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STS-99 Shuttle Radar Topography Mission Stability and Control

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The Shuttle Radar Topography Mission (SRTM) flew aboard Space Shuttle Endeavor February 2000 and used interferometry to map 80% of the Earth's landmass. SRTM employed a 200-foot deployable mast structure to extend a second antenna away from the main antenna located in the Shuttle payload bay. Mapping requirements demanded precision pointing and orbital trajectories from the Shuttle on-orbit Flight Control System (FCS). Mast structural dynamics interaction with the FCS impacted stability and performance of the autopilot for attitude maneuvers and pointing during mapping operations. A damper system added to ensure that mast tip motion remained within the limits of the outboard antenna tracking system while mapping also helped to mitigate structural dynamic interaction with the FCS autopilot. Late changes made to the payload damper system, which actually failed on-orbit, required a redesign and verification of the FCS autopilot filtering schemes necessary to ensure rotational control stability. In-flight measurements using three sensors were used to validate models and gauge the accuracy and robustness of the pre-mission notch filter design.

INTRODUCTION

The Shuttle Radar Topography Mission (SRTM) flew aboard Space Shuttle Endeavor February 11-22, 2000. SRTM used interferometric synthetic aperature radar to map 80% of the Earth's topography, thus creating topographic maps ten times better in resolution than those currently available. A 200-foot flexible truss separated two antennae. Avionics systems tracked the motion of the outboard antenna so that the relative position between the antennae was known at all times. See Figure 1. During data acquisition, mast tip motion could not exceed translational deflection of 2.0 inches and 0.3 deg in rotation. Structural failure of the mast would occur if mast tip deflections exceeded 30 inches. The mast itself was a lightly damped structure that was easily excited by the Shuttle Reaction Control System. A damper system added at the canister base was designed to increase the mast structural damping from 0.5% to 15%. This was to ensure that mast tip motion requirements during data acquisition are met. Jet Propulsion Laboratory (JPL) designed and built the SRTM payload.

The SRTM payload posed several unique challenges for Shuttle Flight Control System (FCS). Precise pointing of the vehicle was required during data acquisition. The FCS held Vernier RCS attitude deadband of 0.1 deg and a rate deadband of 0.01 deg/s. Typical Vernier RCS deadbands are 1-3 deg. Additional filtering needed to be added to the FCS to ensure stability during maneuver and attitude hold during mapping due to RCS-induced flexure of the SRTM mast. The mast damping mechanism increased the number of configurations to assess from one to ten. Additionally, precise orbital trajectories were required to meet radar swath overlay requirements. A special procedure, dubbed Fly-cast, was developed to increase the orbital altitude by pulsing the primary RCS jets while minimizing loads on the mast. This was necessary to preserve the alignment of the antennae. Orbit adjustments burns could only be performed over water passes requiring high maneuver rates between attitudes. Special procedures were developed to

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collapse the deadbands to the tight mapping deadbands after the completion of the maneuver from the trim burn attitude.

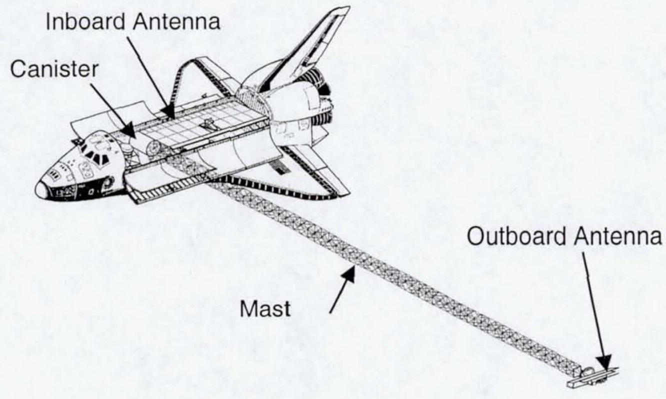


Figure 1 SRTM Mast Extended Configuration

During the mission, a structural dynamics team evaluated the combined Shuttle/Mast structural modes using two payload sensors and the Shuttle IMU. The team's objectives were to identify the mast damper configuration and the as-flown structural characteristics to confirm control system stability and to tune the Fly-cast reboost firings. The team measured responses to sets of pre-planned open-loop thruster firings as well as firings that occurred during closed loop operations such as attitude control and rotational maneuvers. Fast-Fourier Transform (FFT) techniques were used to extract frequency content from the sensor data, and smoothing techniques were used to allow graphical analysis to verify FFT results and analyze non-linear responses.

After mast dampers were commanded to uncage, sensor measurements revealed the failure of all damper cartridges to stroke. Further analysis showed that pre-flight models were quite accurate at high amplitudes, however system nonlinearities caused a decay in frequency at lower amplitudes. Real time analysis showed that the notch filter sets, designed to be robust to damper failures, also provided sufficient stability margin for the non-linear system. Small adjustments were made to the Fly-cast reboost firings and the mast responded precisely as predicted.

This paper will provide a detailed description of the pre-flight stability analysis and notch filter design for the SRTM payload followed by in-flight results. First is a brief overview of the Shuttle on-orbit digital autopilot (DAP) and definition general stability requirements. The SRTM FCS requirements and description of the structural models follows. Notch filter design and verification is covered next. This section includes discussion on the impacts of the notch designs on performance. The next section covers the pre-flight planning for in-flight structural identification tests of the mast. The final section contains a discussion of in-flight structural identification tests and response and the impact of these results on stability. A more detailed overview of the STS-99 SRTM flight is provided in Ref. 1.

SHUTTLE ON-ORBIT FLIGHT CONTROL SYSTEM OVERVIEW

The Shuttle Flight Control System provides translational, rotational, and orbital velocity control of the vehicle via a thruster Reaction Control System (RCS). The RCS system is comprised of a Primary RCS (PRCS) and Vernier RCS (VRCS) set of thrusters. The Primary RCS consists of thirty-eight 870-lbf thrusters arranged in clusters providing a two-fault tolerant rotational and translational control capability. There are six 24-lbf Vernier RCS thrusters and no redundancy. Figure 2 displays a schematic of the reaction control system.

The Shuttle On-orbit Digital Autopilot (DAP) (Refs. 2-3) consists of configuration and moding logic, a state estimator, attitude steering law, a nonlinear phase plane controller, and jet selection algorithms. A block diagram of the DAP is provided in Figure 3. The configuration and moding logic allows the crew to control various attitude control modes automatically. Manual rotational and translational control is available via the hand controllers. The DAP also has the capability to select up to nine vehicle configuration-dependent parameters, such as mass properties and notch filter frequencies. Typically, these parameters are defined many months prior to flight, but a capability exists for ground controllers to uplink these parameters and overwrite existing values real-time.

The state estimator uses a Kalman filter to estimate the vehicle's rigid-body rotational rates and disturbance accelerations of the vehicle from the Inertial Measurement Unit (IMU) attitude measurements (Figure 3). The Shuttle IMU is the only attitude sensor available to the FCS and provides an accurate attitude reference with quantization and noise errors of 20 arcsec. A low-pass filter attenuates low-energy high-frequency (> 1 Hz) bending modes and minimizes the transient effects of IMU sensor noise and quantization. Bandwidth of the low-pass filter is 0.04 Hz for VRCS and 0.12 Hz for Alt. Low-frequency (< 1 Hz) payload flexure sensed by the IMU that is not sufficiently attenuated by the state estimator low-pass filter can lead to rate commands which may reinforce the flexural motion resulting in control instability and possible structural damage. Additional attenuation of undesired payload flexure can be added by designing a series of second-order notch filters around desired structural modes. Notch filter designs must meet model frequency and amplitude uncertainties and are generally limited to structural modes less than 1 Hz. Large notch filters introduce additional phase lag into the control system resulting in degraded performance.

