Acknowledgements

The following individuals at TRW contributed to the Two-Micron LAWS Pointing/Tracking Study:

- **Structural/Mechanical Modeling**
  - Stenner Kleve
  - Mike Waterman
  - Walter Beckman

- **Dynamics Modeling**
  - Ray Manning

- **Optical System**
  - Martin Flannery

- **Controls Systems**
  - Ron Mayo
  - Reid Reynolds

I would like to express my appreciation to these individuals for their dedication and hard work which led to the successful completion of this study. I would also like to express my appreciation to Mr. Bill Grantham, the NASA/LaRC CoTR for his cooperation and guidance.

Scott Manlief
Program Manager
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Executive Summary
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Executive Summary

The Two-Micron Laser Atmospheric Wind Sounder (LAWS) Pointing/Tracking Study was performed by the Space & Technology Division, Space and Electronic Group of TRW for NASA LaRC under Contract No. NAS1-19291, MSOA Task No. 15. The period of performance of the study was from 1 January 1994 to 4 November 1994.

The objective of the study was to identify and model major sources of short-term pointing jitter for a free-flying, full performance 2μm LAWS system and evaluate the impact of the short-term jitter on wind-measurement performance. A fast steering mirror controls system was designed for the short-term jitter compensation. The performance analysis showed that the short-term jitter performance of the controls system over the 5.2 msec round-trip time for a realistic spacecraft environment was = 0.3 μrad, rms, within the specified value of < 0.5 μrad, rms, derived in the 2μm LAWS System Study (6 October 1993).

Our approach was to develop a conceptual, yet detailed, structural and dynamics model for the 2μm LAWS instrument based on the results of the 2 μm LAWS System Study. As in the System Study, the basic optical form, including active beam jitter stabilization, proposed in the GE Phase II LAWS Study Final Report was assumed. The payload model was then merged with an existing spacecraft bus dynamics model for a TRW UAB-940 satellite and a modal analysis run out to 100 Hz. The full-performance 2 μm solid-state LAWS payload/AB-940 bus system is compatible with a Delta-class launch vehicle.

Disturbance models were defined for 1) the Bearing and Power Transfer Assembly (BAPTA) scan bearing, 2) the spacecraft reaction wheel torques, and 3) the solar array drive torques. The scan bearing disturbance was found to be the greatest contributing noise source to the jitter performance. Disturbances from the fast steering mirror reaction torques and a boom-mounted cross-link antenna clocking were also considered but were judged to be...
small compared to the three principal disturbance sources above and were not included in the final controls analysis.

A fast steering mirror controls architecture was defined and loop parameters were defined to compensate for the line-of-sight pointing jitter induced by structural displacements excited by the three principal disturbance sources. The control loop design reduced the short-term X-axis open loop jitter over the 5.2 msec pulse round-trip time from an rms value of \( \approx 2.4 \ \mu \text{rad} \) to \( \approx 0.2 \ \mu \text{rad} \) when the loop was closed. The Y-axis jitter, both open and closed loop was found to be less than the short-term jitter about the X-axis. The Y-axis open-loop rms jitter was \( \approx 0.5 \ \mu \text{rad} \), and the residual short-term rms jitter when the FSM loop was closed was \( \approx 0.2 \ \mu \text{rad} \). The RSS value of the residual rms short-term jitter, then, is \( \approx 0.3 \ \mu \text{rad} \), meeting the specified jitter requirement of \( 0.5 \ \mu \text{rad} \) for the 2 \( \mu \text{m} \) LAWS system.
Objective

- Identify and model major sources of short-term pointing jitter for a free-flying 2 μm LAWS system and evaluate pointing-jitter impact on wind-measurement performance

Study approach

- Develop conceptual structural design and dynamics model for 2 μm LAWS instrument based on
  - 2 μm LAWS System Study results
  - Assuming basic optical form, including active beam jitter stabilization, proposed in GE Phase II LAWS Study final report
- Utilize existing dynamics model for a TRW UAB-940 spacecraft appropriately modified to accommodate the LAWS instrument
- Develop pointing controls model to evaluate jitter effects on system wind measurement performance incorporating as principal disturbance sources
  - Scan drive bearing noise
  - Fast steering mirror reaction torques
  - Spacecraft reaction wheels unbalance and torques
  - Solar array stepping
  - Boom-mounted cross-link antenna
Requirements Summary
be known to less than ±0.5°/hr.

To limit the contribution from spacecraft velocity fluctuations to less than 0.25 m/s, the pointing knowledge must

The limiting pointing knowledge requirement occurs when the line of sight is perpendicular to the orbital plane.

The pointing knowledge requirement is determined by the requirement that fluctuations in the component of the
dirrection of the LOS vector along the pointing line of sight (LOS) be small compared to the desired LOS wind

The pointing knowledge requirement is approximately ±1.4°/hr.

The Laws pointing accuracy requirement is set by the mission's mission density requirement of 3 kilometers per 100

independent of the competing wavefront of the lidar.

The Laws pointing accuracy and pointing knowledge requirements are set by geometrical considerations and are

LAWs Pointing Requirements
LAWS Pointing Requirements

Pointing accuracy and knowledge requirements are independent of the lidar wavelength

- Pointing angle, $\psi$, accuracy requirement to target 30 km area = $\pm$ 14 mrad

- Pointing knowledge requirement determined by requirement that the LOS component of spacecraft velocity errors introduced by ephemeris or attitude fluctuations be small compared to the desired LOS wind velocity measurement accuracy of $\pm$ 1 m/s

\[(\Delta V_{\text{LOS}}) = \Delta(V_s \cos \psi) = V_s \sin \psi \Delta \psi\]

- Limiting knowledge requirement when pointing perpendicular to spacecraft velocity vector

- For $\Delta V_{\text{LOS}} < \pm 0.25$ m/s

\[\Delta \psi \leq \frac{0.25}{V_s \sin \psi} = \pm 36 \mu \text{rad}\]
Our WinDsonde performance model calculates the effect of inter-millisecond on heterodyne mixing.

Wavelengths of 2.05 m and 9.1 m, respectively.

Mixing efficiency is reduced by 0.3 dB and 0.2 dB at 2.05 m and 9.1 m, respectively.

This is shown below. For this further values of 0.5 m and 1.5 m, the wavelength

-4

Re= 0.47 (L) results in spectrums of 0.5 m and 1.5 m for aperture values of 1.33 m and 1.5 m at

Imposing the requirement that the short-term jitter must be less than 1/10th of the transmitt beam divergence

Mixing efficiency and consequently the received signal-to-noise.

Signal and the local oscillator phase noise. The effect of phase-front misalignment is to reduce the heterodyne

scattering volume during the pulse round-trip time to minimize differences between the received backscatter

Operating wavelength of the laser. Physically, the receiver must maintain stable pointing toward the sensor

In contrast to the pointing accuracy and knowledge, the short-term jitter requirement scales directly with the

Short-Term Jitter Requirement Scales as Wavelength
Short-Term Jitter Requirement Scales as Wavelength

Requirement is that receiver maintain stable pointing toward scattering volume (defined by transmit spot diameter) during round-trip time of 5.2 msec

- Jitter effect is to reduce heterodyne mixing efficiency and consequently received SNR

Short-term jitter requirements of 0.5 μrad and 1.5 μrad for 2.06 μm and 9.1 μm, respectively, defined in 2 μm LAWS System Study (Oct 93) and the GE Phase II Study Final Report (Sept 92)

- Corresponds to approximately 1/10th of the transmit beam divergence (∝ λ/D)

WindSounder performance model analysis shows rms jitter values of 0.5 μrad and 1.5 μrad reduce mixing efficiency by – 0.3 dB and – 0.2 dB for 2.06 μm and 9.1 μm, respectively.
The noise floor on the curve shown is set by the reaction torque noise, which, under operational conditions, is

Estimated closed loop performance = (8/2/2) x 0.28 = 0.28 g/rd

The noise floor to an internal source is 8.2 g/rd (16). Then the estimated steady-state closed loop performance is

The short-term pointing jitter applies to the closed loop residual error over the return pulse rounded time of 5.2

Fast Steering Mirror (FSM) Requirments
Fast Steering Mirror (FSM) Requirements

Typical spacecraft vibration levels suggest that the FSM (image motion compensator) disturbance rejection capability at low frequencies be set at $= 200 \, \mu\text{rad}$

Asymptotic plot of allowed target space LOS jitter vs. frequency, using a 0.28 $\mu\text{rad} (1\sigma)$ jitter allocation over 5.2 msec (pulse round-trip time), a travel limit of 3300 $\mu\text{rad}$, a mirror acceleration limit of 500 rad/sec$^2$, and a tracking loop bandwidth of 500 Hz given by
The steering mirror size depends on the aperture diameter and the telescope magnification. The mirror is efficiently sized at 4.5" to the incident beam.

The required travel with 20% margin becomes 3500 ft. The required range of travel is 3300 ft in local space for a low frequency target space variation of 200 ft. The sum expression shown, 

\[ \text{frequency} \times \text{travel} \text{ is } \text{low frequency target space variation} \]

The WLC long sheet sweep capability plot shown on the previous graph is for a single disturbance.

