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ROBUST CONTROL FOR LARGE SPACE ANTENNAS

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OUTLINE OF PAPER

An outline for the presentation is shown in this figure. We begin with a brief description of program objectives and the space-based radar application. Next, we describe general characteristics of the 100-m diameter reflector spacecraft, the intended mission and associated requirements, and dynamic characteristics relevant to that mission. Preliminary control analyses are then carried out for the critical rapid slew and settle maneuver to establish feedback control requirements and fundamental limitations in meeting those requirements with state-of-the-art control hardware for a baseline reaction control system (RCS) jet placement assumed for the open-loop bang-bang slew maneuver. An improved RCS jet placement is proposed which greatly alleviates these limitations. Control moment gyros (CMGs), angular position sensors (integrating rate gyros), and linear translation sensors (double integrating accelerometers) are placed for feedback control. Next, control laws are designed for the improved sensor and actuator placement and evaluated for performance and robustness to unstructured model uncertainty. The robustness of this final control design is also assessed with respect to modal parameter uncertainty. Finally, results of these control designs analyses are summarized, conclusions are drawn, and recommendations for future studies are presented.

PROGRAM OBJECTIVES AND APPLICATION

SPACECRAFT/MISSION DEFINITION

PRELIMINARY CONTROL ANALYSES FOR FAST SLEW MANEUVER

FINAL CONTROL DESIGN AND EVALUATION

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

AFFDL SPONSORED PROGRAM

Current Air Force plans to develop large spacecraft antennas for surveillance and reconnaissance missions pose significant challenges for structural and control designers. The objectives of this AFFDL-funded study were to develop robust control laws for pointing and shape control of a large space antenna and to assess the robustness of such controllers to structural mode parameter uncertainty.

The application for this study was a 100-m diameter offset feed reflector satellite of the class required for radar surveillance missions. The model was developed by General Dynamics (GD) Convair under their AFFDL-funded Large Spacecraft Pointing and Shape Control (LSPSC) study. The most stressing mission requirement was to execute a 45 deg slew maneuver in 60 sec, and settle to meet accuracy specifications of 35 μrad for pointing and 59 milli-in for surface shape within 5 minutes. Angular rate requirements for the primary tracking maneuver were more modest. Accuracy goals were taken to be a factor of 10 smaller than these specifications.

A self-imposed goal of the study was to satisfy all maneuver requirements with current actuator capability. Current CMG capability was assumed to be that of the Bendix MA2000 Double-Gimbaled Advanced Development CMG for Skylab, which has a torque capability of 175 ft-lb and a momentum storage capability of 3000 ft-lb-sec. Corresponding specifications were taken to be a factor of 10 larger than goal. Current force and impulse capability for RCS jets imposed no limitations for the study.

OBJECTIVES:

- To Develop Robust Control Laws For Pointing And Shape Control Of A Large Space Antenna.
- To Assess Robustness Of Such Controllers To Structural Mode Parameter Uncertainty.

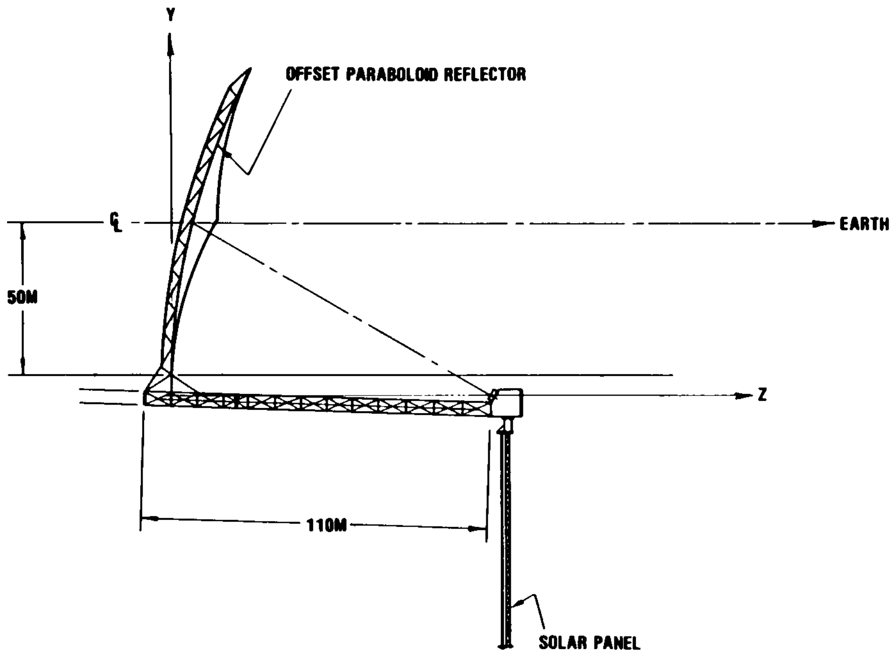
APPLICATION: SPACE-BASED RADAR MISSION

- 100-m Offset Feed Reflector (GD's LSPSC Study)
- Maneuver Requirements
  - Target Tracking: 0.004 deg/sec
  - Max. Rate Slew: 45 deg In 60 sec, 1.5 deg/sec
  - Settling Time To Reach Specifications: 5 min.

  $>$ Total Time To Spec: 6 min.
- Pointing/Shape Specifications
  - Pointing Accuracy : 35 μrad (3.5 μrad Goal)
  - Surface Accuracy: 59 milli-in (5.9 milli-in. Goal)
- CMG Control Limitations (Goal $\triangleq$ Advanced Devel. CMG For SKYLAB)
  - Max. Torque: 1750 ft-lb (175 ft-lb Goal)
  - Max. Momentum: 30,000 ft-lb-sec (3000 ft-lb-sec Goal)

