	302 lbs	5
(-03, -04, -05)	solar sail boom struts				buckling	1266 ksi	259 lbs	3.9
(-06, -07)	SADA struts		99912	STS	yield	35.4 ksi	3.3 ksi	9.7
(-08, -09, -10)	pressurant tank struts			STS	buckling	689 lbs	476 lbs	0.4
(-11 thru -14)	momentum wheel panel struts		99901, 99902	STS	yield	35.4 ksi	3.8 ksi	8.3
570719	collar strut, 0.75" diameter	6061-T6		STS	yield	35.0 ksi	6.3 ksi	4.6
570720	fitting, end strut, 0.75" diameter	2024-T81		STS	yield	58.0 ksi	39.4 ksi	0.47

Frequency Constraint Design Goals

Frequency constraints are imposed on the spacecraft in the launch configuration to avoid interactions with the launch vehicle: i.e. to minimize launch vehicle induced loads. All flexible appendages are stowed in the launch configuration.

Frequency constraints are imposed on the spacecraft in the on-orbit configuration and the deployed appendages to avoid major low frequency interactions with the control systems and to bound the problem when interactions occur. The solar array, solar sail, magnetometer, and T&C boom are all deployed in the on-orbit configuration.

Note that there are no loading contraints on the solar sail since it "unwinds" itself from the stowage canister with no lateral loadings. The solar arrays and other deployed appendages deploy in arc motions and must withstand startup and stopping transient loads.

Frequency Constraint Design Goals

- Frequency constraints are imposed on the spacecraft in the launch configuration to avoid interactions with the launch vehicle: i.e. to minimize launch vehicle induced loads.

Launch Configuration (stowed)

	Recommended Frequency (Hz) Lateral	Axial
STS		
Satellite (fixed at satellite separation interface)	20	25
Spacecraft (satellite/perigee motor) (fixed at spacecraft adapter/cradle interface)	12	20
Cargo (satellite/perigee motor/cradle) (supported at STS interface)	8	8
Atlas I		
Satellite (fixed at satellite separation interface)	10	15
Equipment panels		
Solar arrays	25	50
Propulsion tanks		
Antenna reflectors		
Equipment Components		
Panel mounted	100	100
Bracket mounted	50	50

Deployed Configuration

	Recommended Frequency (Hz)
Solar Arrays (fully deployed)	
Out of plane bending	0.10 to 1.0
In plane bending	0.25 to 1.0
Locked rotor torsion	> 0.75
Solar Arrays (partially deployed)	
Out of plane bending	0.20 to 1.0
Solar Sail/Boom	
Bending	0.1 to 1.0
T&C and magnetometer Booms	
Bending	> 4.0
Trim Tab	1.0 to 5.0

- Frequency constraints are imposed on the spacecraft in the on-orbit configuration and the deployed appendages to avoid major low frequency interactions with the control systems and to bound the problem when interactions occur.

Structural Design Parameters - Summary

There are many structural design components whose margins of safety over the critical failure mode are much larger than required. Although this generally implies that these components could be made weaker (with an attendant mass savings), it is important to realize that the effect of frequency constraints on the structural design components is not directly quantifiable.

Frequency constraints are designed into most of our satellite structures, including GOES-I, in a rather heuristic manner - using the experience of analysts who have done that sort of thing previously. While not certain, it is very possible that many structural elements can be reduced in size and mass without causing the violation of any frequency constraints.

Additional conservativeness in structural design is due to poor knowledge of loading conditions when parts must be designed to manufacturing lead times, and due to other non-structural geometric considerations.

Many times a panel used in a structure does not require all of its structure to satisfy its original purpose. Holes, slots, or other shapes could be cut from these panels with no impact on the mission. However, this is generally not analyzed, or even considered, due to the adverse impact such additional analyses would have on the design schedule, which is typically very tight.

Structural Design Parameters - Summary

Many structural components are stronger than required, and are candidate parameters for structural optimization with the following qualifications:

- some components are larger than that required to handle launch loads due to geometric mating considerations with other components.
- conservative estimates used due to long manufacturing lead times.
- margins of safety are for static loads only, masking effect of structural frequency constraints.

GOES-I Finite Element Models

The model for GOES-I was constructed from the original NASTRAN model by eliminating the apogee motor and simplifying the finite element description of the central cylinder.

All other non-bus (equipment panels, solar array/sail, momentum wheel support panels, instrument support panels) structural components were unchanged from the original model.

The CSI-DESIGN model has less grid points (degrees of freedom) than the original NASTRAN model, but more elements due to the lack of 4 or larger node elements.

Additionally, the CSI-DESIGN finite element code does not contain anisotropic plate elements (used to model composite materials), which places a severe restriction on the fidelity with which the original NASTRAN structural mode can be reproduced using CSI-DESIGN.

GOES-I Finite Element Models

GOES-I NASTRAN model, as original with simplified central cylinder description and no apogee motor, consists of:

	GRID	CELAS2	ROD	CBAR	CTRIA3	CQUAD4	CQUAD8
Bus	2325	0	21	108	113	1368	97
Solar array	397	9	0	83	16	202	0
Solar sail	18	0	0	9	0	0	0
Total	**2740**	**9**	**21**	**200**	**129**	**1570**	**97**

GOES-I CSI-DESIGN model consists of

Total elements	**4273**	**(473 beam, 3788 plate, 12 elastic)**
Grid points	**2305**	
Materials	**65**	**(31 of them are structural design variables)**

Structural Design Variables

This table gives a list of the 31 structural design variables defined for the CSI-DESIGN model. These are some subset of the material geometric properties of the 65 material cards in the GOES model description.

The first 8 strucutral design variables are outside diameters of hollow tubular X-sectioned beam elements of fixed wall thickness. The relevant geometric properties of the beam element (area, area moments of inertia) are updated as the design variables are updated.

The remaining 23 structural design variables are the thicknesses of isotropic plate elements. Other plate material properties are fixed at their initial conditions.