FSM Requirements - II
• If there are multiple frequencies $f_i$, $1 = 1,...,n$, with amplitudes $a_i$, respectively, the normalized sum shall be less than one

$$\sum_{i=1}^{n} \left( \frac{|a_i|}{r(f_i)} \right) \leq 1$$

where $r(f_i)$ is the requirement from the single sine sweep curve at frequency $f_i$

• Range of travel shall be at least $\pm 3960 \mu$rad (local) with 20% margin

• The steering mirror size dictated by

- 1.33 meter aperture
- 33x magnification
- 20% margin

shall be at least 1.9 x 2.7 inches elliptical
Structural/Mechanical/Dynamics Modeling
A conceptual structural model of the 2 μm LAWS instrument assembly, which conforms to the design parameters derived in the 2 μm LAWS System Study, was developed to serve as the basis for a simplified dynamics model. The instrument model was integrated with a modification of existing spacecraft structural dynamics model for TRW's UAB 940 bus.

The structural model for the LAWS instrument was developed using ARIES computer-aided design tool. Individual elements were modeled as solids with appropriate densities assigned. The use of the ARIES tool provided automated calculation of mass properties and center-of-gravity (c.g.) locations for individual elements and/or assemblies.

As shown in the figure, the major sub-assemblies of the instrument mechanical system are:

- The primary and secondary mirrors with the metering structure
- The telescope support structure
- The bearing and power transfer assembly (BATPA) with detorator and transfer optics bench
- The instrument support structure
2 μm LAWS Instrument Assembly

ALIGNMENT LED
SECONDARY MIRROR & SUPPORT CYLINDER
METERING STRUCTURE (3 STRUTS)
TELESCOPE SUPPORT ASSEMBLY
PRIMARY OPTIC (1.33 X 1.33 METERS)
INSTRUMENT SUPPORT ASSEMBLY
LASER TRANSMITTER & RECEIVER ASSEMBLY
BAPTA & DE-ROTATER ASSEMBLY
were estimated from data in the GE Phase I final report.

For the Barta detector and the optical bench with associated components, weights and mass distributions

estimated weight. This permitted a reasonably accurate calculation of the inertia values.

storing the results in the GE Phase I final report. A detailed drawing was assembled in our mirror model to yield the

For the primary mirror, which is a complex, highly lightweight structure, the total weight was estimated by

optical bench in the laser assembly.

The complete Barta with the scanning elements are coupled to the laser transmitter and receiver assembly via

interfacing from the structure to the laser assembly is a 2-point attachment directly from the structure to the

the instrument support structure. The interface from the structure to the Barta is a flanged ring and the

steering mirror (FSM), the large angle scan steering mirror (LAFSM) and the short vector sensor.

Barta supports the detector assembly and the optical bench including the image motion compensator laser

support assembly, the primary and secondary mirrors and the melting structure. The stationery part of the

The rotor in the Barta, which is a large diameter follow-sphere, supports the scanning elements—the telescopes

showing the full extent of the telescope support assembly.

This exploded view is a better illustration of the various elements of the instrument mechanical subsystem.

2 ARM LAWS Instrument - Exploded Assembly
2 μm LAWS Instrument - Exploded Assembly

- Secondary Optic & Support Cylinder
- Alignment Leg
- Primary Optic (1.33 x 1.33 Meters)
- Telescope Support Assembly
- DAPA & De-Rotater Assembly
- Laser Transmitter & Receiver Assembly
- Instrument Support Structure
of the assembly. Laser Transmitter and Receiver Assembly
Laser Transmitter and Receiver Assembly

Conceptual structural design based on
- 8.2 J/pulse, two-pulse burst system as defined in 2μm LAWS System Study
- Results of TRW design studies for space-based laser systems
- Manufacturers specifications or existing hardware for breadboard laser systems

Laser transmitter and receiver subsystems mounted on opposite faces of single optical bench
- Total weight of assembly: 87 kg
- External dimensions of assembly: 35.6 x 11.3 x 8.3 inches
This design greatly reduces loads on the instrument due to thermal distortions of the spacecraft. It does not web into the 940 mm central tube in the spacecraft extending from the instrument support structure. The launch loads are transmitted from the props via shear. A primary mechanical interface with the spacecraft was designed which consists of three bipod struts.

The LAWS Instrument is shown in the Launch Configuration on the TRW VAB-490 spacecraft bus placed on a Delta Launch Vehicle with a 110 inch LD Launch.
2 µm LAWS Launch Configuration

2 µm LAWS instrument mounted on a TRW UAB-940 bus can be accommodated mechanically on a Delta launch vehicle.
The size and material properties of structural members were also provided. These members were resized to

mass moment of inertia about three axes for individual elements as shown in the graph.

The output from the mechanical design task was provided for the payload dynamics model which was merged

2-1m LAWS Instrument Mass Properties
### LAWS Instrument Mass Properties

<table>
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<tr>
<th>Component</th>
<th>Mass Lbₘ</th>
<th>kg</th>
<th>x (in)</th>
<th>y (in)</th>
<th>z (in)</th>
<th>Iₓ</th>
<th>Iᵧ</th>
<th>I₂</th>
<th>Lbₘ-in²</th>
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<td>150</td>
<td>68</td>
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<td>40</td>
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<td>10</td>
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<td>NA</td>
<td>NA</td>
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<td><strong>Total System</strong></td>
<td><strong>1408</strong></td>
<td><strong>640</strong></td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td></td>
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</table>

* Origin is on spin axis at level of spacecraft interface
Two 1 kW Foker solar array wings are mounted onto the spectractor bus oriented along the +Y and -Y axes. The optical bench about the Z axis is also allowed to rotate about the Z axis. Detector rotations relative to modes of the spectractor are allowed through the BAPT/A. Detector rotations are transferred optics of the spectractor as well as to mount the payload (through the BAPT/A) to the spectractor bus. Scan alignment source, the BAPT/A, and a support structure. The support structure is used to align and hold the spectractor assembly in an LED housing. The payload platform is comprised of primary and secondary mirrors. A laser/lightspecifier array is mounted on the platform."
2 μm LAWS System Finite Element Model
then updated to yield the expected modal content of the instrument system. Initial sizes for all structural members were scaled from available conceptual level drawings. These sizes were

were tuned to yield first primary dp and all modes near 70 Hz.

mirror is mounted through stiff bars (representing a rigid mirror) and elastic springs. The elastic spring elements

masses and rotational inertias. Whereas the secondary mirror is integral with the mounting tube, the primary

design described previously. The primary mirror and secondary mirror were each modeled as concentrated

A finite element model of the LAW'S instrument assembly was constructed from the conceptual structural

LAW'S Payload Finite Element Model
LAWS Payload Finite Element Model

Secondary Mirror

Primary Mirror

Interface to Spacecraft Bus
body modes are obtained with the first flexible mode near 300 Hz.

Estimated from BARTA drawings and previous experience, the BARTA model included, rigid
steel, the aluminum and the beam. The beam was treated as a steel spring. The estimated weight of the BARTA was 495 lbs. The CG is an estimated to be on the symmetry axes 17.5 inches from the payload interface.

The beam, radial, axial and moment stiffness are modeled. The beams (displaced from the beam interface) are represented by spring elements that join the DO to the OD. The bearings (deformed from the beam interface) are represented by spring elements that join the DO to the OD. The bearings are modeled following guidelines for bearings in the BARTA data. The stiffness of the bearings is 12.894 and the effective stiffness of the bearings is 12.894 in the BARTA. The stiffness of the bearings is 12.894 in the effective stiffness of the beam. The stiffness of the beam is 12.894 in the effective stiffness of the BARTA. The model is composed of 296 nodes and 228 structural elements. The 228 structural elements are used to represent the structural parts of the BARTA. The model is built using a NASTRAN static analysis. The model is:

"Bearing and Power Transfer Assembly (BARTA) Model"
Bearing and Power Transfer Assembly (BAPTA) Model

BAPTA model including derotator and transfer optics bench constructed based on
- Drawings included in the GE Phase I and Phase II final reports
- TRW experience with similar units

BAPTA NASTRAN FEM model description
- 259 node, 228 shell elements
- Bearings represented using CELAS2 elements and MPCs
- Housings and shafts are assumed to be titanium
- Optical bench assumed to be aluminum
- Non-structural masses (bearings, resolvers, motors, etc.) simulated by increasing density of neighboring shell elements
Assumptions concerning race curvature, contact angle and preload for the bearing are: outer and inner race curvature are 0.555 and 0.557, respectively. The contact angle is 20° and the preload is assumed to be 60 lb.

Deterioration Bearing

If the part was determined as above, a cadet bearing matching the scaled dimensions of the deteriorator bearing was located. The estimated weight and stiffness of the bearing were evaluated and stiffnesses were assigned based on intermediate value. A load for the inner and outer races, respectively. A contact angle of 20° was assumed. Preloads of 60 lb and 600 lb were used for the inner and outer races, respectively. To estimate the stiffnesses of the races, contact angle and race curvature. A load of 60 lb was assigned to the inner race and a load of 600 lb was assigned to the outer race. Estimated by calculating the volume of material in the bearing and balls and multiplying by the density of steel. The weight and stiffness of the bearing was matched to this bearing. No caliper beam was found that matched the standards.

Scan Bearing

The dimensions of the scan and deteriorator bearings were scaled from a drawing of the deteriorator in the CAD database to match the CAD image generated from the scan.