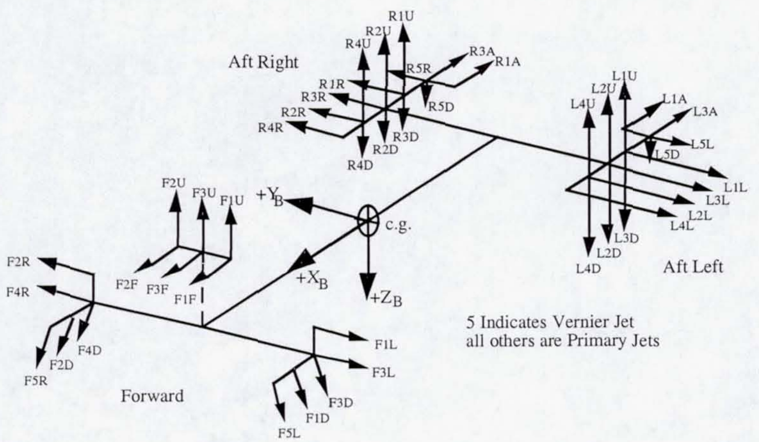


Figure 2 Shuttle Jet Schematic

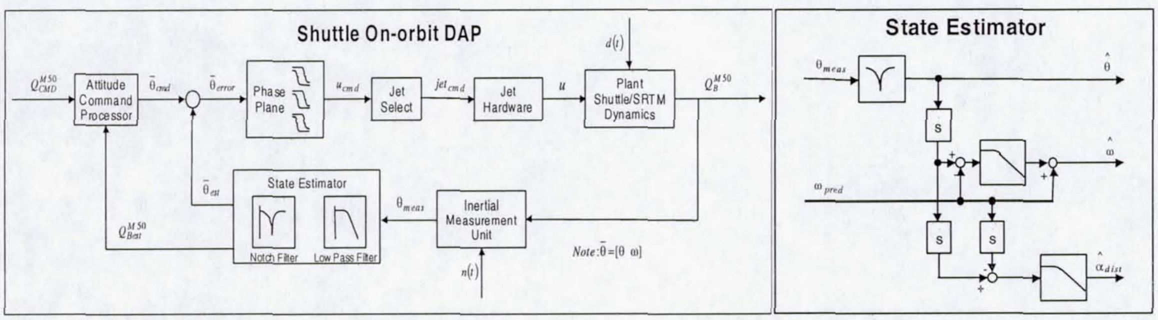


Figure 3 Orbit DAP Block and State Estimator Diagrams

The attitude steering law processes transforms the kinematic attitude states into desired body attitudes and rates. Attitude maneuvers are determined from the magnitude of the kinematic errors and follow an euler axis trajectory at a predefined maneuver rate.

A nonlinear phase plane controller determines required rotational rate commands for each axis, roll, pitch and yaw, independently. The phase plane schematic is provided in Figure 4. Switch lines are a function of attitude deadband, rate deadband, and predicted vehicle control accelerations. Rotational rate commands are generated when attitude and/or rate errors exceed the hysteresis or drift channel regions. The drift channel allows the vehicle to drift back to the hysteresis region when large attitude and rate errors result. Two-sided limit cycles result in the absence of external disturbance on the vehicle, such as gravity or waste dump, while one-sided limit cycles result from the presence of external disturbances. One-sided limit cycles are optimized using the estimated disturbance acceleration from the state estimator. The attitude deadband shelf, which extends out from the deadband, ensures that small overshoots of the deadband do not result in high-rate two-sided limit cycles.

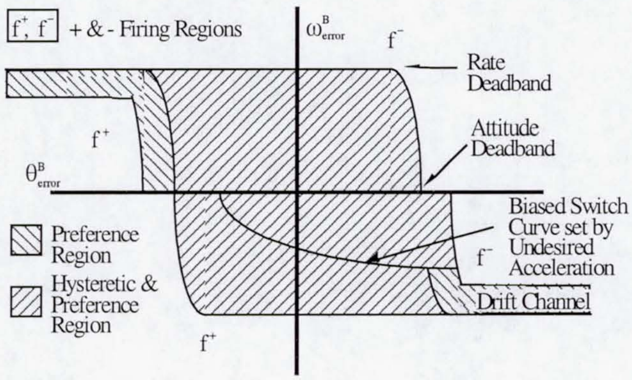


Figure 4 Phase Plane Control Law

Instability results when low frequency payload flex is not sufficiently attenuated by the state estimator low-pass filter. Rate instabilities generally occur during maneuvers when it is possible to be in the drift channel, where the allowable rate amplitude is less than the rate deadband. For Vernier RCS control, this corresponds to 0.4 times the rate deadband. Instability can result when oscillations in the estimated rate exceed one-tenth the rate deadband. During attitude hold, short period limit cycling results when attitude oscillations exceed the attitude deadband. For most Shuttle missions, the attitude deaband is large, e.g. 3 deg, so that attitude stability is not a concern. SRTM requires precise pointing during data collection such that attitude instabilities are now a concern in addition to rate instabilities during maneuvers. Examples of attitude and rate instabilities are provided in Figure 5.

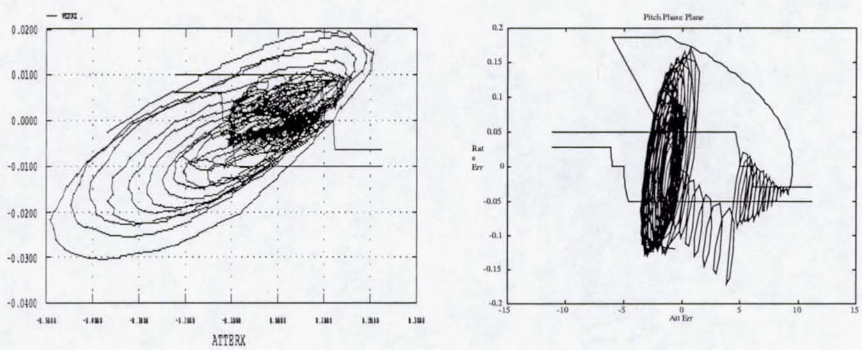


Figure 5 Examples of attitude (left) and rate (right) instabilities

Using the rotational rate commands from the phase plane controller the jet select logic selects the appropriate jets depending on the jet mode. Three jet modes are available: VRCS, PRCS, and Alternate (Alt) PRCS. The VRCS and Alt PRCS use either the maximum dot product or minimum angle algorithm, which select the jets based on the maximum acceleration in the direction of the jet command or the minimum angular error between the resultant jet acceleration and the jet command, respectively. Typically the minimum angle algorithm is used. The standard PRCS mode employs a nonconfigurable lookup table. Furthermore, the Alt PRCS mode allows the on-time (typically 80 msec) and delay time between firings to be constrained minimizing structural loads. Additionally the maximum number of jets allowed to fire simultaneously can be constrained to three jets. For most payloads, VRCS is the primary reaction control system with the PRCS system as the backup.

STABILITY ANALYSIS AND NOTCH FILTER DESIGN PROCESS

The objective of the stability analysis and notch filter design is to develop autopilot configurations that ensure stability, controllability, and meet any performance requirements. More explicitly, DAP parameters, such as attitude and rate deadbands, maneuver rates, and notch designs, are selected to avoid unstable, short period limit cycles in the phase plane. Additionally, FCS jet mode and mass properties dependent on payload configuration are selected to ensure that the orbiter can maneuver from one attitude to another and maintain those attitudes. Performance requirements that must be met include propellant consumption, load limits, mission timeline constraints, and duration and frequency of thruster firings. Minimizing these performance metrics was critical to STS-99 mission success. Rate notch filters are designed when payload structural modes less than 1 Hz are not fully attenuated by the state estimator low pass filter and result in dynamic interaction with the control system. Typically this occurs during maneuvers when the jets are pulsing and attitude errors are greater than the attitude deadband placing the orbiter in the phase plane drift channel where the allowable rate amplitude is significantly less than the rate deadband. For most missions, the VRCS attitude deadband is large, 1-3 degrees. The attitude increment comes directly from the Shuttle IMU and is not filtered by the state estimator. Generally, no payload dynamic interaction with the control system is observed in attitude. For a lightly damped system, such as the bending dampers failed stiff payload dynamic interaction with the control system due to tight SRTM pointing requirement, 0.1 deg, resulted in unstable, short period limit cycles. Therefore, additional filtering of the IMU attitude increment is required. An example of attitude instability is illustrated in Figure 5.

Figure 6 provides a summary of the notch design process (Ref. 4). The stability analysis inputs are desired autopilot parameters and finite element models of the payload combined with the orbiter. This dynamic model has the individual jet commands as inputs and roll, pitch, and yaw rotational displacements (attitude) at the IMU sensor as the output. Knowledge of the associated model uncertainties is also required to ensure the design of robust notch filters. Typically, a frequency weighted balance and truncate modal reduction technique is performed to reduce large models to a more reasonable size (Ref 5). Due to the coupling of modes, which resulted from the damper mechanism in the SRTM model, this technique could not be used. However, to reduce simulation time, the SRTM model was truncated from 30 Hz to 12.5 Hz to reduce simulation time.

Singular value decomposition is used for analysis of linear, multivariable systems. Given a model of the plant augmented by the state estimator low-pass filter,

$$G(s) = \begin{bmatrix} \dot{x} = Ax + Bu \\ y = Cx + Du \end{bmatrix} \tag{1}$$

the multi-input/multi-output plant response can be derived from the singular values

$$\sigma_i = \sqrt{\lambda_i \left[G(-s)^T G(s) \right]} \tag{2}$$

Singular value decomposition also provides the input and output directions from

$$G(j\omega) = U(j\omega)S(j\omega)V^H(j\omega) \tag{3}$$

where S is a diagonal matrix of singular values and U and V are the singular input and output directions. The singular value response provides an excellent screening of the system response to control commands and an indication of which command axes are excited. However, the gain represents the steady-state response to a sinusoidal input at the frequency. For the Shuttle, the driving signal consist of pulsed on/off RCS jets which tend to spread the power over multiple frequencies, lowering the gain at the modal frequency. This is illustrated in Figure 7.