Structural Design Variables

DV	Description	Property Card#	Initial Value (in)	# Linked Elements
1	Primary struts diameter	99910	0.75	4
2	Anti-Earth equipment panel/cylinder, earth equipment panel/cylinder struts diameter	99911	0.75	2
3	SADA struts diameter	99912	0.75	4
4	Cylinder/Cone transition ring element diameter	21950	0.75	25
5		22050	0.75	24
6	Cylinder/IS enclosure longeron element diameter	31401	0.75	10
7	Solar array yoke bar element diameter	103	0.75	41
8	Solar sail boom element diameter	8501	0.75	9
9	North equipment panel element thickness	11001	2.19	282
10	South equipment panel thickness	13001	3.73	317
11		13002	2.169	69
12		13501	0.88	8
13	Lower anti-Earth equipment panel element thickness	12001	2.12	97
14	Upper anti-Earth equipment panel element thickness	12002	2.25	127
15	Earth equipment panel element thickness	14001	2.06	176
16	West equipment panel element thickness	18001	0.88	201
17	East equipment panel element thickness	17001	0.88	263
18	Imager/Sounder enclosure panel element thickness	15001	1.75	161
19	Imager/Sounder mounting panel element thickness	16001	1.76	157
20	Cylinder element thickness	20000	0.35	50
21		20001	0.34	50
22		20002	0.51	175
23		20003	0.5	181
24		20004	0.49	378
25		20020	0.68	40
26		20100	0.094	50
27		20200	0.094	50
28		20300	0.06	32
29	Solar array panel 1/2 element thickness	7	2.2	48
30	Solar array panel 1 element thickness	21	2.18	104
31	Solar array panel 2 element thickness	22	2.18	118
	Total linked elements taking part in optimization			3251

Structural Design Loading Constraints

The structural design constraints are to be imposed in the launch configuration with imposed loading conditions. However, the optimization is to take place on the on-orbit configuration, which includes deployed flexible appendages and free-free boundary conditions.

The launch load constraints are imposed on the on-orbit configuration with side constraints on the design variables. Working from the critical margins of safety presented earlier, maximum design variable changes (resulting in lower bounds on the structural elements) can be determined using a conservative approach.

For each critical condition (stress, yeild, strain, buckling), the most conservative proportionality between the critial loading condition and the design variable is applied to the design variable to provide the maximum deviations from nominal while still providing a 15% magin of safety.

For example, for design variable 4, allowing for a 15% margin to the critical allowed stress value, the stres could increase by a factor of 0.85*45/20 = 1.913. The stress in a tubular beam element is at worst inversely proprtional to the square of the tube's outside diameter (the design variable in this case), so that the design variable can be allowed to decrease by a maximum factor of $\exp^{\ln(1.913)/2} = 1.383$.

Therefore, for an initial value of 0.75, then design variable 4 has a lower limit imposed of 0.75/1.383 = 0.542.

Structural Design Loading Constraints

DV #	Material	Allowed	Predicted	Units	Condition	DV0	DVmin*
1	99910	8555	3606	lbs	buckling	0.75	**0.594**
2	99911	58	36.2	ksi	yield	0.75	**0.643**
3	99912	35.4	3.3	ksi	yield	0.75	**0.248**
4	21950	45	20	ksi	stress	0.75	**0.542**
5	22050	45	20	ksi	stress	0.75	**0.542**
6	31401	94	55.9	ksi	stress	0.75	**0.627**
7	103	2200	1570	in-lbs	bending	0.75	**0.687**
8	8105	-	-	-	none	0.75	**0.600**
9	11001	50	41	psi	core shear	2.19	**2.151**
10	13001	50	34	psi	core shear	3.73	**3.336**
11	13002	50	34	psi	core shear	2.169	**1.940**
12	13501	50	34	psi	core shear	0.88	**0.787**
13	12001	58	24.5	ksi	face shear	2.12	**1.494**
14	12002	10.5	3.4	ksi	face shear	2.25	**1.389**
15	14001	50	28	psi	core shear	2.06	**1.672**
16	18001	10.5	7.5	ksi	face shear	0.88	**0.807**
17	17001	10.5	6.4	ksi	face shear	0.88	**0.745**
18	15001	50	14	psi	core shear	1.75	**1.004**
19	16001	110	64	psi	core shear	1.76	**1.456**
20	20000	46	15.2	ksi	stress	0.35	**0.220**
		46	10.1	ksi	stress		
		46	15.5	ksi	stress		
21	20001	46	15.2	ksi	stress	0.34	**0.214**
		46	10.1	ksi	stress		
		46	15.5	ksi	stress		
22	20002	1240	590	us	strain	0.51	**0.410**
		1240	680	us	strain		
23	20003	1240	680	us	strain	0.5	**0.451**
		1240	750	us	strain		
		110	76	psi	core shear		
24	20004	1240	750	us	strain	0.49	**0.442**
		110	76	psi	core shear		
		1240	465	us	strain		
		1240	250	us	strain		
25	20020	1240	780	us	strain	0.68	**0.659**
		1240	990	us	strain		
26	20100	89	42.7	ksi	stress	0.094	**0.071**
27	20200	45	20	ksi	stress	0.094	**0.068**
28	20300	89	56.8	ksi	stress	0.06	**0.052**
29	7	12.5	8.2	ksi	stress	2.2	**1.933**
30	21	12.5	8.2	ksi	stress	2.18	**1.915**
31	22	12.5	8.2	ksi	stress	2.18	**1.915**

* includes a 15% load margin of safety from allowed value

design variables 1 through 12 are the outside diameters of beam elements with fixed wall thickness

design variables 13 through 37 are the thicknesses of plate elements

- structural design variable lower limits chosen to satisfy stress/strain/buckling launch load constraints with 15% margin of safety from allowable values.
- a total of 3251 elements (76%, out of 4273) take part in the structural optimization.

Primary GOES Control Systems

There are 3 main closed-loop control systems in the GOES-I system.

The rigid-body controller is responsible for attitude control during the imaging phases of the mission. During imaging operations, no thruster activity is allowed to provide the most benign disturbance environment possible.

