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Structural Control Sensors for the CASES GTF

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ABSTRACT: CASES (Controls, Astrophysics and Structures Experiment in Space) is a proposed space experiment to collect x-ray images of the galactic center and solar disk with unprecedented resolution. This requires precision pointing and suppression of vibrations in the long flexible structure that comprises the 32-m x-ray telescope optical bench. Two separate electro-optical sensor systems are provided for the ground test facility (GTF). The Boom Motion Tracker (BMT) measures eigenvector data for post-mission use in system identification. The Tip Displacement Sensor (TDS) measures boom tip position and is used as feedback for the closed-loop control system that stabilizes the boom. Both the BMT and the TDS have met acceptance specifications and were delivered to MSFC in February 1992. This paper describes the sensor concept, the sensor configuration as implemented in the GTF, and the results of characterization and performance testing.

1. CASES GTF DEVELOPMENT

The Controls-Structures Interaction (CSI) Advanced Development Facility (ADF) is under development at Marshall Space Flight Center (MSFC) for the purposes of supporting ground testing of future flight experiments, the investigation of advanced control and system identification methodologies, and structural dynamics studies. The baseline configuration of the facility is that of the Controls, Astrophysics, and Structures Experiment in Space (CASES), a proposed shuttle-based flight experiment that will initiate on-orbit demonstrations of CSI technology. The experiment will provide active control of a 32-m extendible boom structure, using gas thrusters at the tip for pointing and angular momentum exchange devices (AMED) for active damping to suppress vibrations. The boom mechanically links an occulter plate at the boom tip with proportional counters located at the base to comprise an x-ray telescope. The controller goal is to provide accurate alignment of these devices for the purpose of x-ray observation of the galactic center and the Sun. Variations on this proposed experiment include a CASES without the x-ray devices (Controls And Structures Experiment in Space) or a free-flying version launched either by the Shuttle or an expendable booster.

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The CASES ground test facility (GTF) will provide an environment in which advanced control laws, system identification techniques, failure detection and compensation schemes, real-time flight software, and experiment data handling techniques can be verified. Prototypes of sensors, actuators, and flight computers can be functionally verified in the laboratory, as can actual flight hardware. Boom deployment and retraction dynamics, which will require active control, can also be investigated. Rapid reconfiguration capability in the laboratory will allow various flight configurations to be tested and verified, thus reducing development cost, time, and risk.

2. FACILITY DESCRIPTION

The CASES GTF is located in the Load Test Annex high bay in Building 4619 at MSFC. The test article, the boom from the Solar Array Flight Experiment (SAFE) flown in 1984, is suspended vertically from a platform at the 40-m level. The disturbance system, comprised of two electromagnetic shakers, a tripod floated on air bearings, and an annular ring support surface, provides two translational degrees of freedom. A simulated Mission Peculiar Experiment Support Structure (MPESS), suspended from the center of the tripod through the annular ring support, interfaces the disturbance system with the test article to simulate a flight experiment interface with the Shuttle, MPESS, and the payload experiment. The boom supports a simulated occulting plate at the boom tip. The control objective of the flight experiment is to maintain alignment of the tip plate with the detector at the base of the boom on the Shuttle as the occulting plate is pointed towards a star to perform an x-ray experiment. Similarly, the ground experiment will strive to align the tip plate with the simulated detector at the MPESS. Control authority will be provided by the AMEDs for vibration suppression and the bi-directional linear thrusters at the tip. Gravitational effects on the experiment will be processed out. Reference 1 provides a detailed description of the CASES GTF. **See Appendix A for the poster session presentation of this paper.**

The key sensor systems to be used in the GTF are the Boom Motion Tracker (BMT) and the Tip Displacement Sensor (TDS) under development by BECD (Figure 1). The TDS will be used in closed-loop controller experiments as the feedback element, providing information on the precise alignment of the tip plate. The BMT will be used for the identification of boom mode shapes. Initially, the BMT data will be processed post-facto. Future upgrades to the facility will provide the capability to use BMT data real-time in closed-loop control.