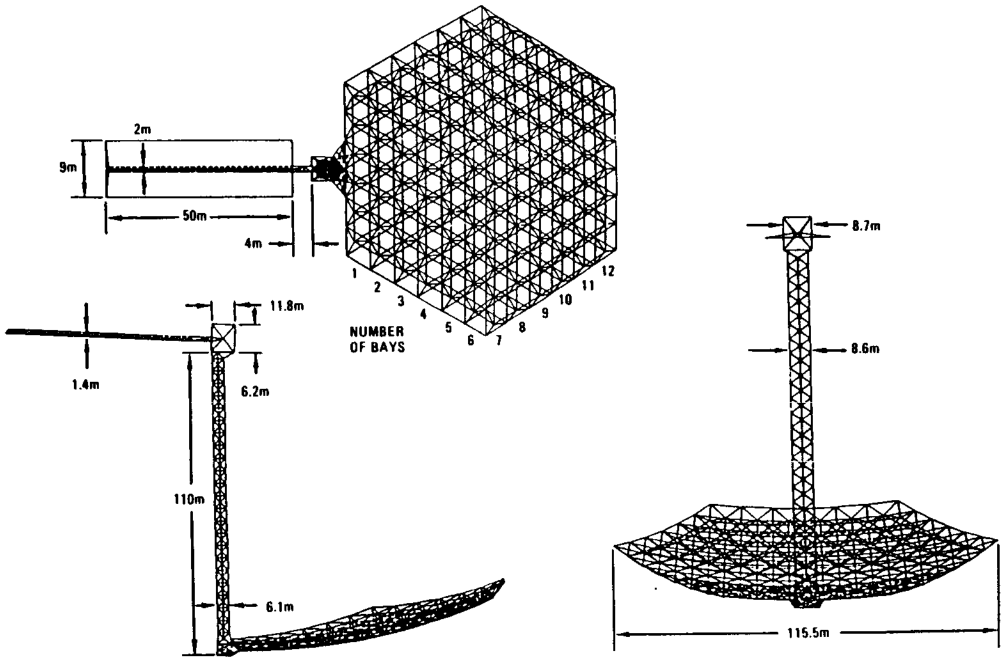
SPACECRAFT DEFINITION

The spacecraft model employed was for an offset feed reflector satellite. It consists of a 100-m diameter hexagonal reflector dish, which is attached to a 110 m boom through the mount. The spacecraft bus, which is attached to the opposite end of the boom, supports the antenna feed and a 50 m by 9 m solar panel to supply the necessary power for both radar surveillance and control requirements. Total weight of the spacecraft was more than 17,000 lb and largest moment of inertia (about the x axis) was 2.5×10^7 slug-ft-sq.



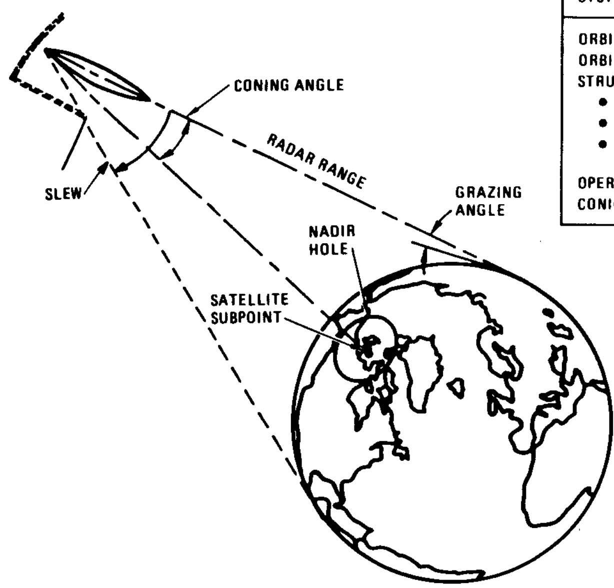
SPACECRAFT GEOMETRY

The GD geodetic truss forms the primary building block for the satellite reflector and boom. It is deployable, employs graphite/epoxy construction, and is designed to be accommodated by the Space Shuttle orbiter cargo bay. Due to the inherent stiffness of this truss structure, the primary free-free mode of the unattached reflector dish was determined by GD to be 1.70 Hz, which is well above the 0.1 Hz estimate typically assumed by the large space structure controls community.



SPACECRAFT MISSION

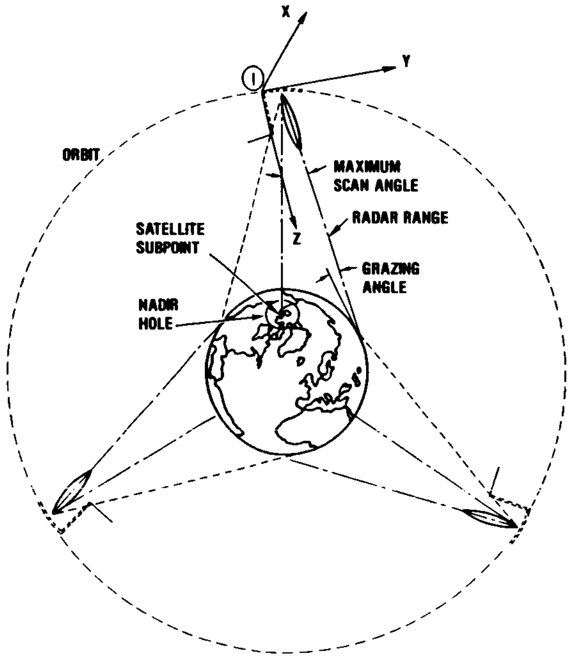
The spacecraft mission characteristics are illustrated in this figure. The spacecraft operates in a 6 hr polar orbit at an altitude of 5600 nmi. Its primary purpose is to track fixed targets on the surface of the Earth or moving targets (such as aircraft) near the Earth. The most stressing mission requirement, which is considered an uncommon occurrence, is to execute a large angle (45.6 deg) fast slew maneuver in 60 sec and settle to within pointing specifications of 35 μrad in minimum time. This maneuver is motivated by a requirement to occasionally acquire and track a critical target (without warning) anywhere near the Earth's surface, which defines a cone of radius 22.4 deg. Thus, the maximum slew angle is roughly twice this angle.



SYSTEM PARAMETERS	
ORBIT ALTITUDE	5,600 N.MI.
ORBIT PLANE	POLAR
STRUCTURE	
• TYPE	DISH ANTENNA
• DIAMETER	100M
• SLEW RATES	2 DEG/SEC (0.8 DEG/SEC)
OPERATING FREQUENCY	10 GHz (3 CM)
CONING ANGLE	22.4 DEG