The stationkeeping controller is used during stationkeeping maneuvers. Since these maneuvers are conducted in thruster mode to accomodate the high level of disturbance torques possible due to thruster misalignment, thruster force variations, and plume impingement forces. The controller operates in high bandwidth rate feedback mode to stabilize the flexible appendage modes that are excited by the relatively large disturbance torques.

The closed-loop instrument servo controllers, which control the NS and EW scanning motions of the instruments' scanning mirrors, are considerably high bandwidth (20 - 30 Hz) to accommodate the very large scanning rate requirements of the instruments.

Primary GOES Control Systems

There are 3 main closed-loop control systems in GOES-I:

- rigid-body controller, for on-orbit use while instruments are being used
- stationkeeping controller, for orbit maneuvers while instruments are not being used
- instrument servo controllers, to close the loop for the scanning mirrors

GOES-I INR Performance Requirements - Imager

The GOES-I Image Navigation and Registration (INR) performance requirements are given in this slide.

Image "navigation" refers to the process of determining the coordinates of each pixel within an image in terms of Earth longitude and lattitude. Knowledge of the spacecraft orbit and instrument attitude at the time of imaging is essential for navigation of the image.

Image "registration" refers to the process of maintaining the coordinates of each pixel at the same Earth longitude and latitude independent of time.

- "image-to-image registration" indicates how well specific pixels remain mapped to the same Earth grid area from image to image (long term stability).
- "registration within an image" indicates how well the relative pixel locations within an image remain constant during the time an image is being collected (25 minutes per image).

The requirements for the sounder instrument are less stringent since the sounder has a lower resolution.

GOES-I INR Performance Requirements - Imager*

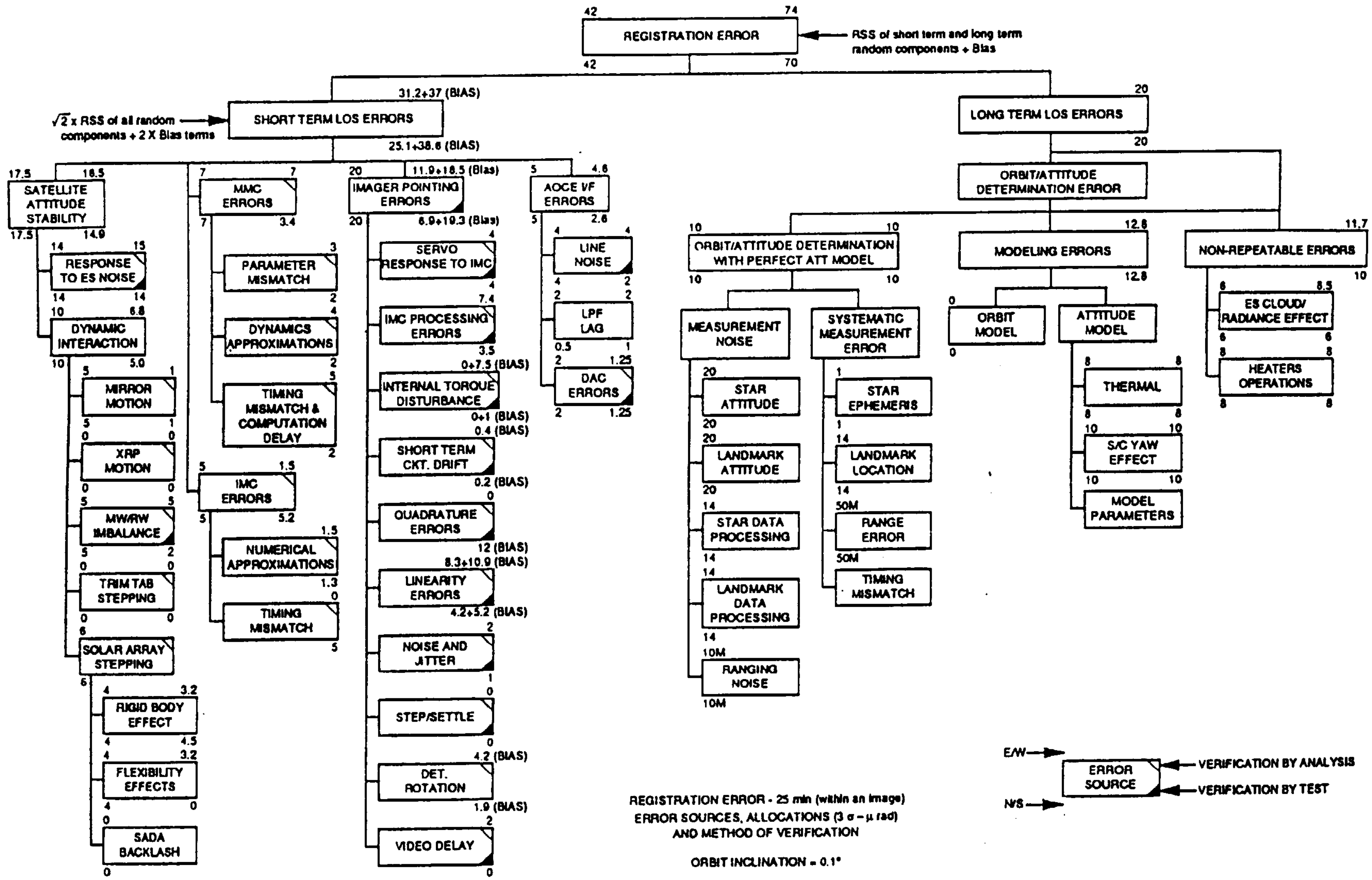
Requirement	**@ 12pm ± 8 hr**	**@ 12am ± 4 hr**
Image navigation accuracy (km at nadir)	4	6
Registration within an image - 25 min (microrad)	42	42
Registration between repeated images (microrad)		
- 15 min	42	70
- 90 min	84	105
- 24 hour	168	168
- 48 hour	210	210
Channel to channel co-registration (microrad)	28	28

* The requirements for the sounder instrument are less stringent since the sounder has a lower resolution.