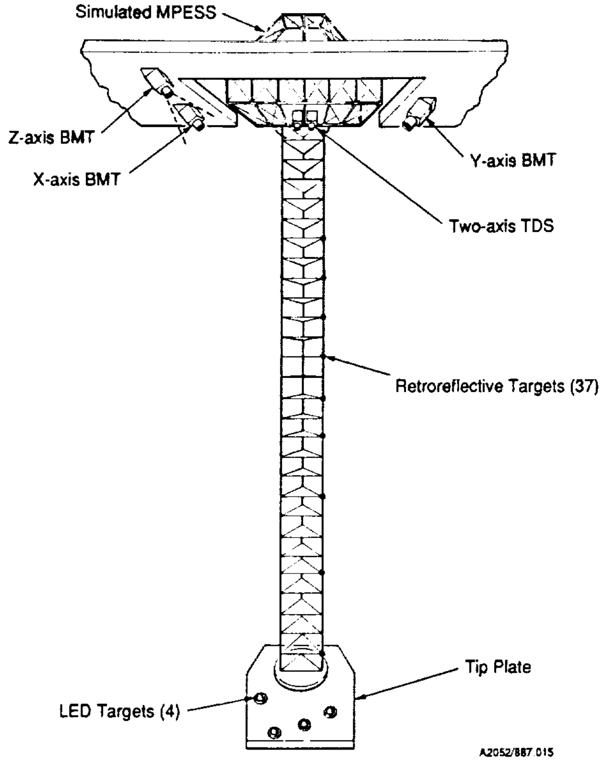

Fig. 1.

3. ROLE OF THE RAMS SENSOR

The Remote Attitude Measurement Sensor (RAMS) was designed by BECD under IR&D to measure dynamic behavior of large, flexible space structures. RAMS provides an unobtrusive sensor with update rates, accuracies, and target capacities which exceed present technology. This capability is needed for both system identification and control feedback applications in space.

In the CASES GTF, the BMT observes and records dynamic behavior of the flexible boom structure. Three single-axis sensors are mounted at the base of the cantilevered boom and each monitors the translational displacements (within its sensitive plane) for 37 reflective targets distributed along the length of the boom. The X and Y sensors are offset equidistant from the base of the boom and oriented such that their sensitive planes are orthogonal to each other. The third (Z) sensor is offset further from the boom but along the same radial line as the X sensor. The increased offset distance improves sensitivity to z-axis motion, which is calculated by subtracting the effect observed by the X sensor. The BMT illuminates and monitors targets at ranges up to 32 m while measuring displacements to accuracies of 0.40 mm for the x and y axes. The Z sensor is less sensitive and measures displacements to an accuracy of 7 mm. Expected target motion for all three sensors is ±25 cm. The BMT updates the position of each target at 100 Hz. Displacement data is output to the CASES control processor in the form of BMT pixel number, with data for all targets multiplexed in digital format.

The TDS provides position feedback for the closed-loop control system that maintains tip position. Two single-axis sensors are mounted near the base of the cantilevered boom and measure 2-axis translational displacements for the four (4) light-emitting diode (LED) active targets. The targets are arranged in a fashion that ensures no overlap of targets in either sensed direction. The TDS observes the four targets at a range of 32.3 m and measures displacements to an accuracy of 0.60 mm. Update rate is selectable between 25 and 500 Hz. Displacement data is output to the CASES control processor in the form of TDS pixel number, with data for each target assigned to a dedicated line and in analog form. A ±10 V change in signal corresponds to a ±25 cm displacement of a TDS target.

4. RAMS IN THE GTF

The RAMS design is derived from proven space sensor technology. The electronic design concepts and interpolation algorithms for RAMS have been demonstrated in space hardware, including the Retroreflector Field Tracker (RFT) that was flown on the Shuttle in 1984 and a variety of Ball-built star trackers. RAMS consists of a simple electro-optical design. It uses a cooperative light source (typically an LED) to illuminate reflective targets within its field of view (FOV). The reflected images are focused onto a linear charge-coupled device (CCD) detector by a cylinder lens to produce a line image. Displacement of a target causes the focused image to shift position on the CCD, giving an accurate indication of the angular displacement. Knowing the range of the target, translational displacement can be calculated.

RAMS (Figure 2) uses a CCD detector with 1 x 2,098 pixels and proprietary BECD interpolation algorithms that permit centroiding of target images to approximately 2% of a pixel. High update rates are achieved by pipeline processing of the CCD data in analog form. RAMS can provide resolution to better than 1:100,000 and update rates of 500 Hz for each of 50+ targets. It uses off-the-shelf, low-cost parts such as Nikon OEM lens, Newport alignment flexures, Kodak CCD detectors and AND brand light-emitting diodes. A detailed description of RAMS and CASES is provided in Reference 2.