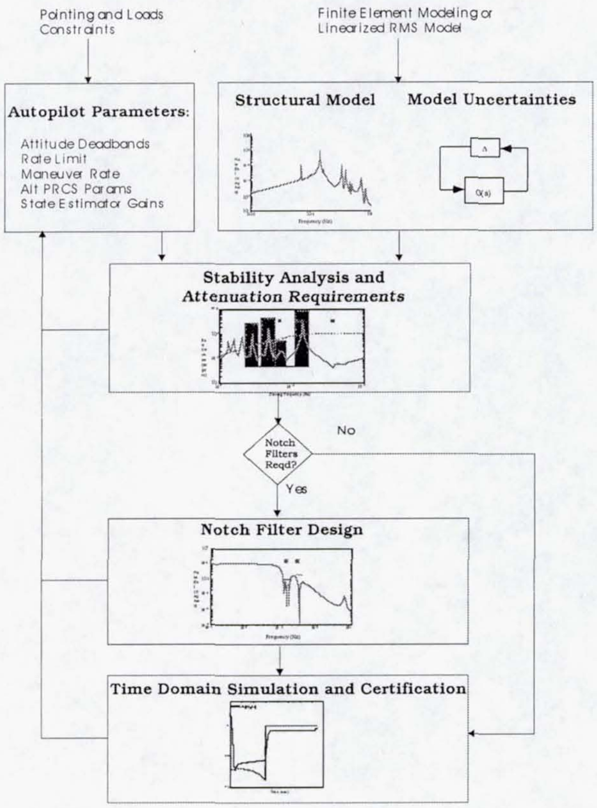


Figure 6 Stability analysis and notch design process

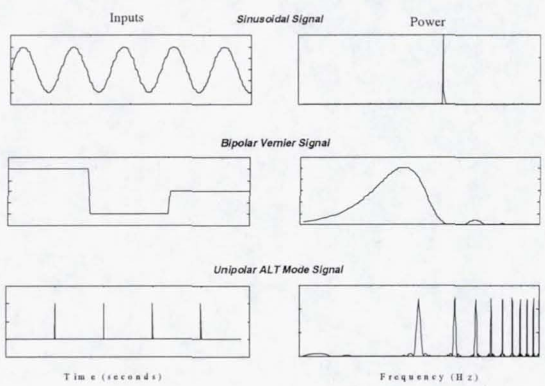


Figure 7 Effects of pulsed jets on system response

Thus, to account for on/off nature of the Shuttle control system commands and deal with the complex nonlinear nature of the phase plane controller, an open-loop analysis technique is used to derive the worst case filtered dynamic response (phase plane input) form a defined set of control commands (phase plane output). Experience indicates that the direction of the control commands generally occurs in the integer command directions limiting the set to the 26 combinations of (+, 0, -) in the roll, pitch, and yaw axes. The worst case dynamic response results from applying the 26-integer control command set to each of the modal frequencies of interest in the model. The set of maximum dynamic responses is then compared to the appropriate deadband to determine if sufficient excitation exist to induce a short period limit cycle.

This technique relies on a well-defined conservative set of jet command forcing functions, a well-defined understanding of the types of responses that excite the control law, and an understanding of multivariable signal transmission theory to provide an accurate response of the linear system to the nonlinear on/off commands. Forcing functions have been defined to test rate stability and vary with the jet mode. For VRCS, four bipolar pulses are used to drive the system. The pulses are tuned to each modal frequency. For the Alt PRCS mode, bipolar or unipolar firings are tuned to each modal frequency. Typically, the firings are 80 msec in duration. The number of pulse for the Alt PRCS mode is a function of the possible commanded acceleration, the rate limit, and the maneuver rate (Ref. 6). STS-99 SRTM is the first Shuttle flight that has required additional attenuation to stabilize the control system due to oscillations in the attitude. Initial forcing function of four bipolar pulses was used for notch design.

Using maximum responses from this open-loop analysis, robust notch filters are designed to stabilize the system taking into account model uncertainties. VRCS rate stability requires that the maximum magnitude of the rate oscillation be less than one quarter the height of the drift channel or one-tenth the rate deadband. Alt PRCS rate stability requires that the maximum magnitude of the oscillation be less than half the height of the drift channel. For VRCS attitude stability, the stability criterion was chose as half the deadband or a quarter of the hysteresis region. For the lightly damped system, simulation results indicated that this was under conservative. Discussion of the actual notch design describes the notch designs.

Finally, after a robust set of notches is defined for each desired payload configuration, simulation of the nominal and off-nominal payload configurations using the DAP parameters designed to provide a stable and controllable system test the robustness of the notch filter designs. Additionally, performance metrics are evaluated to determine the effects of the notch design on overall rigid body performance and provide baseline results during the flight.

During the flight, actual performance of autopilot is monitored. Often times, structural identification tests are scheduled and frequency identification is evaluated near real-time. If the test results indicate that the response of the actual structure is outside the notch design, a new set of notches may be designed, certified and loaded into the flight software.

PRE-FLIGHT CONTROL AND STABILITY ANAYLSIS

SRTM Structural Models

The SRTM payload consisted of a main radar system located in the Orbiter payload bay and a smaller antenna located on the outboard end of a 200-foot mast deployed out of the port side of the payload bay. Due to the highly flexible nature of the mast, dampers were added at the canister base in order that the mast tip deflections do not exceed the radar tip motion requirements. These dampers reduced the motion of the primary yaw and roll bending modes as well as the torsion mode of the mast. The mechanism consisted of four fluid filled cartridges: three cartridges, aligned in parallel, damped the roll and yaw bending modes and a single cartridges was used for the torsional mode. Damping of the primary roll and yaw bending modes was required for mission success. Therefore, redundancy was built into the bending damper system. Failure of the torsional damper would result in a slight degradation of the data, but would not impact the overall success of the mission. The damper system was locked stiff during ascent. Once on-orbit the dampers were unlocked and allowed to stroke. Failures of the system include failure of the caging mechanism, seizure of the plunger in the cartridge, or loss of fluid of the individual cartridges. The first two types of failures were referred to as *stiff* damper failures while the last type was known as a *soft* damper failure. Since the three bending damper cartridges were aligned in parallel, similar failure combination would have the same physical effect on the structure, e.g. a soft failure of bending cartridge one, two, or three resulted in the same model. Therefore, only one model with that damper configuration had to be included in the stability analysis. Initially, up to two soft damper cartridges was deemed credible and stiff damper failures would only result from failure of the caging mechanism. Seizure of the plunger in the cartridge was identified as a viable failure three months prior to flight. This credibility of this failure impacted the initial notch filter design and will be discussed in more detail later. Cases 1, 2, 5, 8, 9, 15, 16, 17, 19, and 20 represent the nominal and all failure cases and are listed in Table 1.

Linear flexible structural models of the SRTM were supplied by JPL (Ref. 7) and combined with a high fidelity flexible model of the orbiter at Johnson Space Center and supplied to (Ref. 8-9). Models of the linear dampers were developed with JPL. The introduction of the physical dampers resulted in coupling among structural modes. The resulting model contained 311 modes and a fully populated damping matrix. Comparison of the resulting CSDL model with the JPL model insured that the dampers and model processing were implemented correctly. The effects of truncating the model at various frequencies from 30 Hz to 10 Hz on the Orbiter FCS and payload displacements, rates, and loads were also evaluated. Model truncation is required to reduce the simulation run time. Truncating the model at 12.5 Hz, 89 modes, reduces computational time and provides accurate results for on-orbit FCS control and stability.

Model uncertainties were specified as 5% in frequency and an amplitude uncertainty factor of 1. Based on previous flight experience, Draper increased the frequency uncertainty to 10% and added an additional 20% in amplitude for conservatism.