GOES-I Pointing Budget

The GOES-I pointing budget is the result of many man-years of analysis, simulation, and experimental verification. In this form, it is easy to see the relative error contributions for differing subsystem components.

GOES-I Pointing Budget



GOES-I Pointing Budget (cont.)

For the current study, we are concerned only with those contributing error sources which an integrated controls-structures design approach could reduce.

Possible LOS error sources are, listed under their respective subsystem:

Controller: (rigid-body)

- flexible body motion
- response to ES noise
- MMC parameter mismatch

Structure:

- flexible body motion
- MW/RW imbalance
- solar array stepping

GOES-I Pointing Budget (cont.)

- only consider contributing error sources which an integrated controls-structures design approach could reduce.

- possible LOS error sources are:

  - flexible body motion
  - response to ES noise
  - MMC parameter mismatch (for feedforward)
  - MW/RW imbalance
  - solar array stepping

GOES Rigid Body Control

The momentum wheels of GOES are arranged in a V-configuration, with a 3.3 deg V-angle centered on the pitch axis. This provides a large momentum bias of 124 Nms in pitch, which decouples pitch dynamics from roll/yaw dynamics. This permits design of rigid body compensators separately in roll/yaw and pitch, but provides very little control authority in yaw; the maximum momentum rate in yaw is only 0.0043 Nm.

The low yaw control saturation threshold must be taken into account when designing compensation to damp the nutation mode, which is undamped with a frequency of 0.037 rad/s. Currently, a second-order non-minimum phase compensator ("Terasaki") increases the nutation damping to about 6% while producing little change in frequency. Control saturation is unlikely with the Terasaki compensator.

A more restrictive requirement for the Terasaki compensator is providing a 0.0005 deg (9 μrad) 3σ SS RMS roll response to Earth Sensor (ES) noise during imaging (roll ES var = 0.005^2 deg^2 @ 4 Hz). To accomplish this the nutation mode (6% damping) is barely stabilized, essentially running the roll/yaw axes "open loop" in order to heavily filter the comparatively large ES noise in the roll feedback.

Due to the large momentum bias, the spacecraft is a simple double-integrator plant in pitch. In this axis a 0.0005 deg (9 μrad) 3-σ steady-state pitch response can be met with straightforward LQG design.

GOES Rigid Body Control

- Large momentum bias in pitch (124 Nms) decouples roll/yaw from pitch, enabling design of separate rigid body compensators
- Small V-wheel angle (1.65 deg) provides very little control authority in yaw
- Nutation mode (roll/yaw) freq. = 0.037 rad/s (period 2.9 mins)
- Second-order compensator (terasaki) in roll/yaw provides about 6% damping of nutation mode (with integral control on roll)
- Controller designed to minimize steady-state (SS) RMS responses in pitch and roll to earth sensor noise during imaging
- Earth sensor noise discrete variance of 0.005^2 deg^2 sampled at 4 Hz

Req'd short term 3σ stability: 0.00052 deg (9 μrad, roll & pitch axes)

Rigid Body Controls-Structures Interaction

LQG Controller permits 30% lower SS RMS in roll for same nutation damping as Terasaki compensation.

Strict roll and pitch pointing requirements during imaging limit closed-loop BW to about 1.5 decades below the lowest flexible frequency. Without a much higher quality Earth sensor, along with greater control authority in yaw, this separation should remain unchanged.

Spectral separation of closed-loop, compensated rigid body spacecraft and low-frequency flex modes is too large for simultaneous optimization of controls and structures.

Rigid Body Controls-Structures Interaction

- GOES LQG controller permits 30% lower SS RMS in roll for same nutation damping than the baseline Terasaki loop.
- Without a much higher quality Earth sensor, compensator BW is fundamentally limited by the strict pointing requirements of imaging.
- Actuator authority is very low, and could not provide much more controller performance even with a perfect sensor.

- **payoff optimizing rigid body controller for controls-structures interactions should be small due to:**
  - **large controller frequency separation from flexible modes,**
  - **fundamental limitations in controller performance improvements due to sensor and actuator limitations.**

StationKeeping Controls-Structures Interaction

The performance of the SK controller could be improved by reducing the effect of the solar array/solar sail flexible modes. This could be accomplished by increasing the modal damping or decreasing the rigid-elastic coupling (REC) scalars. Modal damping is difficult to model and predict, and is usually added after the structural analysis. Increasing the controller order would also likely give better performance.

Increasing the frequency of the solar array/solar sail modes does not result in an equivalent reduction in REC scalars. These REC scalars are dependent on the inertia of the flexible body. Therefore, reducing the mass of the solar array and solar sail would help with SK performance.

However, the payoff for the GOES mission would be small since SK performance is not mission critical. The imager and sounder are not operated during SK, so only the relatively coarse 0.25 deg pointing requirements are specified, and these are met by the current design. Stationkeeping attitude performance is not a GOES mission driver.

The SK loop is optimized for minimum fuel use during the maneuver, which is determined in large part by choosing the deadband. The controller is of low order (only one 2nd order filter, used to guarantee stability)

Stationkeeping (SK) Controls-Structures Interaction

- SK rate controller bandwidth much larger, includes flexible modes
- could improve SK performance by reducing effect of solar array/solar sail flexible modes, or by increasing the controller order.
- increase modal damping or decrease rigid-elastic coupling (REC) scalars.
- solar array/solar sail REC mainly determined by body inertia.
- optimize mass of solar array/solar sail with minimum frequency constraints.
- controllers are simple uncoupled systems with loose (0.25 deg) performance requirements.
- after stability, fuel use most important - mostly determined by deadband choice.

- **payoff optimizing SK controls-structures interaction will be small for GOES mission since SK performance is <u>not a system performance driver</u>.**

Imager/Sounder Controls-Structures Interaction

A significant controls-structures interaction (structural instability for closed-loop EW servo controller at 1500 Hz) did occur early in the instrument design program, during instrument testing (after design and fabrication). This was fixed with a 6th order notch compensation filter .