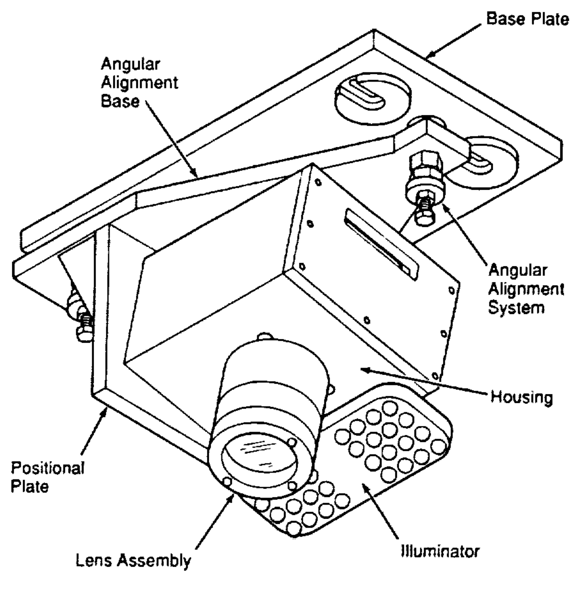

Fig. 2.

4.1 BMT Design

The BMT X and Y sensors are oriented such that their detectors are in the same plane as the boom and tilted at a slope that provides proper focus for every target. (This is guaranteed by the "Scheimpflug" condition.) The required FOV of each sensor (approximately 20 deg) is determined by the viewing geometry (e.g., offset distance from boom, distance to nearest and farthest targets, expected range of motion). The actual FOV exceeds this amount and is based on the detector pixel size, number of pixels, and the focal length of the lens (85 mm). The achievable resolution is determined by the angular subtense of each pixel and the degree to which subpixel interpolation can be achieved. Target distance varies from 3.6 m to 31.3 m. The major design challenges for the BMT are achieving the desired image shape and sufficient optical return signal from the farthest target. These considerations are influenced by the radiometric characteristics of the illuminator and by the size, shape, and retroreflective properties of the target material.

The BMT targets are made from 3M-brand Model 2000X retroreflective tape. This high-gain material contains microscopic corner cubes laminated beneath a protective film. The targets are diamond-shaped, as viewed by each sensor, and sized to subtend a specified angle within the FOV. Thus, target size will vary with range, but image width will remain constant. This condition is necessary in order to maintain precision in the interpolation algorithms. Incident light on this tape material is retroreflected with a luminance factor of 3000 and primarily within a 1.1 deg conical beam (full angle). The targets are illuminated by an array of 36 LEDs mounted on each sensor head. The illuminators must be positioned near the optical axis of the sensor because of the retroreflective nature of the targets. Most of the LEDs are aimed at the farthest target. The quasi-Gaussian illuminator beam pattern provides an appropriate amount of radiance on the mid-range targets. Some LEDs are also tilted towards the upper targets to illuminate them. Each LED is rated at 13 candelas and has a beam divergence of approximately 4 deg.

The sensor head is comprised of a thick-walled aluminum box on which a lens assembly is mounted (Figure 3). The lens assembly includes the off-the-shelf Nikon camera lens which is fitted with a cylinder lens to provide line images and a wide-band filter to reduce background illumination. The CCD detector, preamplifier circuitry, and detector mounting hardware are installed within the sensor head. Proper orientation and positioning of the detector with respect to the lens is crucial to accurate measurement of target position. The Kodak KLI-2103 CCD detector has 2,098 pixels, each 14 x 14 μm in size. This detector was selected for its low noise characteristics, high responsivity, and uniformity of photo-response between adjacent pixels. Data is transferred at rates exceeding 1 MHz and handed off to a separate electronics box containing the analog and digital processing circuitry. The analog pipeline processor detects the presence of targets, interpolates the position of each to within 2% of a pixel, and tags the data with a target number. This analog data is converted to digital form and multiplexed prior to output. The BMT data interface is a 32-bit parallel data word which is read by the CASES control computer upon generation of a strobe by the BMT.