Estimated Characteristics of BAFTA Bearings
## Estimated Characteristics of BAPTA Bearings

<table>
<thead>
<tr>
<th></th>
<th>Scan Bearing</th>
<th>Derotator Bearing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Estimated dimensions/characteristics</strong></td>
<td><strong>Estimated dimensions/characteristics</strong></td>
<td><strong>Estimated dimensions/characteristics</strong></td>
</tr>
<tr>
<td>OD: 16.0 in</td>
<td>OD: 10.5 in</td>
<td>ID: 9.0 in</td>
</tr>
<tr>
<td>ID: 13.1 in</td>
<td>ID: 9.0 in</td>
<td>Pitch diameter: 9.75 in</td>
</tr>
<tr>
<td>Pitch diameter: 14.6 in</td>
<td>Pitch diameter: 9.75 in</td>
<td>Ball row separation: 0.75 in</td>
</tr>
<tr>
<td>Ball row separation: 10.275 in</td>
<td>Ball row separation: 0.75 in</td>
<td>Ball diameter: 0.375 in</td>
</tr>
<tr>
<td>Ball diameter: 0.875 in</td>
<td>Ball diameter: 0.375 in</td>
<td>Number of balls: 62</td>
</tr>
<tr>
<td>Number of balls: 40</td>
<td>Number of balls: 62</td>
<td>Weight: 13 lb (for the pair)</td>
</tr>
<tr>
<td>Weight: 40 lb (for the pair)</td>
<td>Weight: 40 lb (for the pair)</td>
<td></td>
</tr>
<tr>
<td><strong>Stiffnesses</strong></td>
<td><strong>Stiffnesses</strong></td>
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</tr>
<tr>
<td>Axial: 1.0 x 10^6 lb/in</td>
<td>Axial: 0.67 x 10^6 lb/in</td>
<td>Axial: 0.67 x 10^6 lb/in</td>
</tr>
<tr>
<td>Radial: 3.6 x 10^6 lb/in</td>
<td>Radial: 2.36 x 10^6 lb/in</td>
<td>Radial: 2.36 x 10^6 lb/in</td>
</tr>
<tr>
<td>Moment: 190 x 10^6 lb-in/rad</td>
<td>Moment: 11.4 x 10^6 lb-in/rad</td>
<td>Moment: 11.4 x 10^6 lb-in/rad</td>
</tr>
</tbody>
</table>
actual BAPTA

Bearing preload's number of balls, etc. The calculated compliance values could vary as much as 150% from the

Since the model is based on scaled dimensions and several assumptions (materials for housing and shafts,

one exception is that some coupling between radial loads and bending exists, as would be expected.

In order to determine the compliance of the BAPTA unit, load centered on the axis was applied to the payload.

BAPTA Compliance Matrix
BAPTA Compliance Matrix

Estimated compliances between the spacecraft interface and payload interface

- \( x \) = axial direction
- Terms less than \( 10^{-12} \) set to zero
- Bearings are assumed to be free to rotate

<table>
<thead>
<tr>
<th>( d_x ) (in)</th>
<th>( d_y ) (in)</th>
<th>( d_z ) (in)</th>
<th>( \text{Rot}_x ) (rad)</th>
<th>( \text{Rot}_y ) (rad)</th>
<th>( \text{Rot}_z ) (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_x ): 1.0 lb</td>
<td>1.27 E-6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( F_y ): 1.0 lb</td>
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<td>1.34 E-6</td>
<td>0</td>
<td>0</td>
<td>-1.03 E-7</td>
</tr>
<tr>
<td>( F_z ): 1.0 lb</td>
<td>0</td>
<td>0</td>
<td>1.34 E-6</td>
<td>0</td>
<td>1.03 E-7</td>
</tr>
<tr>
<td>( M_x ): 1.0 in-lb</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( M_y ): 1.0 in-lb</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.48 E-8</td>
</tr>
<tr>
<td>( M_z ): 1.0 in-lb</td>
<td>0</td>
<td>-1.03 E-7</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

43
Appendages

Two flexible appendages were used in developing the LAWtS-on-orbit system model. The first was a simplified model of a set of Fokker solar arrays and the second was a model of a ground link antenna.

Two 1-kW Fokker solar array wings were determined to be adequate to meet the power requirements of the 2-μm LAWS mission. Each wing weighs 54 lbs and has two panels measuring 126 x 63 inches. The inboard panel is mounted to the spacecraft bus through a 10000-in-lb/rad in the torsional axis and 25000-in-lb/rad in the spacecraft's two orthogonal bending axes. A detailed model of the Fokker array was taken from an existing spacecraft program and used to design a simplified "stick" model. The stick model has identical properties to the detailed model except that it is planar. Out-of-plane bending modes of the solar array, when fixed at the inboard side of the SADA were 0.2 Hz and 0.2 Hz. The first in-plane bending modes at 0.39 Hz and 1.08 Hz.

A simplified model of a space to ground link (SGL) reflector/boom subsystem was taken from TRW's TDRS-7 model and modified for use in the LAWS analysis. The weight of the SGL was scaled down from the TDRS value of 40 lbs to 25 lbs. The scaling was done to reflect the stresses and material changes for the latest TDRS constellation of satellites. The SGL was mounted to the spacecraft bus in a manner such that it can be stowed without interfering with the bus or payload and can deploy into the proper orientation to establish the ground link. Rotational stiffness values of the biaxial drive unit were taken directly from the TDRS-7 model and were 540400 in-lb/rad, 358000 in-lb/rad, and 250000 in-lb/rad about the scan, elevation and bending axes (X, Y, and Z axes, respectively).
Appendages

Two flexible appendages incorporated into the LAWS on-orbit system model
• A pair of solar array wings (two 1 kW arrays)
• A space to ground link (SGL) communication antenna
Key LAWS Finite Element Model Points

The LAWS finite element model was reduced to modal space using all 112 modes below 100 Hz. Only key points with the LAWS system were used for the open and closed loop jitter simulation to reduce the size and runtime of the simulation.

The points that were retained in the jitter model include all the optical elements, the points where disturbances are to be injected and other points of interest. The vector summarizes the key points that were retained and their locations on the spacecraft.
## Key LAWS Finite Element Model Points

<table>
<thead>
<tr>
<th>Grid Number</th>
<th>Description</th>
<th>Location (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>1001</td>
<td>Separation plane</td>
<td>0.0</td>
</tr>
<tr>
<td>1005</td>
<td>Fuel tank CG</td>
<td>0.0</td>
</tr>
<tr>
<td>2283</td>
<td>RWA assembly</td>
<td>-16.1</td>
</tr>
<tr>
<td>17021</td>
<td>Inboard +Y SADA point</td>
<td>0.0</td>
</tr>
<tr>
<td>19021</td>
<td>Inboard -Y SADA point</td>
<td>0.0</td>
</tr>
<tr>
<td>31001</td>
<td>Outboard +Y SADA point</td>
<td>0.0</td>
</tr>
<tr>
<td>32001</td>
<td>Outboard -Y SADA point</td>
<td>0.0</td>
</tr>
<tr>
<td>46013</td>
<td>Outboard SGL BiAx drive point</td>
<td>-51.8</td>
</tr>
<tr>
<td>56007</td>
<td>Inboard SGL BiAx drive point</td>
<td>-51.8</td>
</tr>
<tr>
<td>60000</td>
<td>Secondary mirror</td>
<td>0.0</td>
</tr>
<tr>
<td>61000</td>
<td>Primary mirror</td>
<td>0.0</td>
</tr>
<tr>
<td>60042</td>
<td>LED assembly</td>
<td>0.0</td>
</tr>
<tr>
<td>60399</td>
<td>Telescope side of BAPTA</td>
<td>0.0</td>
</tr>
<tr>
<td>65199</td>
<td>Spacecraft side of BAPTA</td>
<td>0.0</td>
</tr>
<tr>
<td>70097</td>
<td>Telescope side of BAPTA</td>
<td>0.0</td>
</tr>
<tr>
<td>70100</td>
<td>Spacecraft side of BAPTA</td>
<td>0.0</td>
</tr>
<tr>
<td>70201</td>
<td>Derotator</td>
<td>0.0</td>
</tr>
<tr>
<td>70260</td>
<td>Optical bench of BAPTA</td>
<td>0.0</td>
</tr>
</tbody>
</table>
The complete system model was found to be free from grounding when run in the free-free (i.e., on-orbit) condition. Eigenvalue extraction runs yielded eight rigid body modes for the complete system, one for the payload scan relative to the spacecraft and one for the detector scan relative to the optical bench. The first payload scan relative to the spacecraft, and one for the detector scan relative to the optical bench. The first payload scan relative to the spacecraft, and one for the detector scan relative to the optical bench.