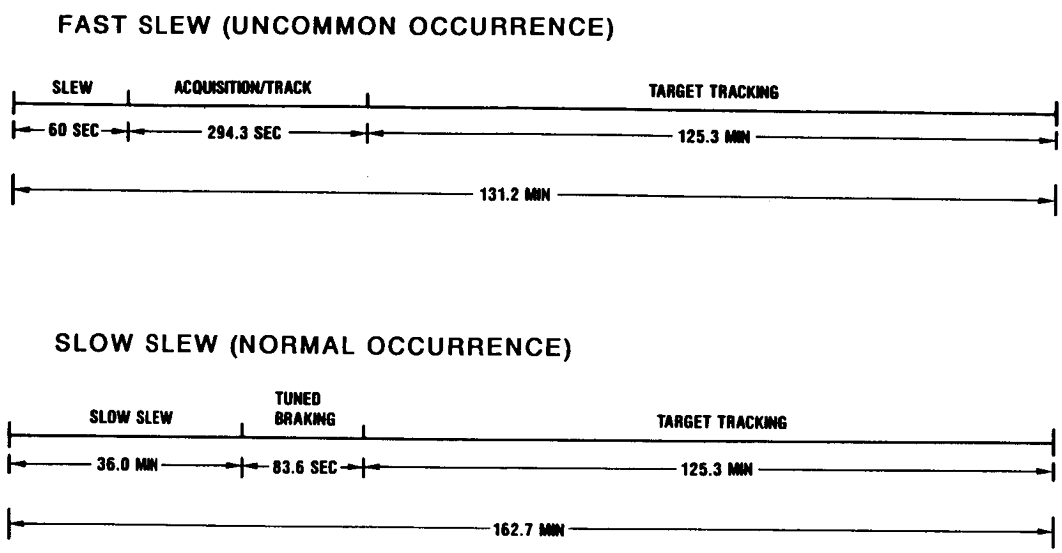
MISSION SCENARIO

To provide continuous coverage of the Earth's surface, a constellation of three satellites would be required as shown in this figure. In order to hand off targets from one satellite to the next, there is also a regular requirement to execute a slow slew from the trailing edge of the Earth to the leading edge, and then track a target until the next satellite hand off some two hours later.



NOMINAL SLEW MANEUVER TIMELINES (NOT TO SCALE)

Nominal timelines for these slew and tracking maneuvers are shown in this **figure.** In both cases the primary tracking maneuver spans just over 2 hr to allow for a smooth handoff of targets between satellites. For the fast slew maneuver, total time to slew and settle within specifications for target acquisition is roughly 6 min. For the slow slew maneuver, total time to slew and settle is roughly 37 min.



MODEL FOR STRUCTURE/ANTENNA

A finite element model was developed by GD using NASTRAN. This model employs 370 nodes and contains mode frequencies and six degree of freedom mode shapes at all nodes for some 207 modes (6 rigid, 201 flexible). This defines 2220 (= 370 × 6) total degrees of freedom for each mode. The model used here, however, contained only the first 103 of these modes, which covers flexible mode frequencies from 0.15 r/s to 78.1 r/s. Modal damping for all flexible modes was assumed to 0.5 percent (ζ = 0.005). Due to the inherent stiffness of truss structures, only the first four flexible modes proved to be critical to antenna performance. These include the first bending and torsion modes for the boom and the first bending mode for the solar panel. To facilitate mixing of translational and rotational degrees of freedom, modal shapes data were scaled to give units of milli-in. for translation and μrad for rotations.

Four of some 15 antenna parameters defined by GD were selected to measure the effects of modal displacements on RF performance. These effects are illustrated in the next two figures.

STRUCTURE

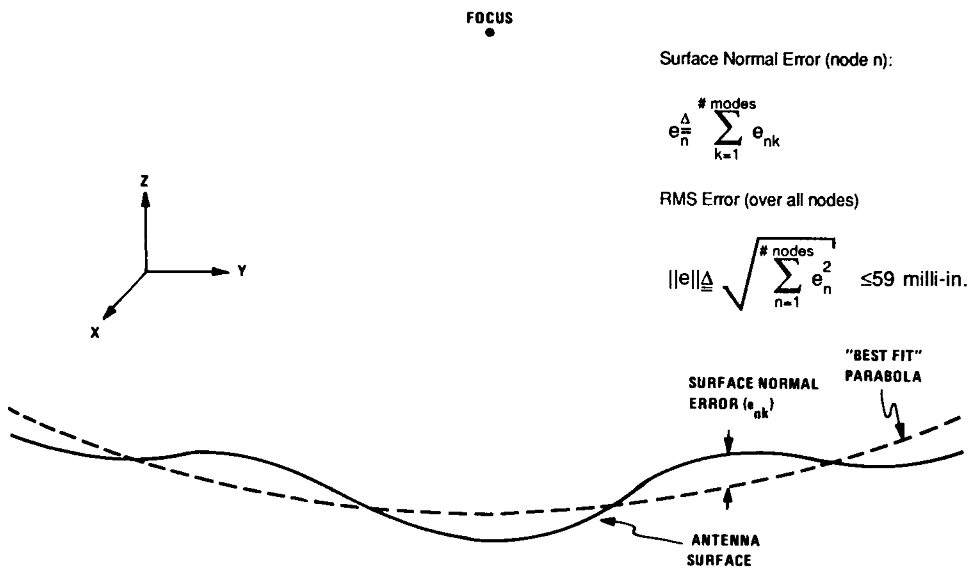
- 2220 DOFs (= 370 Nodes x 6 DOFs/Node)
- 103 Modes (0.15 r/s $\leq \omega_k \leq$ 80 r/s)
- 0.5% Modal Damping (ζ_k = 0.005)
- Four Critical Flexible Modes
  - Y - Axis Boom Bending: Mode 7 -- 0.15 r/s
  - X - Axis Boom Bending: Mode 10 -- 0.37 r/s
  - Z - Axis Boom Torsion: Mode 8 -- 0.24 r/s
  - Z - Axis Solar Panel Bending: Mode 9 -- 0.30 r/s

ANTENNA

- Four Critical Responses
  - Beam Rotation X (LOS_X) : 35 μrad
  - Beam Rotation Y (LOS_Y) : 35 μrad
  - Beam Path Length Change (Defocus): 59 milli-in.
  - RMS Surface Normal: 59 milli-in

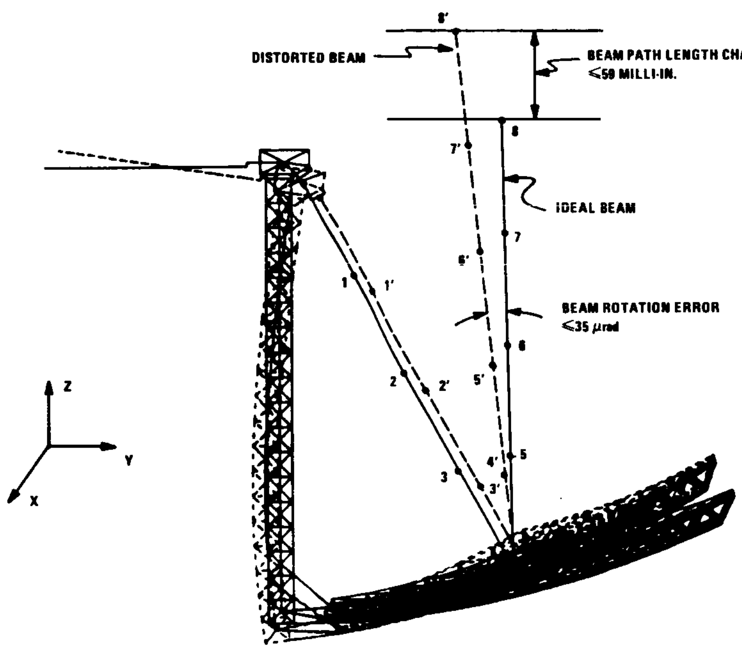
EFFECTS OF FLEXIBILITY ON ANTENNA PERFORMANCE: SURFACE ERRORS

This figure shows the effect of flexibility on antenna surface accuracy, which provides a measure of antenna gain. To do so, requires definition of a *best fit* parabola, in a least squares sense, to the distorted dish for each flexible mode. Total surface error in the normal (z axis) direction for any node n then consists of the sum of the contributions due to each mode. Rms normal surface error is, in turn, given by the RSS contribution over all nodes on the antenna.