Generally, a finite element model prediction of high frequency modes is of dubious use, and essentially is not reliable. Obviously, the original finite element model of the instruments **did not** identify any controls-structures problem at 1500 Hz. Given the nature of the compensation frequency response, an error in the predicted unstable modes of only ±10% would not be disastrous here. However, the finite element analysis may miss this mode entirely, or place it much more than 10% away from the predicted location.

Controller optimization for such high frequncy modes determined by analysis only is, in our opinion, inappropriate. Structural testing for such a high accuracy instrument should definitely be performed. If the integrated design methodology were to be applied after the finite element model has been tuned to match the identified transfer function, then the modelling would be relied upon to once again to capture the effect of any changes to the structure.

For GOES, once this instability was corrected, the contribution to the LOS error budget from residual instrument structural ringing due to servo activity was very small ($\ll 1$ µrad). The consequent payoff to optimizing the instrument controls-structures interaction would be very small due to the small system performance impact.

Imager/Sounder Controls-Structures Interaction

- early in program, a controls-structures instability was found in the EW scan servo loop controller at 1500 Hz. This was fixed using a 6th order notch filter.

- finite element prediction of high frequency instrument modes generally not believable (did not predict 1500 Hz instability), and controller optimization for such modes probably inappropriate.

- contribution to error budget from residual instrument structural ringing due to servo activity very small ($\ll 1\ \mu$rad).

- **payoff optimizing instrument controls-structures interaction will be small due to small system performance impact.**

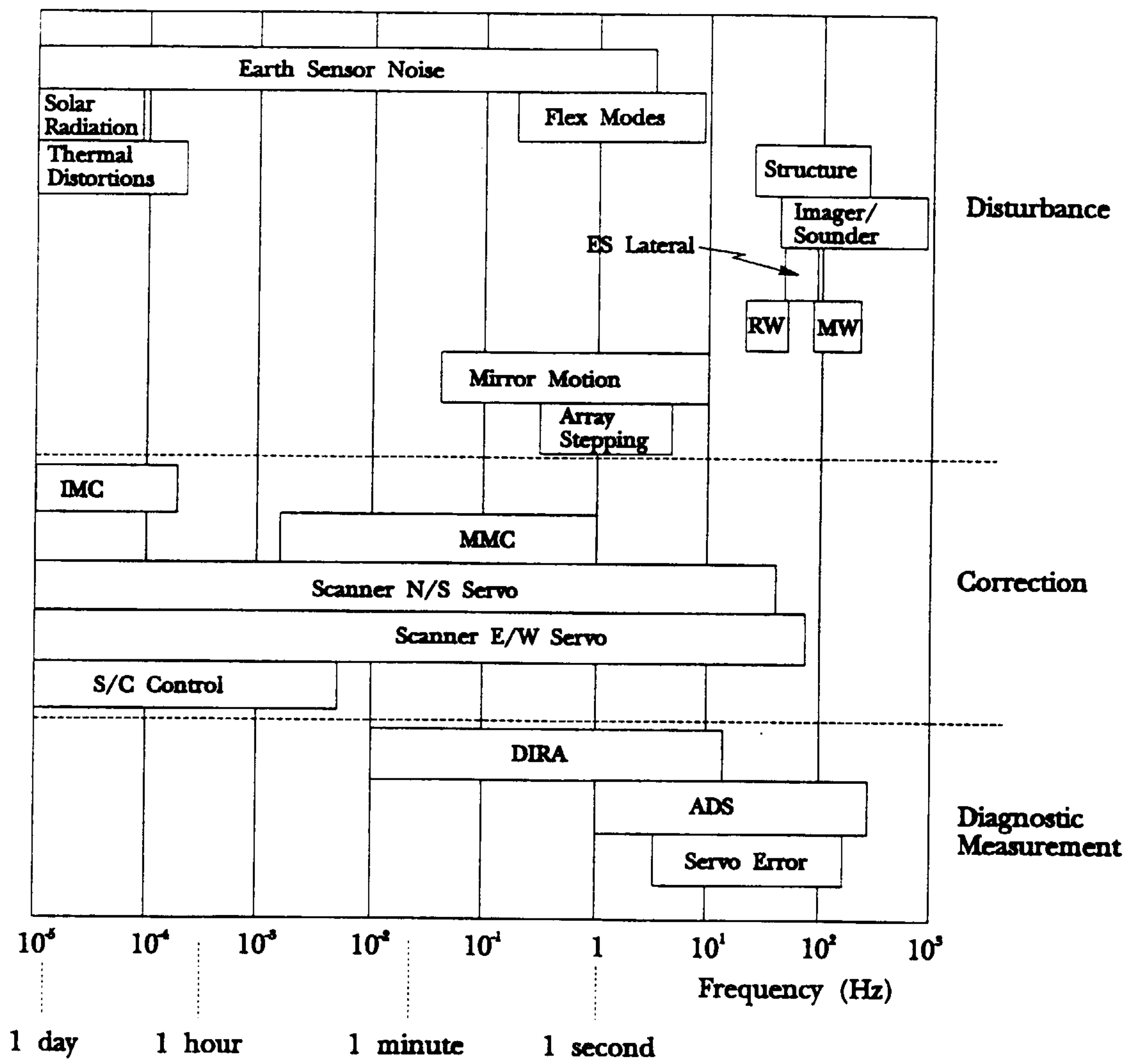
INR Dynamics Environment Summary

The chart shown here summarizes the INR controls-structures interaction issues discussed. It does not show disturbances or control during stationkeeping, since there is no INR performance issue.

It is obvious that the disturbances affecting the performance of the GOES mission are separated from the S/C control (rigid-body controller). The N/S and E/W servos have an extremely wide bandwidth, but residual errors are a very small component of the error budget.

The flexible appendage modes do not impact the system performance even though they are fully within the servo bandwidths. This is because they are not excited in the very benign on-orbit environment.