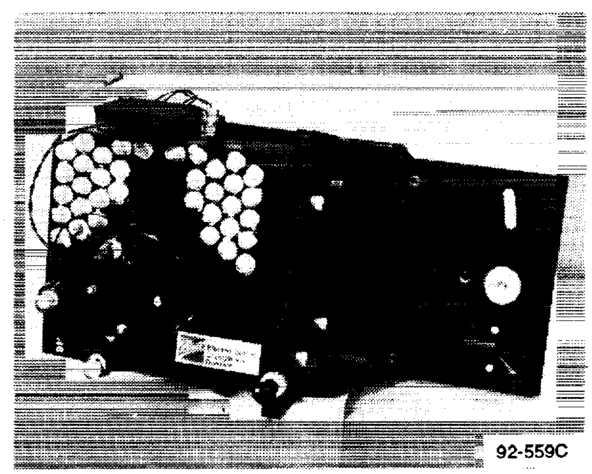

Fig. 3

4.2 TDS Design

The TDS sensors are mounted orthogonal to each other and observe the four (4) LED targets mounted on the upper surface of the tip plate. Using the known locations and unique pattern of the targets with respect to the tip plate, the motion of the tip plate reference point (i.e., target centroid) can be monitored. The required FOV of each TDS sensor (2.3 deg) is determined by the target range, target spacing, and the maximum expected motions of ±25 cm. The actual FOV (5 deg) is larger than necessary because of the intentional use of common detectors for both the TDS and the BMT. The FOV would actually be larger (approximately 15 deg) except that 70% of the pixels have been electronically disabled to preclude the detection of extraneous images (false targets). The major design challenges for the TDS are high update rate, target range and high resolution. The use of active (LED) targets rather than passive (retroreflector) targets improves the radiometric performance significantly and allows the shorter integration times needed for higher update rates. The four TDS targets consist of individual LEDs fitted with an adjustable spherical lens that expands the illumination beam to 15 deg (Figure 4). Beam divergence is based on the angular offset with respect to the sensor head plus an expected tilt of the tip plate of ±5 deg.

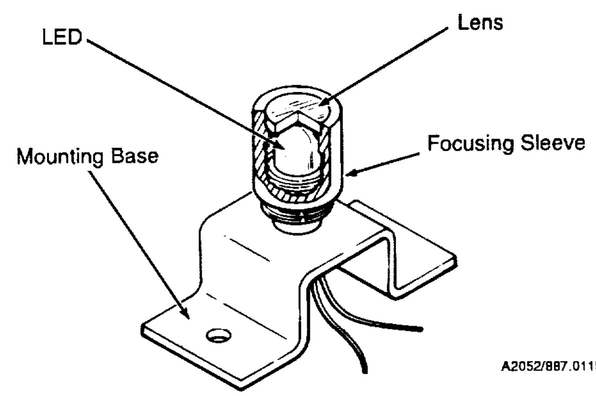

Fig. 4.

The TDS sensor head is identical to the BMT sensor, with two minor exceptions. There are no illuminators on the TDS sensor because active targets are used (Figure 5). The detector mounting block holds the detector normal to the optical axis (rather than tilted) because the targets are equidistant in range and require the same image distances. The TDS uses eight dedicated analog circuits to transmit analog position data for each of the four targets measured by each of the two sensor heads. Each target has a unique offset voltage at its stationary position, such that maximum resolution can be gained from the ±10 V range of the analog output.

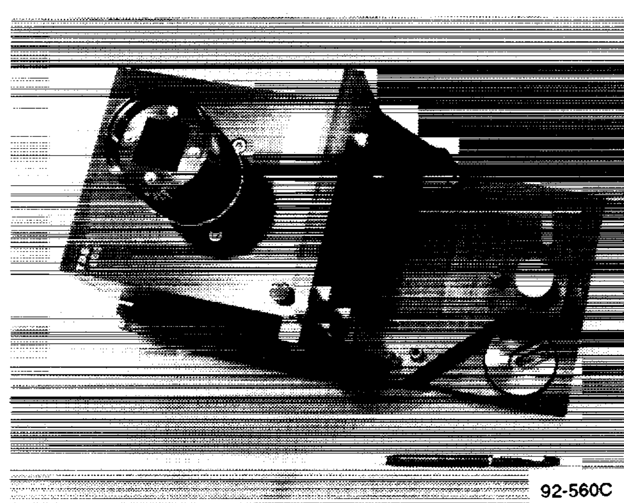

Fig. 5.