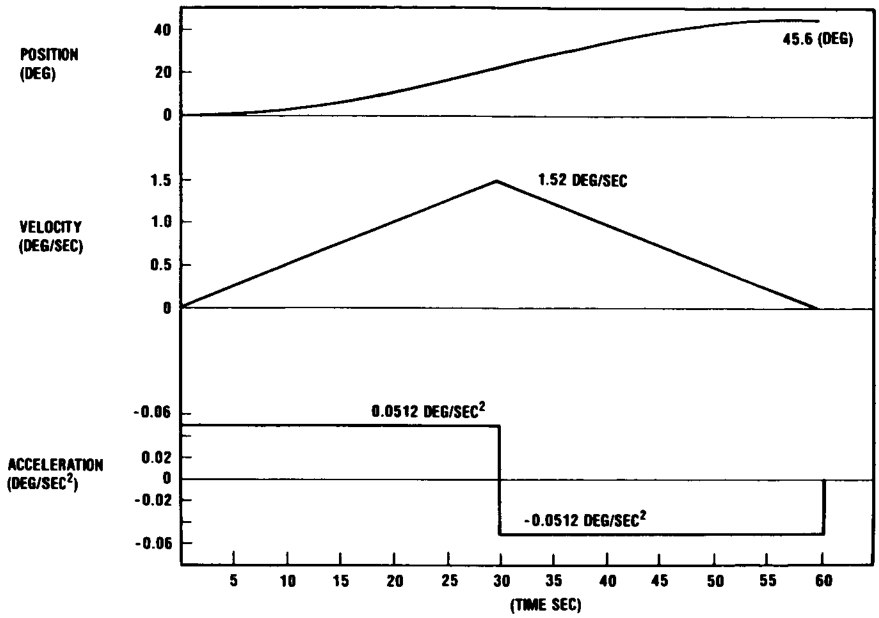
EFFECTS OF FLEXIBILITY ON ANTENNA PERFORMANCE: BEAM POINTING ERRORS

This figure shows the effect of flexibility on beam pointing errors. The solid line denotes the ideal beam generated by a ray traced from the feed to the center of the undistorted reflector to a normal reference plane. The dashed line denotes the corresponding beam for a similar ray traced from the feed on the distorted boom to the center of the distorted best-fit reflector to a second reference plane parallel to the first. Both rays travel an equal distance (8 units) in equal time. The angle between the two beams defines beam rotation error about the x axis. A similar picture defines beam rotation error about the y axis. These errors correspond to traditional line-of-sight errors in optical systems. The distance between the two reference planes defines beam path length change in the normal (z axis) direction. This error corresponds to the traditional defocus error in optical systems.



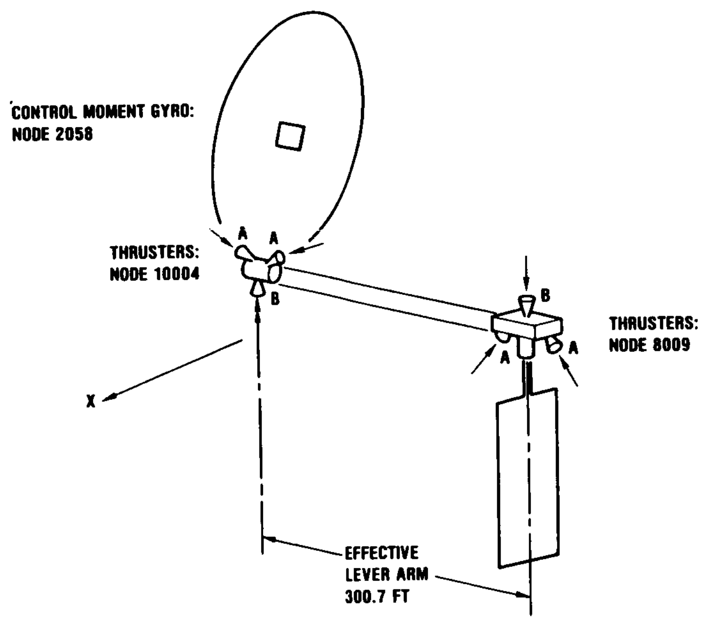
NOMINAL FAST SLEW MANEUVER (FULL EARTH DIAMETER)

Recall that a critical maneuver for the large space antenna is a requirement to execute a large angle (45.6 deg) slew maneuver about the spacecraft +x axis in 60 sec and settle to within specifications in minimum time. This slew can be accomplished with the open-loop time-optimal bang-bang control scheme shown in this **figure.**



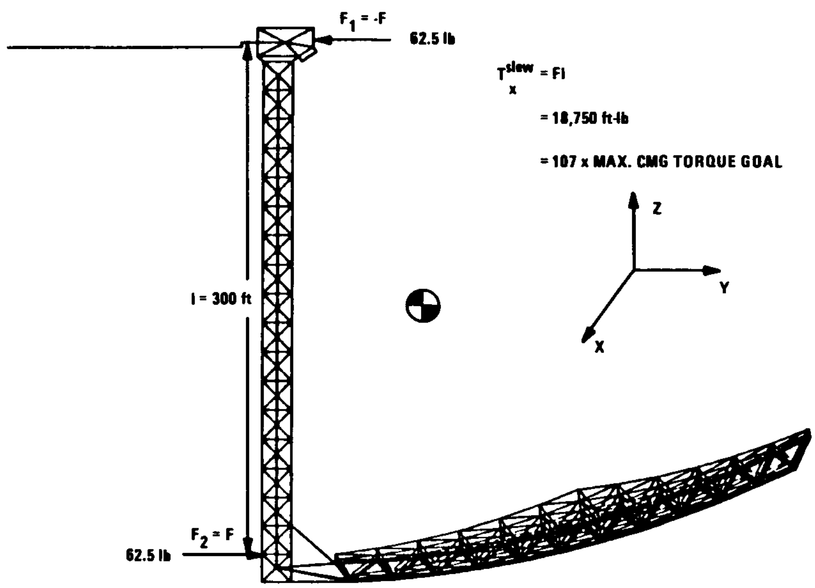
NOMINAL RCS JET PLACEMENT

The nominal placement of reaction control system (RCS) jets chosen by GD to accomplish the nominal fast slew maneuver is shown in this **figure.** It requires simultaneous firing of the "B" RCS jets for the first 30 sec of the maneuver: a +y axis jet at node 10004 (near the mount) and a -y axis jet at node 8009 (center of bus). To arrest the resulting angular accelerations, opposing forces generated in the latter 30 sec of the maneuver by the "A" jets require the use of two pairs of jets in a skewed configuration to avoid thrust impingement on either the solar panels or the antenna surface. Taking into account spacecraft inertia about the x axis, the effective moment arm, the allowable maneuver time, and the desire for no net translation implies jet sizing of 61.5 lb for each of the "B" jets. Assuming a 45 deg skew angle for the "A" jets gives a nominal sizing of 43.5 lb for these jets. Also indicated is GD's nominal placement of three-axis control moment gyros (CMGs) for slow slew and tracking maneuvers.