Table 1
NOMINAL AND DAMPER FAILURE CASES AND FLEX DATA

Case No.	Bending Damper			Torsion Damper	Number of Failures	Yaw		Roll		Torsion	
	#1	#2	#3			Freq. (Hz)	Damp. Coeff.	Freq. (Hz)	Damp. Coeff.	Freq. (Hz)	Damp. Coeff.
1	OK	OK	OK	OK	0	0.096	0.146	0.127	0.176	0.188	0.105
2	**Soft**	OK	OK	OK	1	0.087	0.284	0.116	0.117	0.188	0.106
5	OK	**Soft**	**Soft**	OK	2	0.070	0.184	0.116	0.052	0.188	0.107
8	OK	OK	OK	**Soft**	1	0.096	0.147	0.126	0.158	0.169	0.006
9	**Soft**	OK	OK	**Soft**	2	0.087	0.285	0.116	0.103	0.169	0.004
15	**Stiff**	**Stiff**	**Stiff**	**Stiff**	2	0.095	0.005	0.144	0.005	0.203	0.005
16	OK	OK	OK	**Stiff**	1	0.097	0.147	0.126	0.158	0.203	0.005
17	**Stiff**	**Stiff**	**Stiff**	OK	1	0.095	0.005	0.144	0.010	0.187	0.103
19	**Stiff**	**Stiff**	**Stiff**	**Soft**	2	0.095	0.005	0.141	0.005	0.171	0.005
20	**Soft**	OK	Ok	**Stiff**	2	0.087	0.285	0.116	0.103	0.203	0.005

SRTM FCS Requirements

The SRTM payload required precise pointing of the vehicle during data acquisition. The FCS held VRCS attitude deadband of 0.1 deg and a rate deadband of 0.01 deg/s. Typical Vernier RCS deadbands are 1-3 deg. Additionally, a slow rate yaw maneuver known as "Zero Doppler Steering" was necessary to insure precise pointing of the antennae as the orbiter moved from north to south and back in its 57 degree inclination orbit. Avionics systems tracked the motion of the outboard antenna so that the relative position between the antennae was known at all times. During data acquisition, mast tip motion could not exceed translational deflection of 2.0 inches and 0.3 deg in rotation. Structural failure of the mast would occur if mast tip deflections exceeded 30 inches.

In addition to precision pointing during mapping activities, the SRTM payload also required precise orbital trajectories to meet radar swath and overlay requirements. A special procedure, dubbed Fly-cast, was developed to increase the orbital altitude by pulsing the primary RCS jets while minimizing loads on the mast. This was necessary to preserve the alignment of the antennae. Orbit adjustments burns could only be performed over water passes that lasted approximately 30-45 minutes. To meet this constraint, the orbiter was required to maneuver 180 degrees in pitch at a high rates between the mapping to fly-cast attitudes.

Table 2
STS-99 SRTM DAP PARAMETERS

Jet Mode	VRCS Pointing During Mapping	VRCS Attitude Maneuvers
Attitude DB (deg)	0.1	3.0
Rate Limit (deg/s)	0.01	0.05
Maneuver Rate (deg/s)	0.003	0.2/0.3

VRCS was the only jet mode capable of meeting the tight pointing requirements during mapping. If the VRCS failed, the Alt PRCS mode could be used while the crew and ground controllers evaluated the problem. Concerns with loads, mast tip deflections, and antennae alignment limited the maximum number of simultaneous PRCS jet firings to two. Table 2 summarizes the VRCS DAP configurations.

SRTM Notch Designs

VRCS Attitude Stability

Singular value analysis indicated the mast primary and secondary bending and torsion modes as the SRTM modes most easily excited. The two dominant modes of the system were designated as "yaw" and "roll" modes. These names describe the respective dominant orbiter motions only when applied to the caged bending damper cases. In these cases the orbiter motions were, respectively, nearly pure yaw (with nearly pure X translation at the mast tip), and nearly pure roll (with nearly pure Z translation at the mast tip). In the uncaged bending damper models, both of these modes are primarily orbiter roll, exhibiting roll to yaw rotation ratios of about 5 to 1. The yaw mode does, however, involve predominantly yaw motion of the mast tip, i.e., an X to Z translation ratio of about 2 to 1. The roll mode is also more X than Z at the mast tip but less pronouncedly so (X to Z translation ratio about 1.2:1).

Applying an open-loop forcing function of four bipolar pulses to the nominal and contingency configurations indicated that the system was gain stable for the nominal and torsion damper failure only cases. For all failed bending damper cases, attitude amplitudes exceeded the attitude deadband only in the roll axis. For the soft-failed bending damper cases, excitation of the yaw-bending mode was the dominant mode in the system response with an output direction of roll. This resulted from the cross coupling introduced by the damper mechanism. For the stiff-failed (or uncaged) bending damper cases, the roll mode was the dominant mode in the response. Figure 8 shows the system attitude response from four bipolar pulses compared to the attitude deadband for the nominal and all damper cartridges failed stiff configurations. Initial notch designs (Fig. 9) separated caged damper configurations from uncaged damper configurations to minimize the lag introduced by the notch filters on rigid body performance. The nominal case was grouped with the soft bending damper failure cases since the payload had no means to indicate a soft bending damper failure. Seizure of a damper cartridge post uncaging the dampers was deemed a non-credible failure by the payload.

Certification of the attitude notch filters after the I-load submittal revealed that the system was still unstable for the stiff-failed damper cases where structural damping of the mast was very small, 0.5%. Since this was the first shuttle flight which required additional filtering to provide attitude stability, the worst case forcing function for attitude stability had not been clearly identified. Simulation indicated that an addition 3 dB of attenuation was required to provide a stable system during attitude hold. However, this included no margin for model uncertainties. Propellant margins for this flight were already small. A trade study yielded that an addition 6 dB of margin could be added with minimal impact to propellant usage.

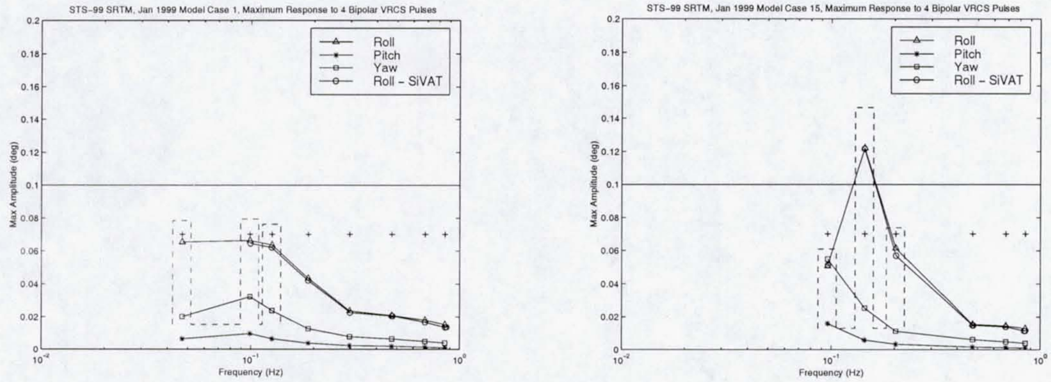


Figure 8 SRTM attitude attenuation requirements for the nominal (left) and stiff damper failure case (right). The solid horizontal line represents the attitude deadband. The dashed boxes bound the frequency and amplitude uncertainty for a given system response.

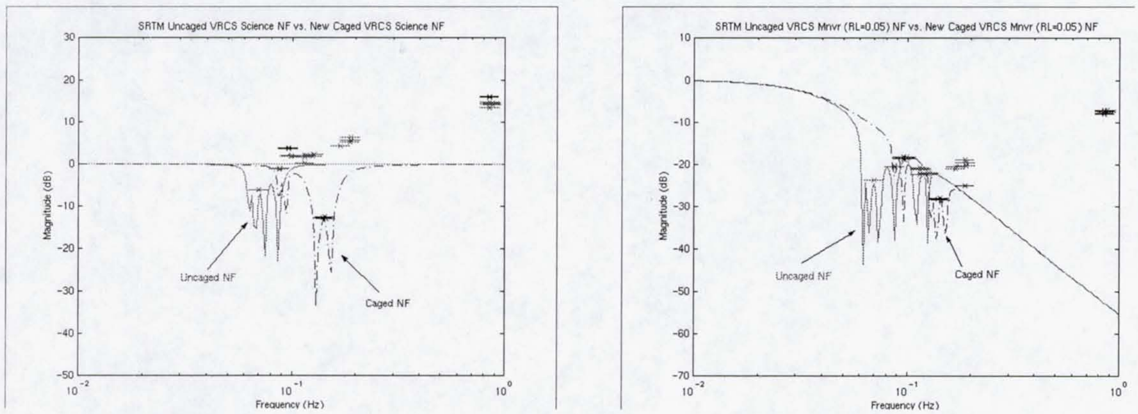


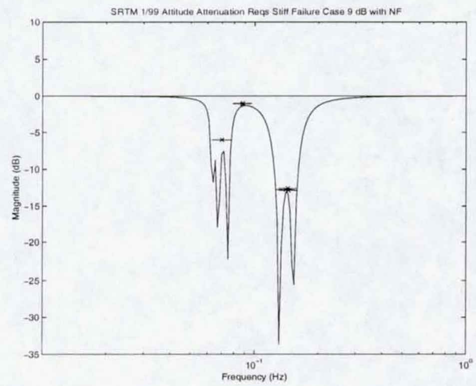
Figure 9 SRTM attitude (left) and rate (right) initial notch filter design for the dampers caged and dampers uncaged configurations. The short horizontal lines with the 'x' represent the maximum flexural response of the system; the 'x' marking the modal frequency and the width of the line the frequency uncertainty. Additional attenuation is required when these lines cross and are below the roll off of the state estimator low-pass filter.