The inertial properties shown in the table inferal properties shown in the table. The resulting LAWS system was used for the on-orbit jitter and stability analysis. The resulting LAWS system model has the inertial properties shown in the table. The inertial properties shown in the table. The resulting LAWS system was used for the on-orbit jitter and stability analysis. The resulting LAWS system model has the inertial properties shown in the table. The resulting LAWS system was used for the on-orbit jitter and stability analysis. The resulting LAWS system model has the inertial properties shown in the table. The resulting LAWS system was used for the on-orbit jitter and stability analysis. The resulting LAWS system model has the inertial properties shown in the table. The resulting LAWS system was used for the on-orbit jitter and stability analysis. The resulting LAWS system model has the

<table>
<thead>
<tr>
<th>2 Jm LAWS System Inertial Properties</th>
<th>9.963</th>
<th>1.935</th>
<th>1.436</th>
<th>1.787</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inertial Matrix (lbs-in)</strong></td>
<td>9.963</td>
<td>1.935</td>
<td>1.436</td>
<td>1.787</td>
</tr>
<tr>
<td>CG Location (in)</td>
<td>X = 0.53</td>
<td>Y = 0.43</td>
<td>Z = 0.75</td>
<td>56.18</td>
</tr>
<tr>
<td>Weight (lbs)</td>
<td>2 Jm LAWS System Inertial Properties</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Jitter and Stability Analysis
### Selected Mode Descriptions

<table>
<thead>
<tr>
<th>Mode Number</th>
<th>Frequency (Hz)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-6</td>
<td>0.0</td>
<td>System rigid body modes</td>
</tr>
<tr>
<td>8</td>
<td>0.00</td>
<td>BAPTA rigid body modes</td>
</tr>
<tr>
<td>9</td>
<td>0.33</td>
<td>Solar array out-of-plane bending (Sym)</td>
</tr>
<tr>
<td>10</td>
<td>0.42</td>
<td>Solar array out-of-plane bending (Asym)</td>
</tr>
<tr>
<td>11</td>
<td>0.59</td>
<td>Solar array in-plane bending (Sym)</td>
</tr>
<tr>
<td>12</td>
<td>1.20</td>
<td>Solar array in-plane bending (Asym)</td>
</tr>
<tr>
<td>13</td>
<td>1.83</td>
<td>Solar array out-of-plane bending (Sym)</td>
</tr>
<tr>
<td>14</td>
<td>1.85</td>
<td>Solar array out-of-plane bending (Asym)</td>
</tr>
<tr>
<td>15</td>
<td>2.09</td>
<td>Solar array torsion (Sym)</td>
</tr>
<tr>
<td>16</td>
<td>2.41</td>
<td>Solar array torsion (Asym)</td>
</tr>
<tr>
<td>17</td>
<td>5.31</td>
<td>Solar array out-of-plane bending</td>
</tr>
<tr>
<td>18</td>
<td>5.32</td>
<td>Solar array out-of-plane bending</td>
</tr>
<tr>
<td>19</td>
<td>6.87</td>
<td>Solar array torsion</td>
</tr>
<tr>
<td>20</td>
<td>6.87</td>
<td>Solar array torsion</td>
</tr>
<tr>
<td>21</td>
<td>8.65</td>
<td>Solar array in-plane bending</td>
</tr>
<tr>
<td>22</td>
<td>8.75</td>
<td>Solar array in-plane bending</td>
</tr>
<tr>
<td>23</td>
<td>8.89</td>
<td>Solar array torsion</td>
</tr>
<tr>
<td>24</td>
<td>8.89</td>
<td>Solar array torsion</td>
</tr>
<tr>
<td>25</td>
<td>11.2</td>
<td>Solar array out-of-plane bending</td>
</tr>
<tr>
<td>26</td>
<td>11.2</td>
<td>Solar array out-of-plane bending</td>
</tr>
<tr>
<td>27</td>
<td>11.9</td>
<td>SGL Y bending</td>
</tr>
<tr>
<td>28</td>
<td>12.9</td>
<td>SGL Z bending</td>
</tr>
<tr>
<td>29</td>
<td>13.6</td>
<td>Payload Y bending</td>
</tr>
<tr>
<td>30</td>
<td>14.7</td>
<td>Payload X bending, SGL mode</td>
</tr>
<tr>
<td>31</td>
<td>15.7</td>
<td>SGL torsion</td>
</tr>
<tr>
<td>32</td>
<td>16.6</td>
<td>Metering truss mode</td>
</tr>
</tbody>
</table>
...
Strain Energy Analysis and Passive Damping Treatment

"Problem modes" identified in control loop studies examined via strain energy analysis

Two principal modes of concern

• Solar array out-of-plane bending modes near 0.4 Hz
  - Addition of passive joint damper to Solar Array Drive Assembly (SADA) reduced effects of mode

• Telescope support structure and metering truss modes near 8.3 and 10.8 Hz
  - Addition of passive damping deemed not as effective as increasing structural stiffness
  - Stiffening of both the telescope support structure and metering trusses shifted mode frequencies to 13.6 and 14.7 Hz where their effect was reduced by the control loop blending filters
Optical Sensitivities
(This page intentionally blank)
• All local-element coordinate systems are parallel to one of the above, with origin located appropriately.

axes. All local-element coordinate systems are parallel to one of the above, with origin located appropriately.

reference. The second system is obtained from the first by rotating the satellites' solid-angle about the satellite X-axis. The second system is obtained from the first by rotating the satellite about the Z-axis.

With respect to motion of the local elements, the satellite is inclined at an angle of 45° relative to the satellite X-axis. These are basically two coordinate systems which include the satellite's velocity of the transceiver and receive beam definitions with change. Since the telescopic is centered at 45° relative to the satellite Z-axis, these are basically two coordinate systems which include the satellite's velocity of the transceiver and receive beam definitions with change.

The angle, this is discussed on the following pages...

Coordinate Frame Definition
Coordinate Frame Definition

Two basic coordinate frames are used within which mechanical motion will be given

- Spacecraft frame with origin at the separation plane
- Primary Mirror (PM) frame with origin at the vertex of the PM
- All other mechanical coordinate frames are parallel to one of the above with origin translated appropriately to the optical element or group of optical elements

Spacecraft frame with origin translated to vertex of PM, O_p

Boresight in YZ-plane for NASTRAN model
Off-nominal transmit and receive deflections are defined relative to the zero strain energy transmit and receive
trials. The nominal transmit direction leads the telescope axis, and the nominal receive direction lags the
telescope axis. The lead and lag angles are

\[
\text{lead/lag angle} = \text{slant range/}(\text{scan } \cos 45^\circ) \approx 0.132 \text{ degrees}
\]

TRW has a program for integrating the time-domain dynamics of two flexible bodies moving through large angles
relative to each other. For this study, however, the scan motion was not modeled to facilitate the required
control loop and strain energy studies.
Transmit and Receive Reference Frames

$S_t = \{X_t, Y_t, Z_t\}$ = transmit (or point ahead) reference

$S_r = \{X_r, Y_r, Z_r\}$ = receive reference

Zero strain energy condition

- Transmit pulse sent in direction $Z_t$ and return pulse (echo) received in direction $Z_r$
The relay optics consist of relay mirrors, the LED, the secondary mirror, the relay optics in the PAPTA, the transmission/receiver assembly, and the optical sensitivities (discussed in the next vignette) are computed for the major optical elements, the primary deflections along X and Y correspond to rotations about the X and Y axes, respectively.

The transmit and receive pointing errors are defined relative to the zero strain energy reference frames as shown.
Definition of Transmit & Receive Pointing Errors

Motion of optical elements in transmit path will cause an equivalent (zero strain energy) deflection of transmit pulse as defined relative to reference $S_t$

Similarly, motion of optical elements in receive path will cause error at receiver equivalent to a return pulse error as defined relative to the reference $S_r$
PM rotational optical sensitivity is then 2 θʃ/θϕ [local rotation] equivalent to returning the stem energy to zero and moving the Far-Field source by 2θ about the same axis. The per inch displacement physical displacement divided by local length. The displacement sensitivities are therefore 15.7 mm (Far-Field) perpendicular to the PM symmetry axes, as indicated by the bolded boxes in the table below. The primary mirror (PM) optical sensitivities are non-zero only for rotations about and displacements

Primary Mirror Optical Sensitivity Coefficients
Primary Mirror Optical Sensitivity Coefficients

$S_p$ denotes reference frame $\{X_p, Y_p, Z_p\}$ with origin at the vertex of primary mirror.

Rotations and deflections of the primary mirror in $S_p$ will cause deflections of the incoming beam at the entrance aperture of the optical bench.

Optical sensitivity coefficients are defined by equivalent far-field deflections about $X_t$, $Y_t$ axes (and the $X_r, Y_r$ axes) divided by the motion of the primary mirror.

PM Optical Sensitivity Coefficients

<table>
<thead>
<tr>
<th>$\theta_x$ Sensitivity</th>
<th>$\partial \theta_x/\partial x_p$</th>
<th>$\partial \theta_x/\partial y_p$</th>
<th>$\partial \theta_x/\partial z_p$</th>
<th>$\partial \theta_x/\partial \theta_{px}$</th>
<th>$\partial \theta_x/\partial \theta_{py}$</th>
<th>$\partial \theta_x/\partial \theta_{pz}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_y$ Sensitivity</td>
<td>$\partial \theta_y/\partial x_p$</td>
<td>$\partial \theta_y/\partial y_p$</td>
<td>$\partial \theta_y/\partial z_p$</td>
<td>$\partial \theta_y/\partial \theta_{px}$</td>
<td>$\partial \theta_y/\partial \theta_{py}$</td>
<td>$\partial \theta_y/\partial \theta_{pz}$</td>
</tr>
</tbody>
</table>

Coefficients in dark border are the only non-zero coefficients for the primary mirror.
Disturbance Models
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A receiver in a typical application is connected to a transmitter. The transmitter emits a signal, which is received by the receiver. The receiver converts the received signal into a usable format. The process involves the following steps:

1. **Signal Reception**: The receiver detects the incoming signal. This signal is usually an RF signal, which is then converted into an electrical signal.

2. **Signal Processing**: The electrical signal is then processed to extract useful information. This involves filtering, amplification, and demodulation steps.