5. CURRENT STATUS

The BMT and TDS systems were delivered to MSFC in February 1992, following extensive testing and acceptance at BECD earlier that month. Both systems performed exceptionally well and satisfied MSFC's specifications for accuracy, update rate, translation range, number of targets, and system weight. Power consumption was the only area that exceeded specification limits, and this was due in part to the addition of LED illuminators and larger power supplies.

Characterization testing of the BMT and TDS illuminators demonstrated ample margins for both radiance and beam angle (Figure 6). Further improvements in the uniformity of the radiation patterns can be achieved by exploiting the characteristic double-hump shape of the LED beam and overlapping the peaks and valleys of adjacent beams.

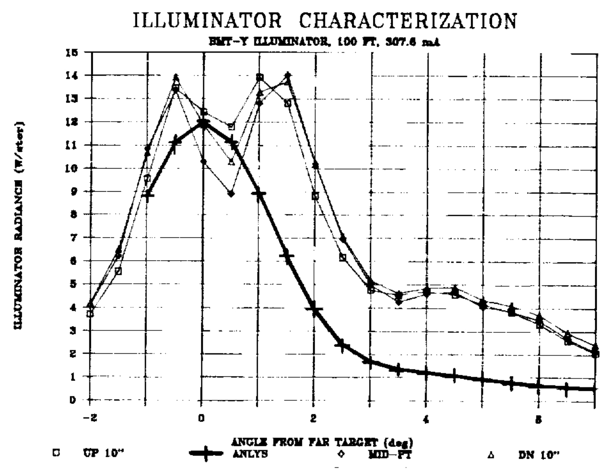

Fig. 6.

Characterization testing of the BMT sensors demonstrated concurrent focus for all 37 targets (as dictated by the "Scheimpflug" condition) and the required image quality for successful implementation of the interpolation algorithms. High signal-to-noise ratio was achieved (Figure 7), which is directly related to low noise-equivalent-displacement and the attainment of high accuracy. A high degree of sub-pixel linearity was achieved (approximately one percent), which is essential for high accuracy performance (Figure 8). Field of view margins were as high as 100%, signifying good coverage by both the optical elements and the illumination beams.

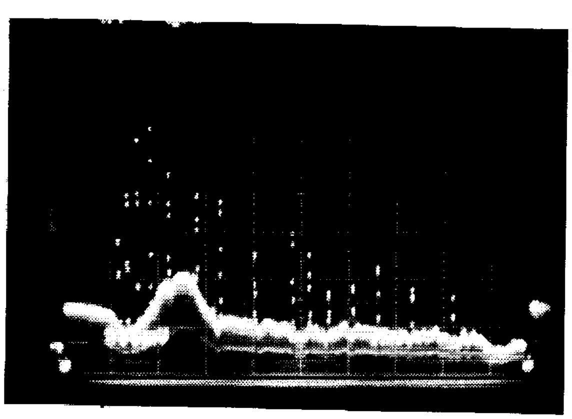

Fig. 7

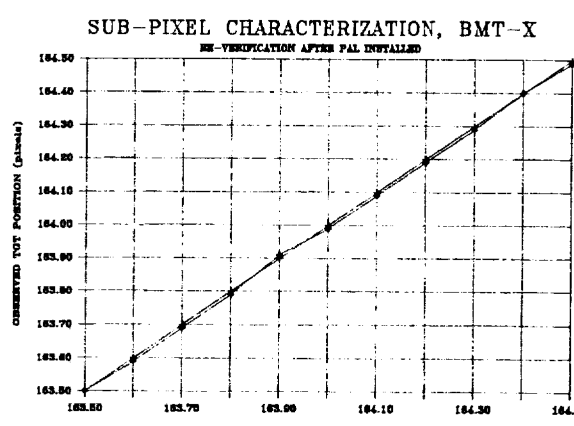

Fig. 8.

The results of the acceptance tests are shown in Table I for both the BMT and the TDS.