Rate Stability

During attitude maneuvers, the attitude deadband was increased to 3 deg and the rate deadband was increased to 0.05 deg/s. Therefore, only rate instabilities were possible during maneuvers. The same VRCS four bipolar pulse forcing function was used to screen for rate stability. As before, the nominal and soft-failed bending damper cases, the flexural response was greatest in the orbiter roll axis. For the stiff-failed bending damper cases, flexural response of the system exceeded the stability criterion of one-quarter the height of the drift channel, 0.005 deg/s, in the roll and yaw axes. In all cases, both the roll and yaw bending modes required additional attenuation to ensure stability during VRCS attitude maneuvers. Following the same logic used in the attitude notch filter design, the initial notch designs (Fig. 9) separated caged damper configurations from uncaged damper configurations to minimize the lag introduced by the notch filters on rigid body performance. A set of rate notch filters was also design to support Alt PRCS control as a contingency to a VRCS failure. This allowed the orbiter to maneuver to a minimum propellant usage attitude while crew and ground controllers evaluated the failure as well as the mast retraction attitude in the event that the failure was non-recoverable.

Composite Failure Notch Filter Design

A damper manufacturing flaw, identified about two months prior to flight, invalidated the assumption that stiff damper configurations only resulted when the damper mechanism is locked. In response the Draper FCS team redesigned single notch (Fig. 10) sets to meet the nominal and nine contingency configuration stability requirements, recertified the notch sets, and assessed impact to overall performance. To facilitate the increased attenuation requirements for the composite design, the rate limit was increased to 0.08 deg/s to minimize the effects on performance. The new set of notches increased pre-flight propellant consumption estimates by approximately 110 lbs. The propellant increase was acceptable, though pre-flight propellant margins were already small. At the beginning of on-orbit operations, these notch sets were uplinked to the Shuttle and overwrote the previous filter design in the flight software.



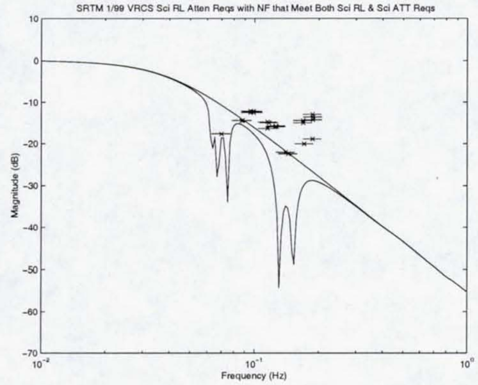


Figure 10 SRTM Composite Science Notches, Attitude and Rate Stability

Certification of DAP Stability and Performance

Flight control system stability and performance were verified using a high-fidelity simulation of the Shuttle flight software and environment. Two classes of simulations were performed: 1) a standard cases used to verify stability and control for typical flight control operations and 2) SRTM specific mission operations to measure baseline performance. A large database of simulations was completed to verify the baseline I-loaded notch filter designs and other FCS parameters. Additional simulations were then completed to verify the composite flight control designs.

The additional filtering required to assure stability by attenuating flexible modes in the rate feedback comes at a price of reduced rigid-body performance. The notch filters introduce additional lag into the system. Lag is measured as the steady state delay in seconds between an input consisting of a ramped rate and the VRCS rate estimate. Therefore, the estimated rate lags the actual rate causing overshoots of the desired rate by the control system. This can result in longer thruster firings and necessary, wasting propellant. Comparison of the maneuver and hold notch filter sets shows that the maneuver notches provide more aggressive filtering, i.e. greater lag. Lower center frequencies, greater widths and more notches all contribute to more flex attenuation and a greater performance penalty.

The performance cost for use of notch filters is most readily measured as propellant penalty. Based on the limited number of attitude hold simulations without notch filters, a 4% penalty due to the notch filters was observed. Another notch-induced performance hit is a small attitude bias during attitude hold. Detailed examination of the simulation output showed that there was a lag between the attitude data used to form the total attitude error and that used to form the single-axis errors. The lag occurred in the notch filters, and was proportional to the inertial body rate. At the LVLH rate prevailing, the total (RSS) lag was about 0.05 deg, causing the total attitude error to exceed 0.2 deg. The SRTM science community was notified of the bias and concluded that it would have negligible adverse impact. Simulation demonstrated that the attitude notch filter flow would provide adequate attenuation of the mast bending modes to ensure stability with the tight pointing requirement for all configurations.

To verify stability using the rate notch filters a standard set of twenty-six inertial maneuvers varying about maneuver direction was simulated. Stability and performance was evaluated for a 0.2 deg/s and a 0.3 deg/s maneuver rate. The amplitude of the response of the flexible modes was increased 20% and the modal frequencies varied within ±10%. This was to ensure that the notch sets met the robustness design requirements. Simulations demonstrated that the robust notch design ensured stability for all configurations.

Larger rate and attitude deadbands were used when maneuvering between the science attitude and the orbit trim attitude. Radar performance required precision orbit trajectories. To ensure precise orbit velocity control, it was desired that the rates were damped and attitude errors minimized prior to commencing the fly-cast maneuver. Thus, an attitude deadband collapse (DBC) procedure was developed at the trim attitude in addition to the one required to return to the tight mapping pointing requirements. During DBC, as the attitude and rate deadbands were decreased from 0.08 deg/s and 3 deg for maneuvers to 0.05 deg/s and 1 deg at the trim attitude or 0.01 deg/s and 0.1 deg at the science attitude, it is possible for a maneuver to be triggered placing the orbiter in the drift channel of the phase plane. For these small rate deadbands, the rate notch filters did not meet the quarter drift channel stability criterion. A set of simulations was used to analyze stability and performance during DBC at the science attitude varying initial conditions which represented a worst case scenario for initiating a deadband collapse.

A hitherto unnoticed effect of the notch filters on performance was found during tests of the DBC at the end of the trim to mapping attitude maneuver. A little background information will assist the explanation. The automatic maneuver capability of the FCS operates in either of two submodes. Maneuver mode drives the attitude toward the target attitude at the I-loaded maneuver rate, and Track mode maintains the target attitude. The target attitude may be inertially static (i.e., an inertial attitude hold) or moving. During ZDS the target attitude moves over a ±2.8-deg LVLH yaw range, and being expressed in inertial coordinates, also rotates with the LVLH coordinate frame. The transition between Maneuver and Track modes is triggered by a hysteresis function. When the total attitude error (i.e., the eigenaxis rotation magnitude) ≥ KH x the attitude deadband, the mode is switched to Maneuver; it changes to Track when the total error ≤ KTRK x the attitude deadband. Based on earlier results, the values of KH and KTRK had been defined to be 3.0 and 1.5 respectively.

DBC is quite likely to trigger an attitude maneuver, since the attitude previously held with a large deadband may have a total error ≥ KH x the new, smaller attitude deadband. However, in one DBC case it was found that a transition to Maneuver mode from Track mode was made even when all three single-axis attitude errors were within the new attitude deadband. This should not happen, because the maximum possible value of the total attitude error should be the RSS of the three single-axis attitude errors (small-angle approximation), or ≤1.732 x the attitude deadband, which is far short of the required approx. 3 x the attitude deadband.

As a further note, the maximum allowable notch lag can be computed as follows. A spurious transition can occur if 1.732 * the attitude deadband + the attitude lag approaches KH * the attitude deadband. Thus the attitude lag must not exceed (KH - 1.732) * the attitude deadband. For the SRTM mapping configuration, the resulting maximum allowable attitude lag is 0.127 deg.

In testing deadband collapse (DBC) performance at the mapping attitude, it soon became apparent that the attitude maneuver notch filters were adversely impacting performance. The notch filter lag was causing both rate overshoots and probably attitude overshooting, resulting in long settling times and repeated cycling between Maneuver and Track modes. Thus it was desired to determine which model configurations could support DBC without notch filters, and later with attitude hold notch filters, when it was found that these did not degrade performance significantly. Accordingly, a test series was performed.