3. **Decoding**: The processed signal is decoded to recover the original data or information transmitted by the transmitter.

4. **Output**: The decoded information is then output as required by the application, which could be a digital signal, audio, video, or any other form of data.

The frequency of the signal transmitted by the transmitter and received by the receiver is crucial. If the frequencies do not match, the receiver will not be able to accurately detect the signal. The receiver must be able to adjust its frequency to match the transmitter's frequency to ensure successful communication.

In the context of an LED-based system, the receiver may need to adjust its sensitivity based on the power level of the transmitted signal. This is particularly important in environments with significant noise or interference, where the receiver must be able to distinguish the desired signal from other sources.

**Example Calculation**: Consider a scenario where the receiver needs to determine the voltage across a resistor in the circuit. If the voltage across a resistor is known, the current flowing through it can be calculated. The formula for this is:

\[ V = IR \]

Where:
- \( V \) is the voltage across the resistor,
- \( I \) is the current flowing through the resistor,
- \( R \) is the resistance of the resistor.

This equation is fundamental in understanding how electrical signals are transmitted and received in various systems.
Receiver Jitter Control

PM Reaction Structure

Bore sight Reference
ADS (inertial)

LED Source
(relative)

SM Control

SM Truss

SOLAR ARRAY

Satellite Bus
- IRU
- Star Trackers

Scan Drive

shut Vector Sensor

Hartman WFS

Optical Bench

Bore sight Sensor

LAFSM

Payload support structure

\[ k_0 = \text{solar array stiffness} \]
\[ k_1 = \text{SM metering truss stiffness} \]
\[ k_2 = \text{stiffness of Bore sight Reference - PM interface} \]
\[ k_3 = \text{BAPTA / Payload support interface stiffness} \]
\[ k_4 = \text{Payload support to satellite bus isolation} \]
\[ k_5 = \text{Optical bench to BAPTA interface stiffness} \]
\[ k_6 = \text{PM support stiffness} \]
\[ k_7 = \text{Xmtr/Revr box to payload support stiffness} \]

Stiffness Relations:

\[ k_0 < k_1 < k_2 < k_4 < k_3 < k_5 < k_6 \]

ADS: Angular Displacement Sensor
Reaction Wheel Loop

The reaction wheel loop is designed for the modified Thrust No. 82 (5000 rpm). This reaction wheel is currently needed to maintain the spacecraft's attitude by providing torques in the three-axis control mode. The loop is based on a simplified model of the spacecraft's reaction wheel system. The loop's control algorithm is designed to stabilize the spacecraft's attitude by adjusting the reaction wheel's torque output in response to attitude errors.

The loop consists of several key components:

1. **Reaction Wheel Assembly (RWA):** This component contains the reaction wheel itself, which is mounted on a gimbal mechanism that allows it to rotate in three axes.
2. **Electronic Control Unit (ECU):** This unit receives commands from the spacecraft's main body computer and generates control signals for the reaction wheel.
3. **Gimbal Mechanism:** The gimbal mechanism allows the reaction wheel to rotate in three axes, providing torque in any direction as needed.
4. **Power and Cooling System:** This system provides the necessary power to the reaction wheel and its electronics, as well as cooling to prevent overheating.

The loop's control algorithm is designed to ensure that the reaction wheel's torque output is proportional to the attitude error, allowing the spacecraft to maintain its desired orientation. The algorithm takes into account the reaction wheel's dynamics, such as its inertia and friction, to accurately calculate the required torque for each axis.

The loop is also equipped with sensors to monitor the reaction wheel's performance, including its speed and position, and to provide feedback to the controller. This feedback is used to adjust the reaction wheel's torque output in real-time, ensuring that the spacecraft's attitude is maintained accurately.

The reaction wheel loop is a critical component of the spacecraft's attitude control system, providing the necessary torque to maintain the spacecraft's orientation in space. The loop's design and implementation are carefully considered to ensure that it can operate reliably over the spacecraft's mission duration.
Reaction Wheel Loop

Reaction wheel loop definition

Open Loop crossover = 0.2 Hz

Digital Interface

Digital Interface

Reaction Wheel Parameters

<table>
<thead>
<tr>
<th>Mnemonic</th>
<th>Description</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Proportional gain</td>
<td>rad/sec</td>
<td>2.29</td>
</tr>
<tr>
<td>b</td>
<td>Integral gain</td>
<td>rad/sec²</td>
<td>0.654</td>
</tr>
<tr>
<td>qf</td>
<td>Equivalent torque cmd quantization</td>
<td>nt-m</td>
<td>0.001</td>
</tr>
<tr>
<td>lw</td>
<td>Reaction wheel inertia</td>
<td>nt-m-sec²</td>
<td>0.18023</td>
</tr>
<tr>
<td>q</td>
<td>Reaction wheel positional quantization</td>
<td>rad</td>
<td>7.5° x π/180°</td>
</tr>
<tr>
<td>Tₚ</td>
<td>Minor cycle sample period</td>
<td>sec</td>
<td>0.256</td>
</tr>
<tr>
<td>q₀</td>
<td>Tachometer scale factor</td>
<td>rad/cnt·sec</td>
<td>0.511327</td>
</tr>
</tbody>
</table>
The simulation diagram representing the reaction wheel control loop discussed on the previous page is shown here.

Reaction Wheel Loop Simulation Diagram
Reaction Wheel Loop Simulation Diagram

Digital Interface
The derivative of the momentum command derivative of the torque out of the spin motor. The torque noise is computed as the spin motor torque minus the time variation in the estimated momentum which represents the DDC software to cause an eventual variation in the reaction wheel spin speed estimate is plotted against the true spin speed. This estimate causes a similar

\[\text{mom}^2(t) = 125 \text{kg-m}^2 \cdot \text{sec}^{-2}\]

Example is to get the torque noise, a sinusoidal momentum command at a given rate is used. The momentum command for this

The momentum loop open-loop crossover is set at 0.2 Hz for an anticipated satellite main body loop of 0.02 Hz. To

Torque Noise Examples
Torque Noise Examples

Torque noise examples without reaction wheel bearing friction, spin motor time constant, or pulse width modulated (PWM) wheel drive
\[ P(\omega) = \int_{-\infty}^{\infty} S(f) df \]

As a point of clarity, a one-sided PSD \( S(f) \) means

\[ S(f) = \begin{cases} 0.049 \frac{10^{-14}}{\text{Hz}^{-1}} & \text{for } 0.1 \text{ Hz to } 4 \text{ Hz} \\ \frac{3}{2} \left( \frac{1}{f} \right)^{4.4} \exp \left( -2 \frac{\omega}{f} \right) & \text{for } 4 \text{ Hz to } 0.01 \text{ Hz} \end{cases} \]

Assuming a constant PSD level from 0.01 Hz to 4 Hz, allowing the PSD to ramp up 40 dB per decade to 0.1 Hz and fall off 40 dB per decade after 4 Hz, the level \( k \) of the plateau for a one-sided PSD is

\[ k = 0.707 \times 0.1 \times 0.65 = 0.045 \text{ in-lbs} \]

The torque noise \( (\epsilon) \) is maximum frequency is governed by the DBC minor cycle and is approximately 4 Hz. The torque noise \( (\epsilon) \) is

Rejection Wheel Torque Noise
Reaction wheel torque noise frequency content changes as the command momentum changes.
which compares favorably with the time simulation shown on the following graph:

\[
5.9 \times 10^{-2} \text{ field} \quad 9.2 \text{ field}
\]

and

\[
4.3 \times 10^{-2} \text{ field} \quad 6.8 \text{ field}
\]

Thus the expected jitter about the \( x \) and \( y \) axes, respectively, is square root of the damping. Thus the expected jitter about the \( x \) and \( y \) axes, respectively, is square root of the damping. The time simulation used a structural damping of 0.2\% The 10-Hz jitter is inversely proportional to the structural damping. The structural damping is 0.5\% percent. To check the sensitivity, the receiver jitter measured relative to a source in initial space is 4.3\% jitter (10-Hz) for a field about the \( y \)-axes. The \( x \) and \( y \) axes are the receiver axes projected to output space as

\[
\text{Jitter (10-Hz) for a field about the } y\text{-axes.}
\]

The receiver jitter measured relative to a source in initial space is 4.3\% jitter (10-Hz) for a field about the \( y \)-axes and 5.8\% for a field about the \( x \)-axes.

Receiver Open Loop Jitter
Receiver Open Loop Jitter

Estimated receiver open loop jitter relative to a source in inertial space from three orthogonal reaction wheels is less than 6 μrad per axis. Damping in structural model is 0.5 percent.

Level at plateau = 0.049 (in-lb)^2/Hz

Table 1: RMS Rcvr Jitter from 3 RWs

<table>
<thead>
<tr>
<th>Θₓp (μ-rad)</th>
<th>Θᵧp (μ-rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.3</td>
<td>5.8</td>
</tr>
</tbody>
</table>
9.2 x 2sin(1 x 1.2 x 0.005) \text{ft} = 0.32 \text{ft}

6.8 x 2sin(1 x 0.2 x 0.005) \text{ft} = 0.09 \text{ft}

Estimated receiver signals about the X and Y axes, respectively, are

The jitter about the X-axis is primarily at 0.42 Hz and the jitter about the Y-axis is primarily at 1.12 Hz. The

elements.