INR Dynamics Environment Summary



GOES LQG Controller Design

The LQG controller implementation in the original CSI-DESIGN code was modified to accomodate the special requirements of the GOES system.

The LQG analysis for GOES revealed that there were very specific LQG design parameters that affected the system performance (rms). These parameters form a minimal set of parameter to tune for an optimal design. The original LQG implementation in CSI-DESIGN provided state weighting on the modal and appended states. Our modification was to provide for output state weighting, to reduce the number of controller design variables.

GOES is a momentum bias spacecraft. The momentum bias can not be specified at the finite element level, as this precluded resolution of the structure into real modal form. Therefore, the momentum bias was added at the state space level as a "feedback" term. Additional dynamics were augmented to handle the reduced order state space model of the instruments, along with colored noise internal and external disturbances.

GOES LQG Controller Design

CSI-DESIGN code included an LQG controller implementation, which was extended to allow:

- output feedback LQG designs. These use a minimal set of control design variables that explicitly relate to controller performance measures.

- augmenting the open-loop plant (structural model) with
  - momentum bias
  - instrument dynamics state space model
  - colored noise disturbance dynamics.
  - external disturbance states

CSI-DESIGN Controller Numerical Implementation

The extensions to the original CSI-DESIGN controller implementation required code modifications. These modifications were much more difficult to perform than anticipated due to the complexity of the code and the lack of documentation written for, and standard interfaces designed for, code modifications.

Eventually, we decided to use MATLAB to perform the entire controller analysis. MATLAB 4.0 has a FORTRAN interface, and can be invoked from within a FORTRAN program as a compute engine. This approach has decided advantages over traditional FORTRAN coding of the controller numerical implementation.

Mainly, this approach is easier in terms of implementation and modifications of the control system. The control analyst is generally very familiar with MATLAB and its programming language (or an equivalent product): indeed the independent controller analyses for GOES were performed in the MATLAB environment. MATLAB removes the memory management overhead from the programmer, which can be a real problem in a large complex code.

A relatively small FORTRAN interface routine *allows the use of the original controller analysis code directly*. Finally, MATLAB numerical routines have been fine tuned for the specific processor on which it runs, and are very fast and robust (much more so than other FORTRAN numerical routines in general).

GOES LQG Controller Numerical Implementation

The LQG implementation extensions required writing additional FORTRAN code for the CSI-DESIGN program.

This was much more difficult than anticipated, due to:

- code complexity
- lack of standard interfaces and code documentation written for this purpose.

⇒ **use MATLAB to perform controller analysis in CSI-DESIGN**

This approach:

- reuses original controller analysis tools
- is less prone to coding errors and memory management problems
- is faster, in both coding and execution time
- is more numerically robust

Controller Design Variables

The controller optimization problem has 5 control design variables associated with output weighting, to go along with the 31 structural design variables. Note that output weighting requires significantly less control design variables than the state weighting formulation.

The controller design variables are all regulator weights:

- weight on nutation damping. This weight has a very similar effect as weights on roll or yaw rates.
- weights on pitch and yaw momentum rates (torques). These weights affect the torque required from the momentum wheels for control.
- weights on roll and pitch angles. These weights affect the maximum roll and pitch excursions. The yaw excursion is dependent on the roll excursion through the momentum bias coupling.

There is no weight on yaw since there is no yaw measurement. Note that yaw is unobservable (no yaw measurement) and that the pitch and yaw momenta (Hy and Hz respectively) are uncontrollable (control is momentum rates -> any momentum level will do)

The estimator process noise (momentum wheel tach loop quantization noise) and measurement noise (Earth sensor noise) are known and fixed. Therefore, the estimator weights are fixed during the optimization process.

Controller Design Variables

There are 5 controller design variables:

Regulator

- weight on nutation damping ζ. Similar to roll or yaw rate weights
- weights on pitch and yaw axis momentum rates, Hzdot and Hydot
- weight on roll and pitch angles, ϕ and θ

Estimator

- prcess noise is momentum wheel tach loop quantization noise
- measurement noise is Earth sensor noise
- process and measurement noises fixed, therefore estimator design fixed

OPTIMIZATION RESULTS

Mass Optimization for GOES

A mass optimization of the GOES-I launch configuration was performed. The deployable flexible appendages were not included in this optimization.

The optimization produced a significant mass savings (10% of structural mass, 4% of total launch mass) by decreasing the thickness of all plate elements. This makes sense since the components described by the plate elements contain most of the mass of the system. An additional propellant mass savings can be realized for any structural mass savings (that then does not need to be boosted to geostationary orbit. Approximately 2 kg of propellant (at separation) can be saved for every kg of satellite dry mass saved.

All beam elements were increased in size. This was to keep the fundamental frequency of the structure larger than the initial frequency.

The level of approximation required to produce the CSI-DESIGN model from the NASTRAN original limits direct application of these results to the actual GOES-I spacecraft design. The fundamental frequency of the original NASTRAN model was about 11 Hz, whereas for the CSI-DESIGN model was 25 Hz. The CSI-DESIGN model could not be solved by NASTRAN due to the large aspect ratio of some of the 3-node CSI-DESIGN elements generated from 4-node NASTRAN elements.

Mass Optimization for GOES

- mass optimization conducted with fixed-base launch configuration model (no solar array or solar sail)

- constraints imposed on design variable minimum values (for critical stress/strain constraints) and on fundamental frequency (not to decrease)

- results indicate a substantial savings (200 lbs) can be realized in total GOES mass (about 10% savings in structural mass)

Initial structural mass	**1854 lbs**	**fundamental S/C freq.:**	**25.4 Hz**
Final structural mass	**1652 lbs**	**fundamental S/C freq.:**	**27.4 Hz**

Mass Optimization for GOES (cont.)

An additional propellant mass savings can be realized for any structural mass savings (that then does not need to be boosted to geostationary orbit. For a fixed satellite design life, approximately 2 kg of propellant (at separation) can be saved for every kg of satellite dry mass saved.

All beam elements were increased in size. This was to keep the fundamental frequency of the structure larger than the initial frequency.