The tests were of two types. First, phase stabilization tests were performed with the closed-loop FCS and the system in a state of initial modal excitation. Each of the three significant flex modes (yaw bending, roll bending, and mast torsion) alone and in all possible phase relationships with the other two modes was tested this way for all damper configurations. Second, amplitude stabilization tests were conducted for any mode and model that failed the first test. These were open-loop excitation tests using VRCS forcing functions applied over the expected frequency range of the given mode with approximately 10% spacing, and subsequent measurement of the responses. Any model containing a mode that failed both tests was considered ineligible for relief from the notch filter requirement; the others were considered OK for notch-free performance testing.

For DBC at the science attitude (RL = 0.01 deg/s) with no bending damper failure or one soft-failed bending damper cartridge, there was phase stabilization in the drift channel, and phase plus amplitude stabilization with respect to the attitude deadband, so no stability problem was expected. For other bending damper failures (two soft failures or a stiff failure), test results showed these configurations were potentially unstable for DBC with RL = 0.01 deg/s. Over 500 DBC simulations of the two soft-failed bending damper and stiff damper configurations with the attitude hold notch filters did not yield any unstable cases. Simulations showed that the time penalty is small or nonexistent when the attitude hold notches are used.

For DBC at the trim attitude (RL = 0.05 deg/s), the attitude maneuver notches will be used. There should be no instability problem in this case

STRUCTURAL IDENTIFICATION BACKGROUND

The on-orbit autopilot stability process included in-flight verification of stability through on-orbit structural identification and real-time stability analysis. During the mission, a structural dynamics team evaluated the Combined Shuttle/Mast vibration using two payload sensors and the Shuttle inertial measurement unit (IMU). The team's objectives were to identify the mast damper configuration and the as-flown structural characteristics to confirm control system stability and to tune the Fly-cast reboost firings. This paper covers the structural ID results related to stability verification. The team measured responses to sets of pre-planned open-loop thruster firings as well as firings that occurred during closed loop operations such as attitude control and rotational maneuvers. Fast-Fourier Transform (FFT) techniques were used to extract frequency content from the sensor data, and detrending and smoothing techniques were used to allow graphical analysis to verify FFT results, determine damping and analyze non-linear responses.

Table 3 summarizes the three sensors that were used to identify the structure and lists their downlist rates. The Shuttle inertial measurement unit (IMU) data is processed by the shuttle flight control computers and downlisted as three angular measurements representing the angular displacement of the shuttle body with respect to an inertial reference. The Astros Target Tracker (ATT) consisted of a laser mounted on the SRTM payload in the bay and reflectors mounted on the radar antenna at the end of the mast. Multiple reflectors gave the ATT the capability to measure mast motion in six dimensions, providing mast tip deflection and rotation. ATT data was processed by JPL into a format which provided three translation and three rotation degrees of freedom. The SRTM payload was also equipped with a set of rate gyros, the Inertial Reference Unit (IRU), which was mounted on the payload and aligned with the mast. IRU results are not presented here since, for stability analysis, the IRU served mainly to confirm other sensor results.

Table 3.
SENSOR SUMMARY

Sensor	Description	Downlist Rate
Shuttle Inertial Measurement Unit (IMU)	Processed attitude data from Shuttle downlist	5 Hz
SRTM Astros Target Tracker (ATT)	SRTM-mounted optical tracker. Provides SRTM mast tip deflections and rotations relative to payload bay	4 Hz
SRTM Inertial Reference Unit (IRU)	SRTM-mounted rate gyros. Provides delta theta measurements	1 Hz

All preflight stability analysis and certification were conducted using models based upon the mast damper failure scenarios or "design cases" in Table 1 above. Therefore, one of the primary goals of the structural identification process was to determine the mast damper configuration in flight. Two sets of tests were planned to verify the structural model and check for damper failures. The first test was a pair of open-loop roll firings of the Shuttle vernier jets (24 lbf) with the mast dampers caged. This test, dubbed VRCS1, was intended to confirm the basic structural model and provide a stiff-damper baseline in the roll direction for comparison with results after damper uncage. The second test, VRCS2, was conducted after uncaging the dampers to confirm the damper configuration. It was the responsibility of the structural identification team to issue a "Go For Deadband Collapse and Mapping" once the damper configuration was known and stability assured. Additional tests were conducted after the VRCS tests, using the Shuttle standard primary RCS jets (870 lbf) to obtain higher amplitude data and tune the Flycast firings, however, this paper covers only the structural ID results related to stability verification. PRCS test results are available in Ref. 10.

IRU and ATT data were available to the frequency identification team only after the pre-planned tests. However, IMU data were analyzed both after the tests and during nominal operations. The pre-planned tests provided structural responses to known forcing functions. This allowed comparison of measured amplitudes with amplitudes predicted preflight by linearized models. The ratio of predicted to measured amplitude was used to determine whether the onboard notch filter designs provided sufficient amplitude robustness. IMU measurements of responses to nominal operations proved useful in providing early frequency and damping measurements, high amplitude VRCS data, and test result confirmation.

STRUCTURAL IDENTIFICATION RESULTS

Table 4 lists the structural identification events that are presented in this section. Additional measurements were taken throughout the flight to confirm initial results and check for changes in structural characteristics. The following sections detail each data analysis period in Table 4.

Table 4.
DATA ANALYSIS TIMELINE

Description	GMT	Sensors
Post Deploy Attitude Hold	043/00:13	IMU
VRCS Test 1	043/00:53	IMU, ATT, IRU
VRCS Test 2	043/01:41	IMU, ATT, IRU
Post VRCS2 Attitude Hold	043/01:55	IMU, ATT

Post Deploy Maneuver and Attitude Hold

After the SRTM mast was deployed and the outboard antenna flipped and locked into position, the autopilot was engaged and a maneuver was commanded to mapping attitude. IMU attitude data were collected to identify primary modal frequencies and damping. During this period, the mast dampers were caged, so frequencies and damping from design case 15 were expected (Table 1). Since the precise firing directions and durations were not know a priori, amplitude data were only checked for reasonableness.

Figure 11 shows the response at the IMU to a post-deploy attitude hold firing. The data have been detrended to remove the rigid component. The right plot shows the frequency content of the roll signal and lists the 4 dominant frequencies. These data were determined by finding the Power Spectral Density (PSD) of the time response. The PSD was calculated using Fast Fourier Transform (FFT) methods.

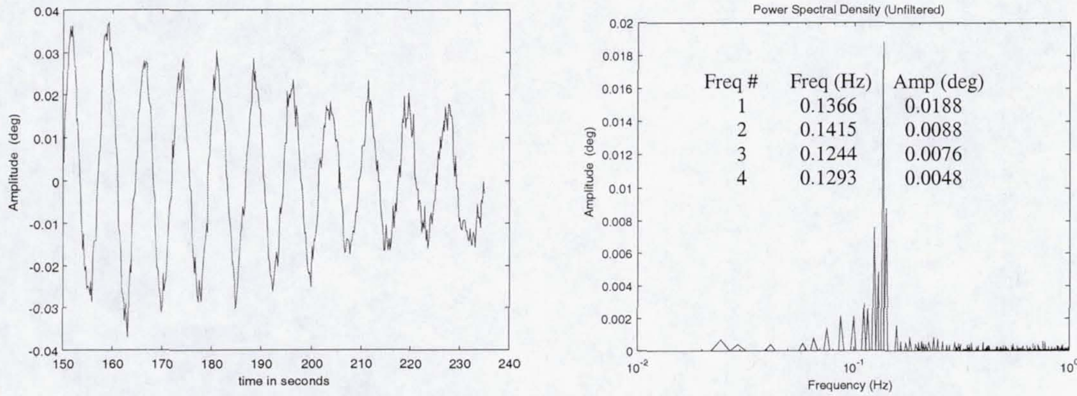


Figure 11. IMU Roll response to post deploy attitude hold firing.

Figure 12 shows the results of graphical analysis of the attitude hold roll response. The left plot shows the roll signal of figure 11, filtered at 0.5 Hz to facilitate measurement of zero-crossing points. The right plot shows the frequencies corresponding to each half-period of the filtered signal. The data are consistent with the PSD results of Figure 11 in that the frequencies corresponding to half periods from the high amplitude portions of the signal average approximately 0.136 Hz. However, the frequency appears to decay at lower amplitudes – below about 0.02° IMU amplitude.