Slopes calculated by the optical sensitivity integrals against the NASTRAN model slopes at distinct optical

modelled as lumped mass and inertia. In this study, the transmitter and receiver have the same effective

the receiver pulse echo = 5 mm later. The receiver and transmitter are located on the optical bench which was

in a direction, the receiver signal measures the change in the structural bending between the transmit pulse and

Open Loop Receiver Response
Open Loop Receiver Response

Open loop receiver response with all main body loops closed and reaction wheel disturbances acting on satellite. Damping in structural model is 0.2 percent.
The open loop receiver response relative to the transmitted pulse launched 5 msec earlier is shown here.
Open loop receiver response relative to pulse transmitted 5 ms earlier. All main body loops closed and reaction wheel disturbances acting on satellite. Structural damping at 0.2 percent.
between the LED and the BS on the optical bench. The opens loop Bore sight signal is computed by finding a source to the primary mirror at the LED location.
Open Loop Boresight Response

Open loop boresight sensor response with all main body loops closed and reaction wheel disturbances acting on satellite
To check the dominant modes, the structural transmission from the reaction wheel to the receiver:

structural transmission from reaction wheel to receiver
Structural Transmission from Reaction Wheel to Receiver

Transfer functions for reaction wheels to receiver relative to inertial source
The SADAS is a stepper with a 1:1 harmonic drive. The cardinal step is 0.015°. The two SADAS are synchronized to command the open loop fashion every 256 steps. The equivalent drive stiffness in torsion is 100'000 Nm°/rad. The +y SADAS disturbance is modeled as the difference between the continuous ramp and the quenching ramp acting through the drive stiffness on the unloaded structural node. An equal and opposite reaction torque acts on the loaded node. The +y SADAS experiences the same actuation/longitudinal forces.

Fretter arrays:

There is an equivalent size blanket array under preloaded. Thus, there is no thermal snap problem anticipated for the equilibrium configuration to another through a jump discontinuity. The fretter panel array has more thermal mass than an equivalent size blanket array under preloaded. Thus, there is no thermal snap problem anticipated for the.

The only solar array disturbances included in this study originate at the two SADAS. The array is representative of the preloaded blanket array taken from TMY's DFS-FIGURE 7 model. It is our understanding that thermal loading on the fretter panel array taken from TMY's DFS-FIGURE 7 model is.

Solar Array Drive Assembly Induced Disturbances
Solar Array Drive Assembly Induced Disturbances

There are two solar array wings each driven with an independent solar array drive assembly (SADA)

Each SADA is basically a stepper with a 101:1 harmonic drive

The cardinal step is 0.015 degrees

Each SADA is commanded in an open loop fashion based on the satellite and sun ephemerides

The disturbance generated at ±Y SADAs is given by the following

$$K_{\text{sada}} = 100,000 \text{ in-lb/rad}$$

$$q_{\text{pos}} = 0.015 \text{ deg}$$
Directly on the satellite.

Letting the reaction wheel command torques, as computed in the DCE, following the bending-mode filtering act
receive direction (is = 3.5 rad). The responses were estimated by turning off the scan bending disturbances and
orthogonal x-axis is only 4 to 5 mrad. The disturbance response about the Vp direction (orthogonal to the nominal
meas. The solar arrays are gimbaled about the satellite X-axis and the disturbance response about the

The SADA disturbances produce an open-loop inter at the receiver relative to the transmitter LOS delayed = 5

Open Loop Receiver Response to SADA Disturbances
Open Loop Receiver Response to SADA Disturbances

Open loop receiver response to SADA disturbances relative to a transmitted pulse 5 ms earlier

- Estimated in the time domain by taking the command torque from the satellite main body controller after bending mode filtering and allowing it to act on the satellite, thus bypassing the three reaction wheel models.
The estimated bearing test data for a 14-inch BAPTA is shown in the table on the next page.

- Non-repeatability fault: generates random motion
- Radial unbalance: generates slight vibration in the 15th harmonic and additional harmonics
- Misalignment: generates dc and 1st harmonic pointing error

Grouped as:

The scan bearing (BAPTA) mechanism consists of a duplex pair of bearings. To measure the pointing errors introduced by this mechanism, the complete BAPTA, with optical telescope, is placed in a test STARE. The BAPTA

Summary
Nonrepeatable runout generates random bearing noise described by psd.

Repeateable runout: generates fundamental at 12 rpm plus harmonics; can, in part, be calibrated out.

Estimated Bearing Test Data for 14 Inch BAPTA

<table>
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<td>Phase</td>
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<td>dc misalignment component</td>
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<tr>
<td>Tilt</td>
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<td>Misalignment fundamental</td>
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<tr>
<td>Repeatable runout</td>
<td>0.0004&quot; (p-p)</td>
<td>Mechanically non-correctable</td>
<td>6.3 arc sec</td>
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<td>Nonrepeatable (dr/dθ)</td>
<td>0.0001&quot;(p-p)/30° segment</td>
<td>Ball mismatch and race waviness</td>
<td>0.6 arc sec</td>
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interface points. The stiffness between these two nodes corresponds to the stiffness between the two structural nodes. The telescope assembly interface nodes are merged in azimuth to define an equivalent outboard nodes are averaged in azimuth to define an equivalent structural node. Similarly, the telescope model nodes are averaged in plate to define an equivalent satellite structural node. The satellite interface structure at the interface points with action, reaction torque, respectively.

The bearing torque disturbance is computed by taking the spectral representation of the rotational noise about the interface points.
BAPTA Induced Disturbances

Estimated bearing test data assumes BAPTA scan mechanism effectively tied to ground in a test fixture. An autocollimator projects a collimated source toward a flat on the base of the scan motor rotor. The reflected beam tracks twice the bearing error which changes as the rotor is moved in azimuth.

Taking test data to a free-free satellite LAWS payload is accomplished by putting action and reaction torques on the outboard and inboard equivalent nodes in the structural model.

\[
\begin{align*}
\text{Repetable Runout Fourier Representation}^1 \quad & \quad \omega_{\text{scan}}^t \quad \text{k}_{\text{bapta}} \\
\text{Nonrepeatable*} \quad & \quad \text{Runout Stochastic Model}^1
\end{align*}
\]

*Studied in frequency domain

\[ K_{\text{bapta}} = 1.46 \times 10^8 \text{ in-lb/rad} \]
\[ \omega_{\text{scan}} = 2\pi/5 \text{ rad/sec} \]
motion about $\mathbf{r}_p$ is $80$ mrad.

For the first three harmonics in the repeatable runout, the LOS motion about the $X$ axis is $35$ mrad. The LOS motion about $Y$ is $80$ mrad.

Thus, the excitation of the structural mode at $13$ Hz is not present in these time histories. LOS 5 mesh earlier. The SADA and reaction wheel disturbances are set to zero. The random bearing disturbance is subtracted from the transducer.

The open loop receiver jitter is computed by taking the receiver LOS at time $t$ and subtracting the transducer.

Open Loop Receiver Response to B Anita Disturbances
Open Loop Receiver Response to BAPTA Disturbances

Open loop receiver response to BAPTA disturbances relative to a pulse transmitted 5 ms earlier

- Estimated in the time domain by taking the command torque from the satellite main body controller after bending mode filtering and allowing it to act on the satellite, thus bypassing the three reaction wheel models. Only the first three harmonics in the repeatable runout were used.

![Graph showing the response](image-url)
Boresight Jitter and Receive Path Control
Open Loop Time Domain Response
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The approach taken in the time and frequency domain analyses which follow is summarized on the following two pages.

Time and Frequency Domain Analyses
Time and Frequency Domain Analyses

Studies performed in three axes

Studies focus on two distinct aspects of problem

- Performance in lab setting where receiver jitter is measured for a fixed inertial source in the lab
- Performance on orbit where the receiver jitter is actually the difference between the receiver LOS and transmit LOS 5 msec earlier

Frequency Domain studies performed include

- Blending of IRU, ADS, and boresight FSM loop tracking mirror position to estimate LED inertial motion
- Performance with high frequency FSM and LAFSM loops closed
- On-orbit closed loop performance estimated by taking the lab performance estimate against an inertial source and applying weighting function representing the time lag between the transmit and receive pulse times
Time and Frequency Domain Analysis (con't)

Time Domain studies demonstrate

- Open loop receiver jitter for an inertial source (excluding non-common optics) is the sum of the open loop boresight signal and the LED inertial motion

- Consistency between the receiver open loop jitter estimates from the frequency domain and the receiver open loop time histories

Time simulation closes the three main body loops against a flexible representation of the payload and satellite

- Main body open loop crossovers set at 0.02 Hz

- Bending filters taken from the AXAF-I Powered Flight Model provide ample gain and phase margins on all three axes

- Scan and derotator loops closed in structural model using 2.5 Hz and 2.9 Hz stiffness, respectively. The damping for these modes set at 0.707
The main body controller is a PID controller. The proportional loop operates on the rate error. The integral path
represents the weighted position error, and the double integral path represents the weighted integral position.