CRITICAL DISTURBANCE: SLEW MANEUVER

Although RCS jets are essential to provide the necessary control power for the fast slew maneuver, the resulting disturbance torque of 18,750 ft-lb (= 61.5 lb $\times$ 300 ft) easily dominates all natural disturbances. This torque is more than two orders of magnitude larger than current CMG capability (goal). Since nominal slew torques for each half of the slew maneuver are designed to oppose one another, the net effect on the rigid body is ideally only an attitude change. In practice, force imbalances between jets and misalignments of the jet plumes produce disturbances in all axes. Even in the absence of such imperfections, however, flexible mode excitations due to RCS jet forces during the first half of the slew maneuver are not in general canceled by those generated during the second half. Therefore, residual antenna parameter errors due to these excitations that remain after the open-loop slew maneuver must be reduced by feedback control to meet specifications.



CONTROL PROBLEM FOR FAST SLEW MANEUVER (WITH BASELINE RCS JET PLACEMENT)

To assess the enormous difficulty of the feedback control problem, transient responses of both rigid-body and flexible-body models were compared for the nominal open-loop RCS jet force profile. Responses for the flexible-body model show large excitation of mode 7 for all four antenna parameters and some excitation of modes 9 and 10 for beam y. Beam rotation x overshoots the commanded value by roughly 15 deg, which is nearly 7000 times the 35 μrad specification that applies after settling. Note that for the nominal 0.5 percent natural damping assumed for all modes, beam x would require a settling time of roughly 200 min (40 × spec) to reach specification without closed-loop feedback control for settling. Specification violations for beam rotation y and path length are far less severe. Nevertheless, settling time requirements for these parameters would still exceed reasonable limits. The response for rms normal, however, never exceeds its specification of 59 milli-in. and therefore requires no closed-loop feedback control for settling. Thus a factor-of-40 increase in closed-loop over open-loop damping is required to meet specifications for all antenna parameters.

PEAK ANTENNA RESPONSES

- Beam Rotation x : 15 deg (7000 x spec)
- Beam Rotation y : 0.75 deg (350 X spec)
- Beam Path Length : 60 in. (1000 x spec)
- RMS Surface Normal: 50 milli-in. (0.8 x spec)

SETTLING TIME: $\zeta_{ol} = 0.005$ (0.5%)

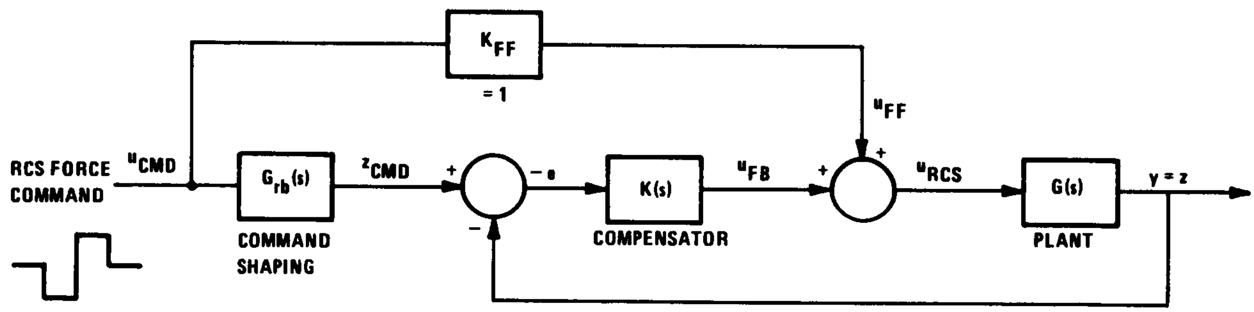
- T_s = 200 min. (40 x spec)

REQUIRED CLOSED-LOOP DAMPING (CRITICAL MODES)

- $\zeta_{cl} > 40\ \zeta_{ol} = 0.2$ (20%)

FEEDBACK CONTROL STRUCTURE FOR SLEW MANEUVER: SINGLE-AXIS (IDEALIZED)

A candidate feedback control structure for the RCS slew maneuver is shown in this figure for an ideal case in which measurements y are equal to the regulated variables z and control inputs u enter at the disturbance inputs d. Here we have assumed that the primary disturbance, due to the open-loop RCS jet command, drives the antenna structure directly through a feed forward gain K_{ff} and the command generation logic through a command shaping prefilter $G_{rb}(s)$. A natural candidate for this prefilter is a rigid-body model of the antenna response to RCS jet command inputs. When the feed forward gain K_{ff} is set equal to one, this ensures that the feedback compensator $K(s)$ controls only the error e between the flexible-body and rigid-body response to RCS jet inputs. This particular structure was chosen because it ensures that the bulk of the control power required for the slew maneuver is supplied by the RCS jets to move the rigid body. A much smaller control effort is supplied by the actuators used for feedback control which, for the preliminary analyses that follow, will be assumed to be *continuous* RCS jets. Although this assumption is unrealistic, results produced for this ideal case serve to define an upper bound on achievable performance for feedback control using more realistic actuators.



SUMMARY OF PRELIMINARY CONTROL DESIGN RESULTS

A nominal feedback control law was designed for this case using the LQG/LTR methodology with loop transfer recovery at the input to achieve a desired crossover frequency (or bandwidth) of roughly 1 r/s. This design achieved good stability margins for the feedback loop broken at the input. An examination of closed-loop eigenvalues indicates that this design provides substantial damping ($\zeta = 0.87$) for the critical mode 7 at 0.15 r/s, but much smaller damping for modes 9 and 10.

Transient responses for this control design show that beam rotation errors require 15 min to fall within their specifications of 35 μrad (3 × spec). Note also that peak values in control force are about 100 lb. These imply control torques of 30,000 ft-lb peak assuming a 300 ft moment arm. To achieve continuous control inputs, these torques must in practice be supplied by continuous actuators such as CMGs. These peak torque requirements exceed spec by a factor of 17, and the current CMG torque capability goal by a factor of 170. To meet the 5 min settling time spec implies peak torque requirements of 50 times spec, or 500 times goal. These results emphasize a fundamental tradeoff between control power and time to settle following the slew maneuver.