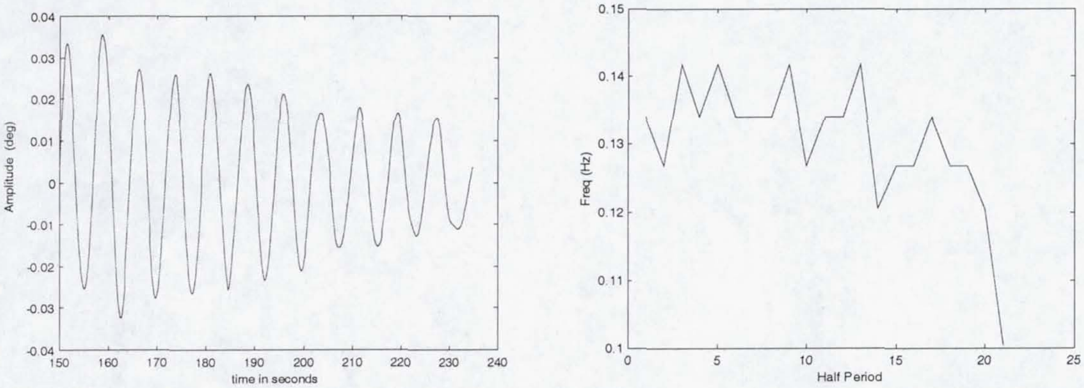


Figure 12. Graphical analysis of IMU roll response to post deploy firing.

VRCS Test 1: Caged Dampers

ATT data for the "up/down" or Z deflection of the ATT within the SRTM frame are shown in Figure 13 for the positive roll VRCS1 firing. The ATT has better signal-to-noise characteristics than the IMU, so it was not necessary to filter the response to analyze damping or half-periods. Minus Roll ATT Z results were very similar and so omitted. The half period results are consistent with those shown for the attitude hold firing above. Fortunately the attitude hold firing provided a higher level of excitation than the test firing, so the high amplitude behavior could be observed. In both cases, frequency decays below amplitudes corresponding to approximately 0.02° of IMU Roll. Therefore it was concluded that the frequency domain results were unreliable at low amplitude due to the non-linear nature of the system.

Graphical damping measurements of the ATT Z response showed a damping ratio of about 1.8 to 2.0%, agreeing approximately with the IMU results.

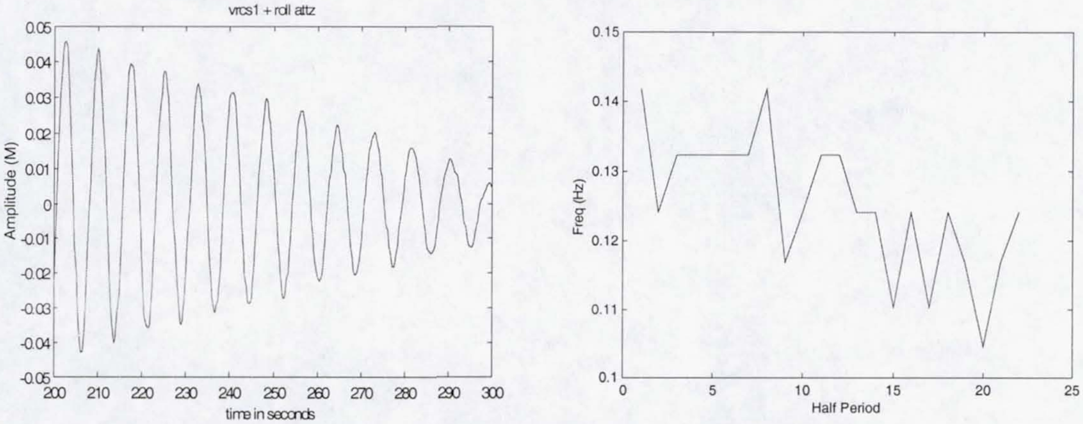


Figure 13. ATT Z tranlation response to VRCS1 firing

VRCS Test 2: Uncaged Dampers

After commanding the dampers to uncage, the VRCS2 series of pulses was executed. The left plot of Figure 14 shows the ATT Z translation response to theVRCS2 +Roll firing. For comparison, the expected response is plotted from simulation results. The IRU and IMU results are again omitted for brevity.

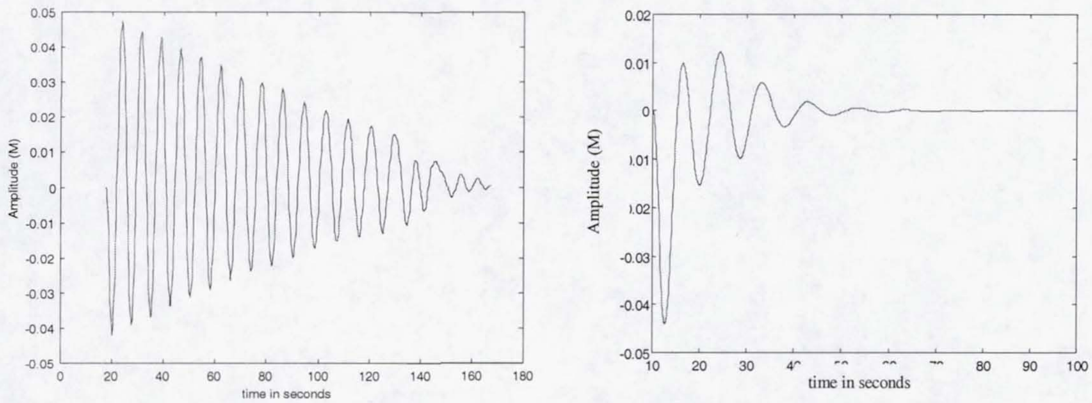


Figure 14. Observed (left) and expected (right) ATT Z responses to VRCS2 +Roll firing

These results immediately identified a problem with the mast bending dampers. Further investigation (Figure 15) showed that the roll response from the VRCS1 (caged dampers) was virtually identical to the VRCS2 (uncaged damper) response further demonstrating that the dampers had no effect.

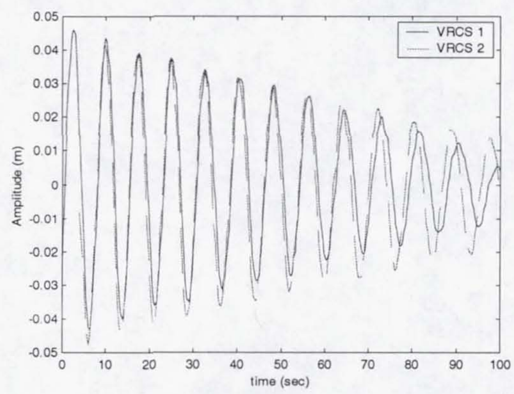


Figure 15. Comparison of ATT Z responses to VRCS1 and VRCS2 roll firings.

Figures 15 and 16 show the ATT time responses and associated PSD plots for the VRCS2 pitch and yaw firings. The time responses clearly show very little damping and the PSD dominant frequencies (again listed in order from 1 to 4) are consistent with the failed damper design case (Case 15 in table X). These data indicate a total failure of all mast dampers.

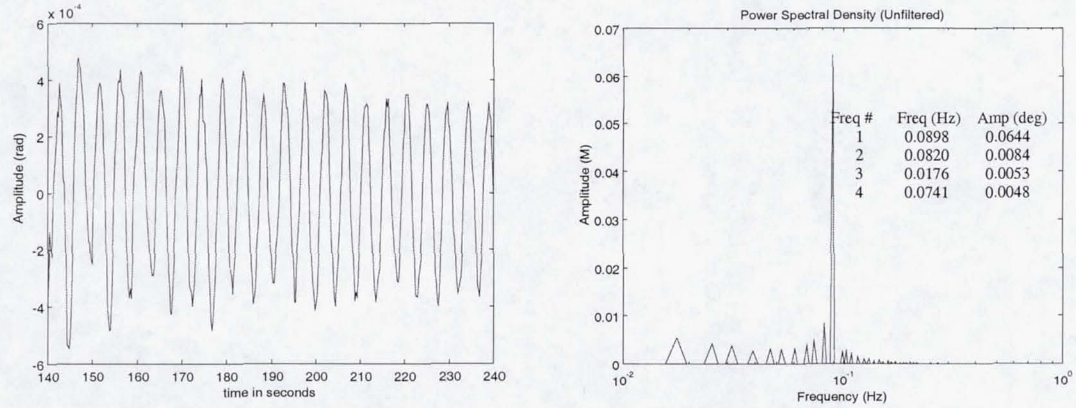


Figure 15. ATT Y rotation response to VRCS2 +Pitch Firing

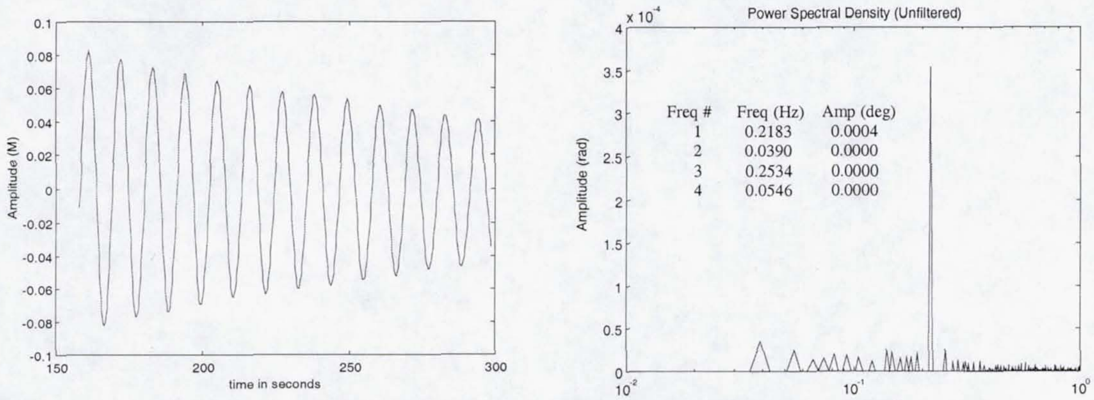


Figure 16. ATT X translation response to VRCS2 +Yaw Firing

Figure 17 shows the half-period analysis of the ATT Z time response. Again, these results are consistent with the VRCS1 results, and indicate a non-linear response that approaches a frequency of about 0.13 to 0.14 Hz at amplitudes above about 0.04 meters in ATT Z deflection.