Including so that bounding performance could be estimated.

symbolically. Also, the bounding filter's not shown, operate on the state x2. The gyro frequency limitation is not

sampled (a zero-order-hold, not shown, follows each sample). The reaction wheel electronics is shown

between the reaction wheel drive electronics and the structural model is represented by the synchronized

The QBC implementation of the main body controller is shown in the block diagram. The digital interface

On-board Computer (OBC) Implementation
Satellite Main Body Controller
The integrated output from a PII controller provides momentum commands to the reaction wheel OBC loops

\[ \Theta_{c} \]

\[ \omega_1 \]

\[ x_{c1} \]

\[ x_{c2} \]

\[ x_{c3} \]

\[ x_{c4} \]

\[ x_{c5} \]

\[ h_p \]

\[ k_r \]

\[ \text{Digital interface} \]

\[ 256 \text{ ms} \]

\[ \text{Symbollic of RW Electronics} \]

\[ \text{Structural Model} \]

\[ \text{tending mode filters inserted at this point in simulation} \]

\[ x_{cj} = j^{th} \text{ state in OBC satellite main body controller} \]
The open loop receiver signal in X is 12 ft and in Y is approximately 36 ft/rd.

LOS motions will produce a shift difference in the LED inertial plus boresight LOS and the receiver-sensed modeling of the detector. Optics in the receive path through the BPTA, which was not included in this study, will produce a signal difference in the boresight sensor signal plus signal. The sum of the two signals shows the boresight sensor signal. The receiver-sensed model shown in the graph is not simplified model.

Performance with actual hardware can be accomplished at minimal cost using an inertial source. The receiver-sensed model shown in the graph is not simplified model.
Performance Against Inertial Source in Lab

Open loop boresight signal minus LED inertial motion matches receiver signals
The estimated on-orbit open loop receiver jitter is approximately 120 nsec in x and 16 nsec in y. The downlink on-orbit jitter is 108 nsec in x and 16 nsec in y. The on-orbit open-loop receiver performance estimate is shown on the graph. It is computed by taking the antenna mounted on a boom out along the x-axis, contributing to the motion about y.

On-orbit Performance
On-Orbit Performance

Receiver open loop performance estimated as receiver LOS at time (t) minus transmitter line of sight at time (t-0.005) seconds. Reaction wheel, SADAs and the BAPTA harmonics (n = 1, 2, 3) modeled. Telescope primary mirror support structure mode at ≈ 13 Hz not excited for this example.
sensor—the bipolariese sensor.

boregirish sensor: the alignment from the optical bench to the LED is measured by the FSM position readout.

The LED motion is the sum of (1) the inertial motion at the IUU, (2) the relative motion between the IUU and the motion about the same axes at the IUU structural node.

The next two paragraphs compare the X (satellite roll) axis and the Y-axis LED inertial motion with the inertia.
X-axis response

Structure near the primary mirror causes difference in inertial motions. Structural path between IRU on main satellite bus and LED mounted on meteoring.

IRU and LED Inertial Motions
The frequency content of the motion at the IRU node projected on the Y_p axis is noticeably different from the LED motion about Y_p. Since the LED is relatively near the ADS, the LED motion over the ADS bandpass can be combined with the optical bench to LED alignment data from the FSM bicapacitive sensor and the IRU data on the satellite bus to estimate the LED motion from dc through the ADS bandpass. Blending filter constants, discussed in the following Steady State Controls Analysis Section can be calibrated by measuring performance against an inertial source.
Fast steering mirror steady state analysis addresses LED motion estimation. ADS provides LED motion above 3 Hz but IRU fails to provide good estimate of LED motion from DC through gyro bandwidth of 15 Hz.
Fast Steering Mirrors

Steady State Controls Analysis
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Single Axis Control Loop Model

The overall fast steering mirror control loops for a single axis are shown here. The top and bottom paths at the final summing node comprise the "open loop" disturbances consisting of the structural motion and the motion of the boresight alignment LED, respectively. The path coming in from the left represents the control action which attempts to null the disturbances.

The design objectives are:

- Compensate structural vibration to 500 Hz using the LED and boresight sensor with the fast steering mirror (FSM) in the image motion compensator loop to less than 0.5 μrad (rms-far field)

- Compensate inertial motion down to DC using blended inertial reference unit (IRU), angular displacement sensor (ADS) and FSM bicapacitive sensor data. Command lag angle fast steering mirror (LAFSM) to center return beam on receiver. Maintain stability and attenuate disturbance to less than 0.5 μrad (rms-far field) within the controller bandwidth

As will be shown, the design objectives are attained with a margin of a factor of approximately 1.5 or a short-term jitter of approximately 0.3 μrad (rms-far field) when the largest expected disturbance sources--the BAPTA or scan bearing noise, the solar array stepping and the spacecraft reaction wheel unbalance and torques--are considered.

Cross coupling of torques applied to the FSM and LAFSM are shown in the diagram. However, these reaction torques are expected to be several orders of magnitude less that those of the above disturbances and, therefore, were neglected in this study.
Single Axis Control Loop Model
The frequency response of a fast steering mirror used in several TRW programs is shown here. The mirror weight, for this application, is estimated to be approximately 4.5 lbs. Note the structural harmonics which appear around 1500 Hz. These limit the performance bandwidth of the mirror. Fast steering mirrors exist which can achieve wider bandwidths, however, the bandwidth of the mirror shown here is adequate for this application.
TRW Fast Steering Mirror Frequency Response
Lag Angle Fast Steering Mirror (LAFSM) Compensation

The LAFSM loop compensation is a straightforward loop design problem. The gain needs to roll off before the structural modes which occur at 1500 Hz. Integral control is used to ensure high open loop gain so that tracking is good at low frequencies.

The loop parameters are:

\[ I = 5.30 \times 10^{-4} \text{ in-lb-sec}^2/\text{rad} \]
\[ D = 15.1 \times 10^{-3} \text{ in-lb-sec/ rad} \]
\[ K = 14.2 \text{ in-lb/ rad} \]
Use Integral (Type I) control for high open loop gain.

Design Goal: Make $K_p$ as small as possible over a 100 Hz band.

LAFSM Compensation

Lag Angle Fast Steering Mirror (LAFSM) Compensation
LAFSM Controller Performance

The LAFSM controller performance is shown on the facing vugraph. The performance parameters are, considering the mirror assembly as a rigid body:

- Controller order = 3
- Gain margin = 7.3 dB
- Phase margin = 55°

The first significant parasitic modes are expected to occur at approximately 1500 Hz.
LAFSM Controller Performance
In the FSM loop compensation design, the loop is closed around the boresight sensor which is assumed to have a 2nd order butterworth response with a corner frequency of 500 Hz.

The loop parameters are:

\[ I = 5.30 \times 10^{-4} \text{ in-lb-sec}^2/\text{rad} \]

\[ D = 15.1 \times 10^{-3} \text{ in-lb-sec/rad} \]

\[ K = 14.2 \text{ in-lb/rad} \]
A Structural Modes

Roll Off Loop Gain Before 1000 Hz To Maintain Stability From Mirror

Design Goals: Make $G_{FSM} \leq 0.01$ As Small As Possible Over Bore Sight Sensor Bandwidth

Note: Optical Sensitivity Ignored For Purposes Of Design

Fast Steering Mirror (FSM) Compensation
The FSM loop controller performance is shown on the facing vugraph. The performance parameters are, considering the mirror assembly as a rigid body:

- Controller order = 5
- Gain margin = 4.1 dB
- Phase margin = 50°

As with the LAFSM, the first significant parasitic modes are expected to occur at approximately 1500 Hz. The FSM is closed about the boresight sensor in contrast to the LAFSM which is closed about the bicapacitive sensors.
FSM Controller Performance
This function represents the greatest relative excursion of a sinusoid at the given frequency within the 5.2 msec round trip time of the laser pulse. The dashed line in the graph is an envelope function given by

\[ E(s) = \frac{2s}{s + \frac{2\pi}{3\Delta t}} \]

which may easily be put in matrix differential form to ease computations of the effective rms errors.
This function may be applied to produce an equivalent reduction of the disturbances at the receiver.

\[ \Delta t_{\text{max}} = 2 \left( \frac{\pi}{\sqrt{2}} \right) \]

Additional consideration:
- Evaluate receiver short-term jitter error spectrum from all disturbances.
- Evaluation of performance.
Angular Displacement Sensor (ADS) & Inertial Reference Unit (IRU) Frequency Responses

The ADS is assumed to have corner frequencies of 3 Hz and 2000 Hz, and the IRU model is assumed to have a corner frequency of 15 Hz. These are assumed characteristics but are typical of these sensors. The design is not particularly dependent the sensor characteristics, except insofar as they can be modeled accurately.
The ADS and IRU are assumed to have the frequency responses shown below.

Angular Displacement Sensor (ADS) & Inertial Reference Unit (IRU)
The scan drive disturbance was assumed to have a flat frequency content distributed between 1.2 and 12 Hz with an rms value of 1.4 μrad and harmonics at multiples of the scan frequency of 0.2 Hz falling off at the index of the harmonics cubed, with an aggregate rms value of 14.5 μrad. These rms values are converted to in-lbs by the stiffness of the BAPTA.

The scan drive disturbance is the most significant jitter error source considered. The PSD shown here is believed to be conservative--the actual bearing disturbances should not exceed the magnitude or the bandwidths shown here.

Slight damping was added to the harmonics to ease the computations of the effective rms disturbances.
BAPTA Scan Drive Torque disturbance Spectrum
Solar Array Drive Assembly (SADA) Drive Torque Disturbance Spectrum

For this disturbance, the solar array drive is assumed to be stepped at 0.015 degree increments to achieve 360° during the orbital period leading to a sawtooth error disturbance with the fundamental harmonic at 4.2 Hz.