SUMMARY

- Design Has Good Stability Margins (± 10 db, 55 deg)
- Mode 7 Is Well Damped (ζ_{cl} =0.87)
- But, Modes 9 & 10 Are Less Well Damped (ζ_{cl} = 0.03, 0.05)
- Thus Settling Time of T_s = 15 min Is Long (3 x spec)
- Implied Peak Control Torque Is Excessive (300 ft Moment Arm)
  - 30,000 ft-lb In First 60 sec (17 x spec)
  - 90,000 ft-lb Required To Meet T_s spec (50 x spec)

OBSERVATIONS

- Jet Input For Slew Puts Enormous Momentum Into Structure
  H = 62.5 lb x 300 ft x 30 sec = 562 500 ft-lb-sec
- Momentum Put into Flexible Modes Must Be Removed

∴ $\boxed{\text{Fundamental Tradeoff: Control Power vs. Time To Settle}}$

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IMPROVED RCS JET PLACEMENT FOR FAST SLEW MANEUVER

To appreciably improve the potential for improved slew maneuver performance requires drastic measures to minimize excitation of y-axis boom bending. One approach, which has been pursued by GD in their LSPSC study, is to adjust the period of the open-loop slew so that some even harmonic of the RCS jet input (which is zero for a symmetric waveform) coincides with the period of the critical mode 7 boom bending mode. This also minimizes excitation of mode 9, which has a frequency that is approximately twice that of mode 7. The effectiveness of this approach, however, is quite sensitive to mode frequency, and could in practice require on-orbit identification to isolate this mode frequency.

An alternative approach, that was pursued in this study, is to spatially distribute RCS jets in such a manner as to essentially eliminate excitation of the critical mode 7 boom bending mode. This fundamental change in objectives, however, can be accomplished with only minor modification to the baseline GD-defined placement. The new placement uses the two existing jet locations plus one additional location at the outer edge of the antenna to achieve the desired x-axis rotation, no translation in the y or z axes, and (ideally) no excitation of the critical mode 7 boom bending. To account for RCS jet imperfections, thrust imbalances of 5 percent of nominal (3 σ) and plume misalignments of 3 deg (3 σ) were also assumed. The latter misalignments give rise to cross-axis thrust errors that are also 5 percent of nominal. The resulting jets produce net translations and rotations in all axes and excite all flexible-body modes. Thus, three-axis control of rotations is unavoidable in practice.

OBJECTIVE: PLACE RCS JETS TO MINIMIZE EXCITATION OF FLEXIBILITY

NEW PLACEMENT

- Uses Existing Y-Axis Jets At Base And Tip Of Boom
- But Allows Combined Y And Z Axis Forces At Base
- Adds New Z-Axis Jet To Outer Edge Of Antenna

RCS BLENDING SCHEME: DISTRIBUTE NOMINAL JET FORCES TO ACHIEVE

- Desired Rotation About X Axis (1)
- No Translation In Y or Z Axes (2)
- No Excitation Of Mode 7 Y-Axis Beam Bending (1)

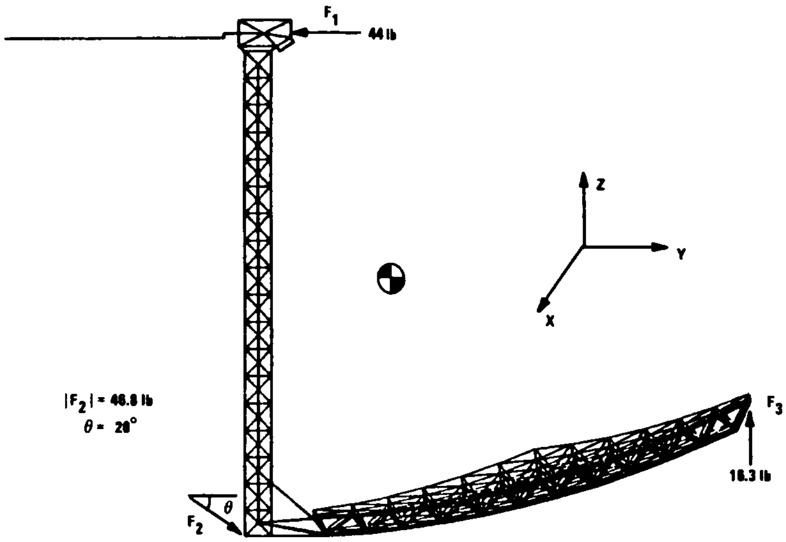
RCS JET IMPERFECTIONS: EACH JET ASSUMES RANDOM

- Thrust Imbalances : 5% Of Nominal (3 σ)
- Plume Misalignments : 5% Of Nominal (3 σ)

$\therefore$ $\boxed{\text{Actual Jets Produce Net Translations and Rotations In All Axes And Excite All Flex Modes!}}$
$\boxed{\Rightarrow \text{ Need 3-Axis Control Of Rotations}}$

IMPROVED RCS JET PLACEMENT FOR FAST SLEW MANEUVER (CONT.)

The resulting improved RCS jet placement for the fast slew maneuver is shown in this **figure.** Note that the jet at the top of the boom (node 8009) allows only y-axis force (-44 lb), while that at the outer edge of the antenna (node 1025) allows only z axis force (+16.3 lb). The jet at bottom of the boom (node 10004) allows a combination of y and z axis forces to ideally balance net forces and thereby eliminate translation. This scheme can be expected to yield greater performance robustness to model uncertainty than tuned slew maneuvers since it depends only on mode shapes rather than on mode frequencies.



CONTROL PROBLEM FOR FAST SLEW MANEUVER (WITH IMPROVED RCS JET PLACEMENT)

To illustrate the dramatic reduction in modal excitation for this RCS placement, a transient response was generated for a 60 sec open-loop slew maneuver. Peak errors for beam x and y rotations and path length change are now all roughly 100 times specification, while rms surface normal is well within specification. Comparing these plots with those for the original placement shows error reductions of 70 for beam x, 3 for beam y, 10 for path length, and 1.6 for rms surface. The magnitude of these reductions indicates a strong potential for improved performance with this new RCS jet placement. For the nominal 0.5 percent natural damping assumed for all modes, a settling time of roughly 52 min (10 × spec) is required to reach specification without closed-loop feedback control for settling. Thus a factor of 10 increase in closed-loop over open-loop damping is required to meet specifications for all antenna parameters.