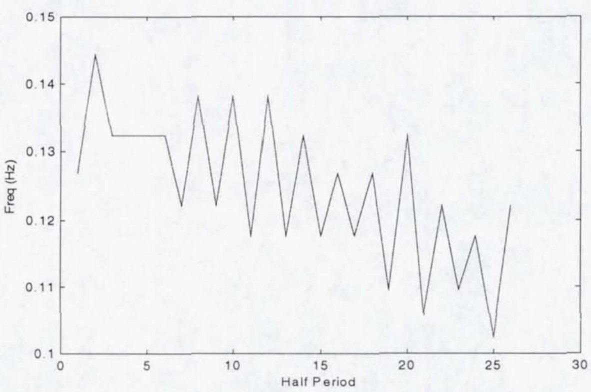


Figure 17. Frequencies per Half Period for ATT Z Resonse,VRCS2

VRCS Test Results Summary

Table X.3 summarizes the VRCS results for the high amplitude portion of the test responses. All results represent a composite from all three sensors. Frequencies, amplitudes and damping for the SRTM Roll, Pitch and Yaw modes are compared to the expected results of design case 15. Errors for frequency and amplitude are given in percent, while damping errors are absolute. Frequencies and damping in the table represent the frequency and damping for each mode measured at the highest available amplitude. Amplitude errors compare the measured versus expected amplitudes for the pre-planned VRCS tests.

Table 5.
SUMMARY OF HIGH AMPLITUDE MEASUREMENT RESULTS.

	Frequency	**Amplitude**	**Damping Ratio**
	Roll Mode		
Measured	0.135 Hz	0.043 M	0.018
Expected	0.144 Hz	0.046 M	0.005
Error	-6.25%	-6%	+0.013
	Pitch Mode		
Measured	0.218 Hz	5.5e-4 rad	Not measured
Expected	0.203 Hz	6.7e-4 rad	
Error	+0.07%	-17%	
	Yaw Mode		
Measured	0.095 Hz	0.030 M	0.008
Expected	0.095 Hz	0.041 M	0.005
Error	0%	-26.8% *	+0.003

IN-FLIGHT STABILITY VERIFICATION

Draper structural identification results were compared to those from the other members of the Structural Identification Team and delivered to JPL for assessment of the design case. Based on the results, design case15 (dampers failed stiff) was identified. In order to insure that the system response would remain predictable, it was decided to re-cage the mast dampers prior to deadband collapse.

The I-loaded composite notch filters were designed to attenuate roll vibrations from design case 15, assuming a linear system with frequencies within +/-10% of nominal. Measurements of the system roll mode revealed that the vibration frequencies decayed with increasing amplitude, and that the high-amplitude frequency was approximately 6% below the expected value. Figure 18 shows a plot of composite measured frequencies versus graphically measured amplitudes. The figure shows that the frequency tended to level out at about 0.136 Hz at high amplitudes. The 0.136 Hz value was considered to be fairly accurate, since PSD measurements of high amplitude signals agreed with graphical measurements.

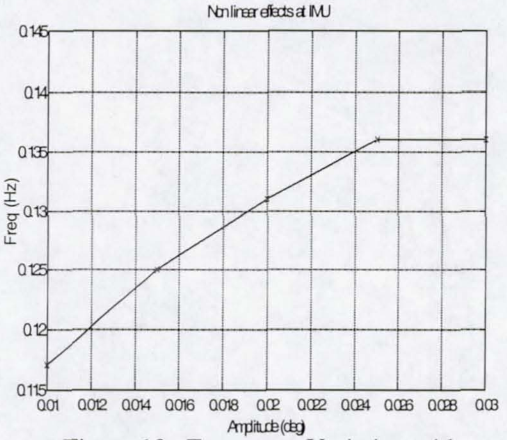


Figure 18. Frequency Variation with Amplitude for Roll Mode.

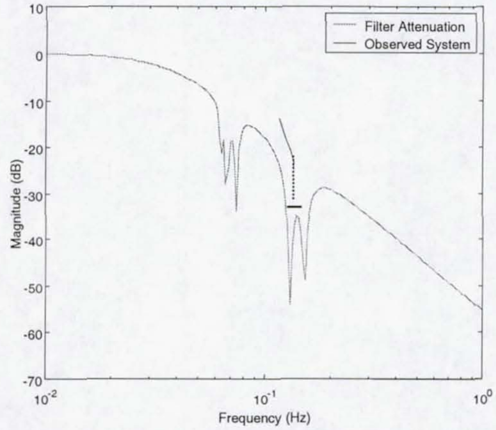


Figure 19. Comparison of Rate Filter Attenuation with ¼ Drift Channel Requirement from Observed System

Figure 19 summarizes the frequency domain stability analysis for the roll mode. Roll mode attenuation was considered critical with the caged system since simulation results had indicated that instability was highly likely with unfiltered roll feedback. The solid line in the figure represents the gain/attenuation provided by the combined low-pass and series notch filters. For each amplitude/frequency pair from Figure 18 a corresponding attenuation requirement is generated in Figure 19 (dashed curve). Each point on this curve represents the amount of attenuation needed to reduce the IMU amplitude at the input of the rate filter, to a height of not more than ¼ of the phase plane drift channel. Amplitude increases along the dashed curve from top to bottom causing the required attenuation to increase (become larger negative). The solid bar represents the highest expected amplitude from the observed system. Note that the "bend" in the attenuation requirement (dashed) curve occurs above the solid filter gain curve.

At high amplitudes, the data approached 0.136 Hz. This is about 6% below the center of the +/-10% region protected by the roll notches. These data indicated that the roll notches were robust to the measured system, and that significant frequency shifting did not occur until amplitude decayed to a "small" value relative to the drift channel.

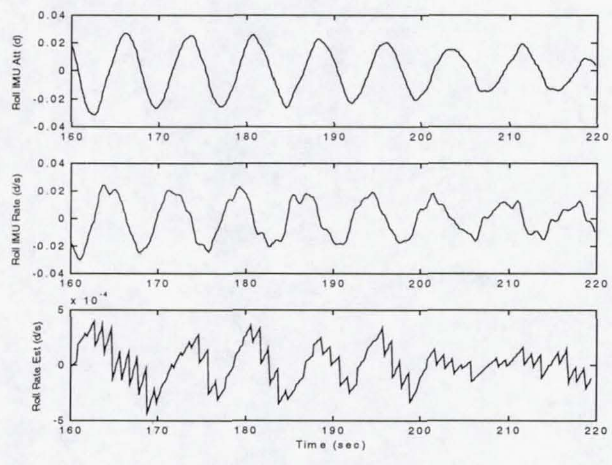


Figure 20. Comparison of Rate Filter Attenuation with ¼ Drift Channel Requirement from Observed System

Similar analysis on the Yaw mode indicated that the system was robustly stable in yaw. The same process was used to assess stability for the attitude hold notches in the presence of measured data. These data, together with good general control performance, provided confidence that the filter was sufficiently attenuating the existing system. This, together with the decision to re-cage the dampers led the FCS team to issue a "GO" for deadband collapse to science attitude.

Results from the later PRCS tests and continued monitoring confirmed that the notch filters designed to be robust to a "dampers failed stiff" condition, provided sufficient attenuation to stabilize the control system throughout the mission.

CONCLUSIONS

The contingency planning of the pre-flight design team together with rapid in-flight analysis, insured that the Shuttle FCS could meet demanding performance requirements while maintaining sufficient stability margin. This helped make SRTM a hugely successful mission.

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