Seven harmonics are modeled as significant. Slight damping was added to the harmonics to ease computations of the effective rms disturbances.
The spectrum of the reaction wheel torque disturbances was assumed to be distributed as shown on the facing vugraph.
Reaction Wheel Torque Disturbance Spectrum

\[ \rho(\theta, N) = 0.625 \text{ in-lb} \]
The X-axis structural response at various structural nodes resulting from the X-axis scan bearing disturbance are shown here. The finite element dynamics model includes modes only up to 100 Hz, as evident in the response curves. This, however, is where most of the strain energy is concentrated.

Note that the disturbance at the IRU node is much less observable than the disturbances at the other sensor nodes. This means that, at low frequencies, the IRU is relatively insensitive to LED motions in inertial space. It is necessary to blend boresight sensor data derived from the bicapacitive sensors of the FSM mirror when the loop is closed with the inertial data.
Structural Responses Due to Scan Bearing Disturbances
Inertial sensor data from the spacecraft IRU and the ADS at the boresight sensor source (LED) must be blended with the relative motion data between the LED and the boresight sensor for the FSM loop closure. The blending filter architecture used is shown below.

The boresight sensor/LED ensemble corrects for the relative motion of the structure. In order to correct for the inertial motion, we need to estimate what the LED displacements are. The ADS provides information down to 3 Hz. The IRU provides low frequency information at the IRU location. The FSM mirror position provides the link between the ADS and IRU.

The filter gain may be selected by a variety of methods. An \( \text{H}_\infty \) design technique was initially investigated since it does not constrain the input noise spectrum. The \( \text{H}_\infty \) is best used when significant components of the input noise are localized in frequencies separated from the dominant plant response band.

In this case, however, the dominant error contributor is a plant structural mode at 13 Hz excited by the flat spectral region of the scan bearing disturbance. Consequently, an \( \text{H}_2 \) (Kalman) filter design proved to yield the best performance.
Estimator Design Considerations

The IRU and ADS sensors both provide information that can be unobservable at any of the other sensors. Therefore, the approach used to obtain the estimator was to use these measurements directly, and then to use only the boresight sensor information and the combined IRU plus ADS data to estimate the residual LED motion.

A comparison of the frequency responses for the X-axis scan bearing disturbance for these three sensors and the LED motion to be estimated is shown on this vugraph. A reduced order structural model in which all modes except the dominant 13 Hz payload mode was suppressed was used for the estimator optimization. All the disturbances and the key structural modes were included in the jitter performance analysis.
Disturbance responses used for estimator design and X-axis blending filter optimization

Estimator Design Considerations
The two blending filter responses, $F_1$ for the IRU-ADS sum and $F_2$ for the boresight sensor, are shown below. The filter, $F_1$, blends the IRU and ADS data to produce a smoothly varying response across all frequencies and the filter, $F_2$, acts upon the boresight sensor data to produce an estimate of the structural motion between these two nodes. As desired, the responses fall off above approximately 20 Hz.

All sensor measurements are combined into the same filter design algorithm because any single measurement has non-minimum phase characteristics (right-half plane zeroes) due to the structural model that would limit the performance of any single measurement estimator.

For the filter design, the FSM loop and LAFSM loop were treated as unity gains. As indicated in the control loop diagram at the beginning of this section, the actual quantities used in the filter are then effectively the IRU-ADS sum and boresight sensor data.

The filter design is quite robust. There are no peaks in the responses to create sensitivity.
X-Axis Blending Filter Responses
The X-axis far-field jitter spectrum is shown below with the fast steering mirror loop both open and closed. The open loop jitter is shown by the dashed curve, and the closed loop response is shown by the solid curve. The disturbances about all three of the spacecraft axes (as appropriate) from the scan bearing, the reaction wheels and the solar array stepping are included.

As indicated on the figure, the open loop rms jitter is 2.4 μrad and the residual short-term rms jitter when the FSM loop is closed is ~0.2 μrad.

Open and closed loop X-axis jitter contributions from the three disturbance sources, individually, are shown on subsequent vugraphs.
Single Axis Open & Closed Loop Jitter Spectrum
The dominant X-axis jitter source for the entire system is seen to be the 13 Hz disturbance excited by the scan bearing broad band disturbance about the x-axis. This disturbance is the most significant contributor to the overall jitter. As before, the open loop response is shown by the dashed curves and the closed loop residual jitter is shown by the solid curves. The closed loop residual rms jitter is reduced by approximately an order of magnitude below the open loop response.
Scan Bearing Induced Jitter Contributions

The x and y-axes show open and closed loop x-axis jitter responses due to scan bearing disturbances about...
SADA Induced Jitter Contributions

The open (dashed curve) and closed (solid curve) loop X-axis jitter resulting from solar array-induced disturbances at both the +Y and -Y locations are shown here. On the diagram, the closed loop jitter appears to be worse than the open loop response. At the dominant mode near 13 Hz, the closed loop performance is improved over the open loop, and this is where the major jitter contribution is concentrated. The integrated closed-loop performance is improved over the open-loop performance by approximately a factor of two as indicated by the rms values of about 9 nrad open loop to about 4 nrad closed loop.
Open and closed loop X-axis jitter responses due to SADA-induced disturbances at the +X and -Y locations.
Reaction Wheel Induced Jitter Contributions

As with the previous two vugraphs, the open and closed loop X-axis jitter contributions are shown for disturbances about the X, Y, and Z spacecraft axes. The rms jitter contributions from the reaction wheels are seen to be small compared to the scan bearing disturbances.
Open and closed loop X-axis jitter responses due to reaction wheel disturbances about the X, Y, and Z axes.

Reaction wheel induced jitter contributions
The Y-axis far-field jitter spectrum is shown below with the fast steering mirror loop both open and closed. As on the previous vugraph, the open loop jitter is shown by the dashed curve, and the closed loop response is shown by the solid curve. The disturbances about all three of the spacecraft axes (as appropriate) from the scan bearing, the reaction wheels and the solar array stepping are again included.

The Y-axis jitter, both open and closed loop, is less than the short-term jitter about the X-axis. As indicated on the figure, the open loop rms jitter is $= 0.5 \mu \text{rad}$ and the residual short-term rms jitter when the FSM loop is closed is $= 0.2 \mu \text{rad}$.

The RSS value of the residual rms short-term jitter, then, is $= 0.3 \mu \text{rad}$, meeting the specified jitter requirement for the 2 $\mu \text{m}$ LAWS system.
Single Axis Open & Closed Loop Jitter Spectrum (Y-Axis)
Summary and Conclusions
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Summary & Conclusions

A conceptual, but detailed, structural model of the 2 μm LAWS instrument assembly, which conforms to the design parameters derived in the 2 μm LAWS System Study (6 October 1993), was developed and used to construct a finite element dynamics model. This was merged with an existing dynamics model for a TRW UAB-940 spacecraft and used to investigate the short-term jitter performance of the solid state LAWS payload/spacecraft system in a realistic spacecraft environment.

Disturbance sources included in the analysis were the bearing and power train assembly (BAPTA) or scan bearing noise, spacecraft reaction wheels unbalance and torques, and solar array stepping torques. The scan bearing noise was found to dominate the other disturbances.

A fast steering mirror control loop system was designed to provide for the short-term jitter control and its performance analyzed subjected to the above disturbance environment. The performance analysis shows that the short-term jitter over the 5.2 msec pulse round-trip time can be controlled to within approximately 0.3 μrad rms. This is within the short-term jitter requirement of ≤ 0.5 μrad rms defined in the 2μm LAWS System Study required to yield a S/N loss < 0.3 dB.
Within specified value of \( \pm 0.5 \) r.m.s. to yield S/N loss < 0.3 dB

Short-term jitter performance over 5.2 msec pulse round-trip time \( \approx 0.3 \) r.m.s.

Controls analysis shows that for real-life spacecraft environment

Fast steering mirror control loops designed to compensate for short-term jitter

Scan beam alignment disturbance greatest contributing jitter source

- Solar array drive torques
- Spacecraft reaction wheel torques
- BAPP (scan bearing) noise

Disturbance models derived for

- LAWS payload/AB-940 buss compatible with Delta-class launch vehicle
- Merged with existing TRW UAB-940 spacecraft bus dynamics model

 Implemented

Conceptual structural/dynamics model for 2 nm solid-state LAWS payload defined and

Summary & Conclusions
**REPORT DOCUMENTATION PAGE**

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<td>The objective of the study was to identify and model major sources of short-term pointing jitter for a free-flying, full performance 2um LAWS system and evaluate the impact of the short-term jitter on wind-measurement performance. A fast steering mirror controls system was designed for the short-term jitter compensation. The performance analysis showed that the short-term jitter performance of the controls system over the 5.2 msec round-trip time for a realistic spacecraft environment was &lt; 0.3 μrad, rms, within the specified value of &lt; 0.5 μrad, rms, derived in a 2um LAWS System Study (6 October 1993). Disturbance models were defined for 1) the Bearing and Power Transfer Assembly (BAPTA) scan bearing, 2) the spacecraft reaction wheel torques, and 3) the solar array drive torques. The scan bearing disturbance was found to be the greatest contributing noise source to the jitter performance. Disturbances from the fast steering mirror reaction torques and a boom-mounted cross-link antenna clocking were also considered but were judged to be small compared to the three principal disturbance sources above and were not included in the final controls analysis.</td>
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<th>14. SUBJECT TERMS</th>
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<tr>
<td>Pointing Jitter, Atmospheric Remote Sensing, Laser Wind Sounder</td>
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