PEAK ANTENNA RESPONSES (IDEAL JETS)

- Beam Rotation x : 3500 μrad (100 x spec)
- Beam Rotation y : 3500 μrad (100 x spec)
- Beam Path Length : 4500 milli-in. (75 x spec)
- RMS Surface Normal : 30 milli-in. (0.5 x spec)

SETTLING TIME: ζ_{ol} = 0.005 (0.5%)

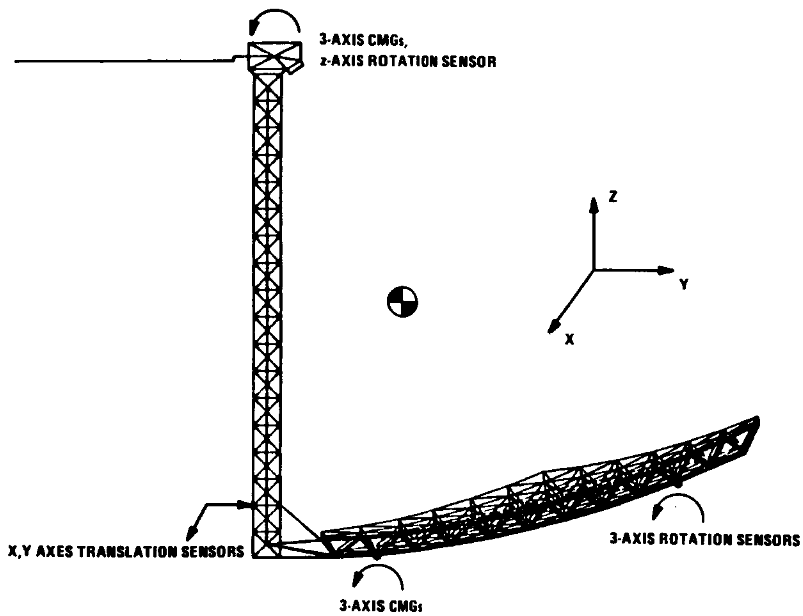
- T_S = 52 min. (10 x spec)

REQUIRED CLOSED-LOOP DAMPING (CRITICAL MODES)

- $\zeta_{cl} > 10\,\zeta_{ol} = 0.05$ (5%)

ASSUMED SENSOR AND ACTUATOR PLACEMENT: 3-AXIS

Prior to final feedback control design, a set of actuators was placed with a simple least-squares algorithm to best approximate the effect of disturbances on desired antenna responses. Similarly, a set of sensors was placed with a simple least-squares algorithm to best approximate the effect of disturbances on desired antenna responses. The resulting actuator set had x, y and z axis CMGs at node 2083 (bottom of the dish) and at node 10072 (top of the boom). The sensor set was made up of x, y and z rotation sensors at node 2033 (bottom of the dish), a z rotation sensor at node 10072, and x and y translation sensors at node 10008 (near the bottom of the boom).



FEEDBACK CONTROL SOLUTION

For the final feedback control design, these latter translation sensors were compensated with second-order hi-passes to washout low-frequency measurements due to rigid-body translations, which are uncontrollable with CMGs. This also washes out rigid-body rotations. The LQG/LTR methodology was again applied with loop transfer recovery at the output to achieve an LQG loop crossover frequency (or bandwidth) of about 0.5 r/s. The resulting compensator included 40 states, but could likely be reduced to 10-20 states using model reduction.

ASSUMPTIONS

- 6 CMG Actuators (3 Dish, 3 Bus)
- 4 Rotation Sensors (3 Dish, 1 Bus)
- 2 Translation Sensors (Boom) With Second-Order Hi-Passes (To Eliminate Uncontrollable Translations)

LQG/LTR METHODOLOGY: OUTPUT RECOVERY

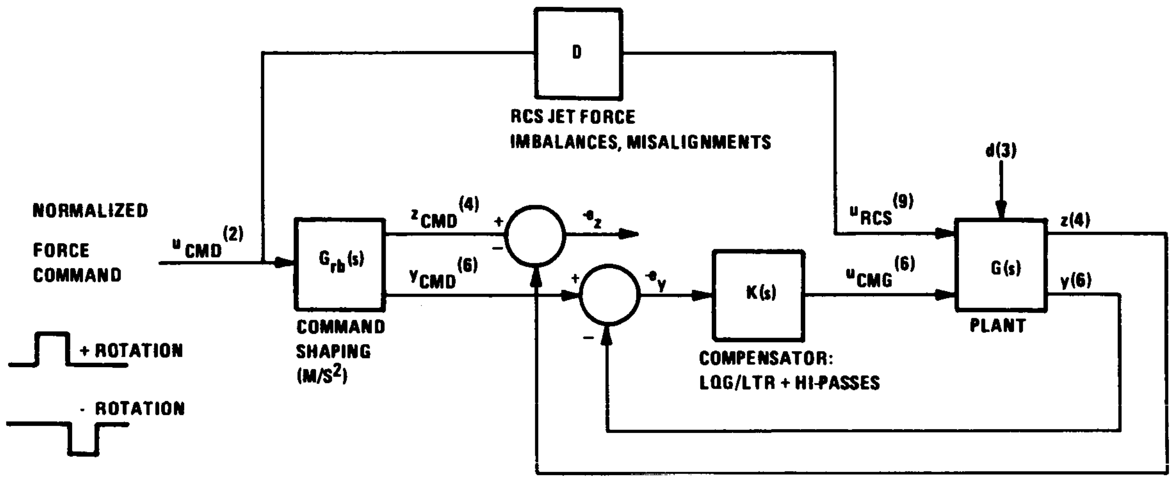
- KF Loop Crossover : $\omega_f = 0.5$ r/s
- LQ Loop Crossover : $\omega_c = 5$ r/s

COMPENSATOR COMPLEXITY

- 6 Inputs
- 6 Outputs
- 40 States (Could Be Reduced To 10-20 States With Model Reduction)

FEEDBACK CONTROL STRUCTURE FOR SLEW MANEUVER: 3-AXIS

For closed-loop simulation, the feedback control design was implemented as shown here. This loop is equivalent, in a feedback sense, to a loop that feeds back the four rotation measurements plus the two high-passed translation measurements. In addition, it also high-passes the commanded translations, as desired. The matrix D distributes thrust imbalances and misalignments for both positive and negative RCS jets to produce net forces in three directions for each of the three jet locations.



FINAL CONTROL DESIGN PERFORMANCE FOR FAST SLEW MANEUVER

Closed loop transient responses using the perturbed RCS jet disturbances were run for several different slew periods. In all cases the time for all antenna responses to fall within performance specifications is well within the 5 min settling time specification, while peak CMG torques lie well within spec (but outside of goal). In addition, time to goal in all cases is roughly 7 min. Results also show that a slew period cf 1.5 min with 2.7 min settling gives a minimum time to spec of 4.2 min, with peak control torques that are 2.6 times goal. However, a slew period of 2.5 min with 2.2 min settling gives only a slightly longer time to spec of 4.7 min, with peak control torques that approach goal. The latter choice represents a much better compromise between time to spec and required control torque.