The level of approximation required to produce the CSI-DESIGN model from the NASTRAN original limits direct application of these results to the actual GOES-I spacecraft design. The fundamental frequency of the original NASTRAN model was about 11 Hz, whereas for the CSI-DESIGN model was 25 Hz. The CSI-DESIGN model could not be easily solved by NASTRAN due to the large aspect ratio of some of the 3-node CSI-DESIGN elements generated from 4-node NASTRAN elements.

It is highly desirable that the CSI-DESIGN mass optimization results be validated in NASTRAN at the earliest possible time. This would give management a large degree of confidence that the mass savings indicated are indeed realistic.

Mass Optimization for GOES (cont.)

- not included in the 200 lb mass savings above is an additional orbit-raising propellant mass savings of about 400 lbs (an approximate 2-1 ratio, for fixed lifetime) which would be realized due to the reduced structural mass.

- **The total mass savings would therefore be about 600 lbs (~14% of original launch mass).**

- All beam elements increase size, all plate elements decrease size

- Level of approximations required to produce CSI-DESIGN model from NASTRAN model limits direct application to actual spacecraft design.

- **The optimized design should be validated using the NASTRAN model.**

Controller Optimization

A purely controller optimization was performed on the nominal LQG controller.

With no external disturbance inputs, the controller is driven by ES noise only. The optimization process therefore reduces effect of ES noise by reducing gains, that is by driving the controller open-loop.

The regulator is moved open-loop by increasing the weight on control use (torques Hzdot and Hydot) and decreasing the weight on the outputs (roll and pitch), until stopped by either the design variable limits or by the level of applied external distrubance (solar torques) specified; i.e.

In the absence of external disturbance, the optimal control is no control at all.

Since the external disturbances are small (solar torque, ~10^{-6} Nm level), the controller bandwidth does not increase.

The solutions did not always "converge" to exactly the same values, due to numerical convergence effects. However, the optimal controller was always heading toward open loop before the optimization process stopped.

Controller Optimization

Without external disturbances, the optimal controller is open loop.

- jitter response due to actuator following ES noise within its bandwidth.
- minimize this by reducing the feedback gains, driving controller open-loop
- roll/yaw control: nutation weight to 0, Hzdot weight increase
- pitch plant: pitch weight to 0, Hydot weight increase

With external disturbances, the optimal controller moves open-loop just far enough to accommodate the external disturbances specified.

- same trend for weights observed as above

Optimal controller is no controller at all

CSI-DESIGN Structure

The CSI-DESIGN structural model differs significantly from the original NASTRAN model due to the approximations required during the translation.

The main difference is that the beam elements that comprise the solar sail model and most of the solar array yoke model have simple tubular cross-sections in the CSI-DESIGN model and have more complicated, non-symmetric, non-isoparametric cross-sections in the NASTRAN model.

This slide shows the first few non-rigid body modal frequencies and mode shapes for both models. These lower frequency results were obtained after tuning of the NASTRAN to CSI-DESIGN translation of the solar array and solar sail material properties to acheive similar fundamental frequencies.

CSI-DESIGN Structure

CSI-DESIGN structural model differs significantly from original NASTRAN model due to the translation approximations.

NASTRAN Model

Flex mode	Freq (rad/s)	Mode shape
1	1.12	solar array, 1st out-of-plane bending
2	1.41	solar sail, 1st x-axis bending
3	1.41	solar sail, 1st z-axis bending
4	4.50	solar array, 1st in-plane bending
5	6.15	solar sail, 1st torsion

CSI-DESIGN Model

Flex mode	Freq (rad/s)	Mode shape
1	0.94	solar sail, 1st x-axis bending
2	1.09	solar sail, 1st z-axis bending
3	3.46	solar array, 1st out-of-plane bending
4	34.5	
5	35.0	

Integrated Controls-Structures Optimization

For the integrated controls-structures dsign optimization runs, there are constraints imposed on the total mass (not to increase, but can decrease) and the first 3 flex mode frequencies (not to decrease).

The optimization results show that the controller design variables follow same pattern as in the controller optimization cases; i.e. the LQG weights change to reduce regulator gains until prevented further by either the controller design variable lower limits or the specified external disturbance level. The rms pointing reduces from a nominal value of about 15 μrad, to about 2.3 μrad (for one particular level of defined external disturbance level).

The mass and frequency constraints are satisfied. The structural design variables all decrease, some to their lower limits. Those structural components whose design variables descrease to their lower limits do not contribute to the stiffness of the modes that are contrained.

The RMS control power has a nominal value of about 20 Watts. As the gains decrease, so does the control power. However, it will never decrease below the approximately 13 Watts required to simply overcome the drag torque in the momentum wheel at the nominal wheel speed (574 rad/s, or 5480 rpm).

The optimal integrated design controller is the same as the controller determined from the controller only optimization. This indicates the expected:

There is very little controls-structures interaction on the nominal GOES-I spacecraft

Integrated Controls-Structures Optimization

Constraints imposed:

- mass not to increase (can decrease)
- first 3 flex mode frequencies (not to decrease)

Optimization result:

- controller design variables follow same pattern as in controller only optimization
- structural design variables decrease, some to lower limits.
- mass constraint satisfied
- frequency constraints satisfied
- controller gains decreasing (rms from 15 μrad to 2.3 μrad)
- control power decreasing (from 20 W, to minimum of 13 W)

Optimal integrated design controller same as that obtained in controller only optimization.

Upgraded GOES Controller

In light of the minimal controls-structures interaction on the nominal GOES system, the controller was upgraded by reducing the sensor noise and increasing the actuator bandwidth.

The ES noise was reduced to that of a state-of-the-art star tracker (by an order of magnitude, to about 10 μrad, 3σ, at 10 Hz), and the actuator bandwidth was increased an order of magnitude (to 2.5 rad/s). The actuator bandwidth increase is reasonable since this is set in the wheel electronics, and was originally chosen to minimize the possibility of actuator torque saturation. Lower sensor noise would allow a larger actuator bandwidth.