SLEW PERIOD (MIN.)	TIME TO SPEC (MIN.)	TIME TO GOAL (MIN.)	PEAK CMG TORQUE (FT-LB.)	
1.0	4.3	6.7	920 (5.2 X Goal)	
1.5	$\boxed{4.2}$	6.7	$\boxed{430 (2.6 x Goal)}$	TIME OPTIMAL!
2.0	4.4	7.0	280 (1.6 x Goal)	
2.5	$\boxed{4.7}$	7.2	$\boxed{200 (1.1 X Goal)}$	BETTER COMPROMISE!

STABILITY/ROBUSTNESS PROPERTIES FOR FINAL CONTROL DESIGN

Robustness to unstructured uncertainty, as measured by multivariable singular value analyses of sensitivity and complementary sensitivity, was mixed for this control design. That at the output (design point) was good since it allows sensor uncertainty as large as 67 percent. That at the input was poor since it only allows actuator uncertainty as large as 10 percent. This poor robustness is due to the standard problem of achieving good robustness an evaluation point different than the design point. It is further aggravated by the ambiguity in controlling only three rigid-body rotation modes at low frequency with six inputs and six outputs.

Robustness to modal parameter uncertainty, as measured by structured singular value analysis for real perturbations, is quite encouraging. Allowable relative error variations in all parameters of 24 percent or more are reasonable for the first few modes in a dynamic model. Even greater robustness to modal frequencies would be highly desirable, however.

ROBUSTNESS TO UNSTRUCTURED UNCERTAINTY (SVs): SENS./COMP. SENS.

- Good At Output : $\sigma \leq 1.5 \Rightarrow$ 67% Sensor Uncertainty (Design Point)
- Poor At Input : $\sigma \leq 10 \Rightarrow$ 10% Actuator Uncertainty
- Poor Input Robustness At Low Frequency Due To
  - Evaluation Point Different From Design Point
  - Six Inputs/Outputs With Only Three RB Modes (Rotations)

ROBUSTNESS TO MODAL PARAMETER UNCERTAINTY (REAL μ):
ALLOWABLE VARIATIONS IN

• Mode Frequency	$\leq$ 24% Of Nominal	For first 4 Flex Modes
• Mode Damping	$\leq$ 1200% Of Nominal	
• Mode Shapes (Input or Output)	$\leq$ 63% Of Nominal	

THESE ALLOWABLE VARIATIONS ARE REASONABLE FOR FIRST FEW FLEXIBLE MODES!

SUMMARY

Performance results for this study can be summarized as follows. Control torque requirements for the nominal fast slew maneuver with nominal RCS jet placement are 500 times goal. Using a longer slew period with correspondingly shorter settling time buys a factor of 25 reduction in control torque, but this is still not enough. A new RCS jet placement using one additional jet allows a factor of 70 reduction in boom bending excitation. An LQG/LTR control design for the fast slew maneuver using the new RCS jet placement meets performance specifications within a 5 min settling period and performance goals within a 7 min period. This design also meets performance requirements for more modest slow slew and target tracking maneuvers, and could meet goal in the face of solar and gravity gradient torques with minor redesign.

PERFORMANCE

- Control Torque Requirements For Fast Slew Maneuver (1 min. Slew + 5 min. Settling) Using Nominal RCS Jet Placement Are Unacceptable (500 X SKLYLAB)
- Using Longer Slew Period (~3 min.) With Shorter Settling Time (~ 3 min.) Allows Substantial Reduction In Control Torque (20 X SKYLAB) ...But, Not Enough!
- New RCS Placement, Using One Additional Jet, Allows Factor Of 70 Reduction In Beam Bending Excitation!
- LQG/LTR Control Design Performance For New RCS Placement And SKYLAB-Sized CMGs Meets
    - 35 μ rad Spec Within 5 min. For Fast Slew Maneuver
    - 3.5 μ rad Goal Within 7 min. For Fast Slew Maneuver
    - 35 μ rad "Spec" Throughout Slow Slew Maneuver } Not Presented Here!
    - 3.5 μ rad Goal For Target Tracking
- Control Performance In The Face Of Solar Torques Nearly Meets Spec, And Could Meet Goal With Minor Refinements To Control Design! (Also Not Presented Here!)

SUMMARY (CONT.)

Robustness to unstructured uncertainty was mixed for this control design. That at the input (design point) was good since it allows sensor uncertainty as large as 67 percent. That at the output was poor since it only allows actuator uncertainty as large as 10 percent. A dual LQG/LTR control design procedure with loop transfer recovery at the input would reverse these results. More sophisticated design techniques would allow a better compromise between input and output robustness.

Robustness to modal parameter uncertainty is quite encouraging. Allowable relative error variations in all parameters of 24 percent or more are reasonable for the first few modes in a dynamic model.

ROBUSTNESS TO UNSTRUCTURED UNCERTAINTY

- Good At Output: $\sigma \leq 1.5 \Rightarrow$ 67% Sensor Uncertainty (Design Point)
- Poor At Input: $\sigma \leq 10 \Rightarrow$ 10% Actuator Uncertainty
- LQG/LTR With Input Recovery Reverses These Results
- More Sophisticated Design Techniques (μ Synthesis) Could Achieve A Better Compromise Between Input and Output

ALLOWABLE VARIATIONS IN MODAL PARAMETERS

- 24% for Mode Frequencies
- 1200% for Mode Dampings
- 63% for Mode Shapes (Input or Output)

RECOMMENDATIONS

The final LQG/LTR control design would require at least two modifications before practical implementation: further refinements to meet performance in the face of solar and other environmental disturbances and compensator simplification via model reduction. A number of more fundamental research issues might also be addressed to achieve improved robustness to unstructured and parametric uncertainty. Ultimately more efficient methods for analysis of robustness to parametric uncertainty would be desirable.

FINAL LQG/LTR CONTROL DESIGN REQUIRES

- Further Refinements To Meet Performance Specs (Goals) In The Face Of Solar And Other Environmental Disturbances
- Simplication Via Model Reduction Before Practical Implementation

MORE FUNDAMENTAL RESEARCH ISSUES

- Improved Robustness At Both Input And Output (μ Synthesis)
- Improved Robustness At Input And/Or Output When Number Of Rigid-Body Modes Is Less Than Number Of Controls Or Measurements
- Improved Robustness To Parametric Uncertainty (e. g., Mode Frequencies)
- More Efficient Methods For Analysis Of Robustness To Parametric Uncertainty