The first 2 flexible modes (of the solar sail) are now within the actuator bandwidth, which is the limit of the possible controller bandwidth.

Upgraded GOES Controller

- decrease ES noise by order of magnitude to star sensor levels

  (10 μrad, 3σ, @ 10 Hz)

- increase actuator bandwidth by order of magnitude (to 2.5 rad/s) by choice of time constant in electronics

- solar sail fundamental bending modes within actuator bandwidth

Integrated Controls-Structures Optimization with Upgraded Controller

When the GOES system with upgraded controller was optimized, the controller again moves toward open-loop operation and the control power again decreases to its minimum value. This is expected since the bandwidth and magnitude of the external disturbance, that is the only reason to have any control at all, has not increased. Reducing the regulator gains has the effect of reducing the bandwidth of the controller.

The structural elements generally decrease, except for the solar sail beam element diameters thereby increasing the solar sail (2 axis) fundamental frequency. This is expected since the higher the frequency, the less the interaction within the controller bandwidth, i.e. there is less transmission of the sensor noise to the system.

Integrated Controls-Structures Optimization with Upgraded Controller

- Same mass and frequency constraints

- **Controller moves toward open-loop (decrease regulator gains)**. OK since external disturbances have not increased.
- control power decreasing

- contraints satisfied
- solar sail beam element diameter increases, increasing solar sail fundamental frequency
- solar array yoke beam element diameter does not increase
- other elements, that have smaller effect on frequencies, decrease
- **effect is redistribution of mass to increase flexible mode frequencies**

CONCLUSIONS

and

RECOMMENDATIONS

Conclusions

- **the GOES spacecraft system performance has been thoroughly optimized and fine tuned by design and time, and little significant controls-structures interaction remains.**

- **significant** structural mass saving may be possible by systematic structural optimization of GOES using launch configuration stress/strain and frequency constraints.

- **optimal controller, in theory, is no controller at all**. Controller gains are limited in practice by requirement to reject very low level, low frequency, solar torques.

- integrated controls-structures optimization of the nominal GOES system, with a constraint on total mass (not to increase), results in an equivalent controller only optimization, while the structural elements remain basically unchanged (within numerical variance) for the RMS response objective function.

Conclusions (continued)

- On-orbit (imaging) controller bandwidth can be increased to include appendage flexible modes using improved sensor (star sensor), and decreasing the (arbitrary) actuator electronics time constant.

- integrated controls-structures optimization of upgraded GOES system, with a constraint on total mass (not to increase) and on appendage fundamental frequencies (not to decrease), results in a reduction of controller gains as far as possible, and a redistribution of S/C mass to increase appendage frequencies.

- Numerical results validate preliminary conclusions.

- **for the GOES-I mission and disturbance scenarios used, the optimal system is one where the control system/structural frequency domains overlap as little as possible.**

Major CSI-DESIGN Code Improvements

Provide seamless acceptance of NASTRAN bulk data input decks, with:

- arbitrarily large grid point IDs and element numbers
- automatic decomposition of NASTRAN 4-node and higher plate elements into appropriate 3-node elements
- automatic approximations for composite material properties, or more desirably,
- composite material elements, similar to NASTRAN PCOMP cards
- on-line bandwidth optimization for systems with plate elements

- **If this had been available at the beginning of this project, the transformation of the GOES NASTRAN input decks into their CSI-DESIGN equivalents would have been accomplished in an order of magnitude less time.**

Major CSI-DESIGN Code Improvements (cont.)

Provide a direct interface with MATLAB/MATRIXX (or equivalent)

- This improvement would give the capability for controller definition and evaluation with the same tools used to design and analyse the controller
- Also would allow almost arbitrary controller design and eliminate costly and inefficient FORTRAN coding of controller evaluation.

- **If this had been available at the beginning of this project, the controller implementation and integration with the CSI-DESIGN code would have been accomplished in an order of magnitude less time.**

Other Suggested CSI-DESIGN Code Improvements

- modify **Skyline** storage scheme to full **sparse** storage scheme to minimize memory usage and allow larger problems to be tackled on smaller machines.

- provide **output in formats compatible** with current NASTRAN **post-processing** tools such as PATRAN and MSC/XL, for viewing such things as of elements, grid points, material numbers, mode shapes, stress contours, and deflections.

- Provide **standard interface specifications**, and/or document critical dimensioning parameters, variable and array naming, and program structure and flow.

- provide **substructure analysis technique** to perform off-line analysis of components not participating in optimization, such as instruments, reflectors, etc, as desired.

Suggested Process Improvements

- Project progress was adversely affected by running CSI-DESIGN host on machines at LaRC.
- At the time, SS/L had no local computers with the RAM/swap space combination large enough to use CSI-DESIGN in-house.
- With a minimal outlay of $$ (~$5k), SS/L could have purchased an additional 128Mb of RAM and 1Gb of disk swap space for a Sun workstation, which would have enabled us to run CSI-DESIGN in-house and
    - avoid conflicts with other LaRC users competing for CPU time and memory,
    - eliminate the need to maintain mirrored file structures at both SS/L and LaRC,
    - eliminate frustrating time delays when transferring files via ftp or when editing at the remote site via telnet,
    - eliminate dependence on the SS/L link to the outside world, which was oftentimes tenuous,
    - give immediate access to all relevant system and language documentation when required.

Recommendations

- Application of CSI optimized design methodology to GOES type spacecraft provides little more insight than engineering judgement since GOES disturbance scenarios do not promote controls-structures interactions.

- To be both useful and accepted by the commerical sector spacecraft design community, the CSI-DESIGN code must be compatible with the major tools currently used:
  - structural analysis using NASTRAN (or equivalent)
  - control analysis using MATLAB (or equivalent)

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The objective of this study is to apply the integrated design methodology to the mature GOES-I spacecraft design, and to assess the possible advantages to be gained using this approach over the conventional sequential design approach used for the current design. In the process, the development of this technology into a tool that can be utilized for future near-term spacecraft designs is emphasized.

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