TABLE I
TEST RESULTS

PARAMETER	BMT	TDS
Accuracy: Translation	< 0.015 in. @ 102 ft (X,Y)	< 0.024 in. @ 105 ft
Angular	< 2.5 arcsec (X,Y)	< 3.9 arcsec
Translation	< 0.27 in. @ 102 ft (Z)	
Field of View	20 deg by 4 deg	5 deg by 5 deg
Update Rate	100 Hz	25 Hz to 500 Hz (10 selectable steps)

At the time of publication of this paper, the BMT and TDS systems had not been integrated into the CASES facility at MSFC. The performance of both systems in a dynamic environment will be demonstrated and reported in a future technical paper.

References:

1. Jones, V.L., Bukley, A.P. and Patterson, A.F., "NASA/MSFC Large Space Structures Ground Test Facility," Proc. AIAA Guidance & Control Conf., New Orleans, LA, August 1991.
2. Davis, H.W., Sharkey, J.P., and Carrington, C.K., "Structural Control Sensors for Control, Astrophysics, and Structures Experiment in Space (CASES)," Advances in Optical Structure Systems, Volume 1303, Proc. SPIE, Orlando, FL, April 1990.

APPENDIX A:

Structural Control Sensors for the CASES GTF

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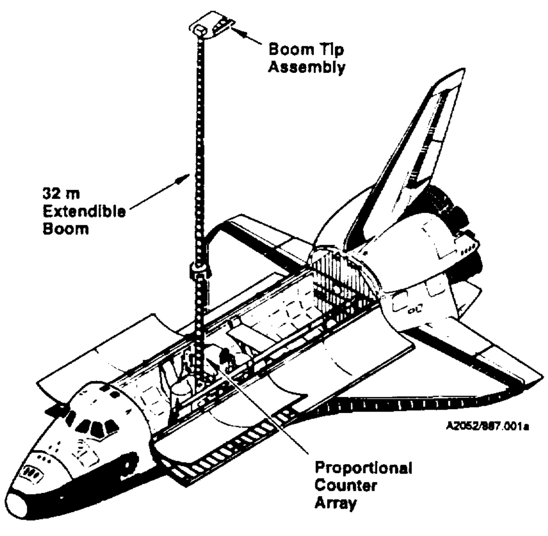
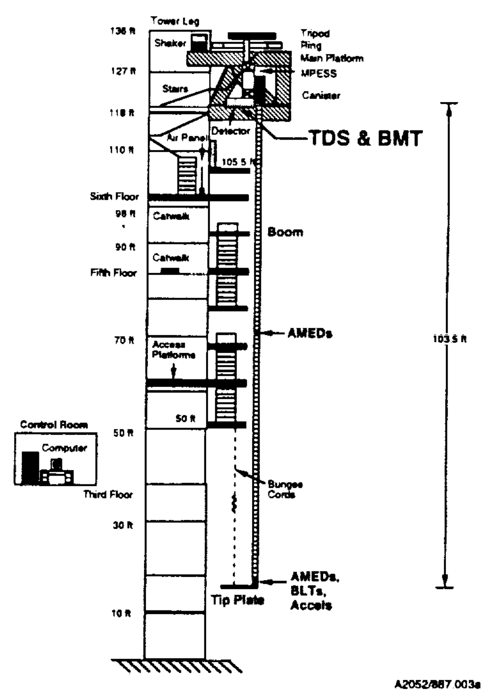
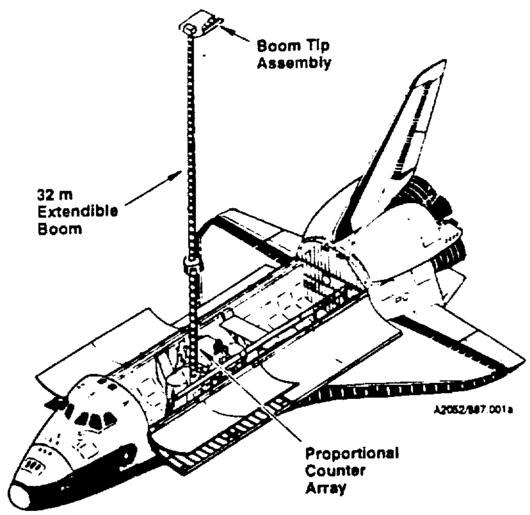


CASES Flight Experiment



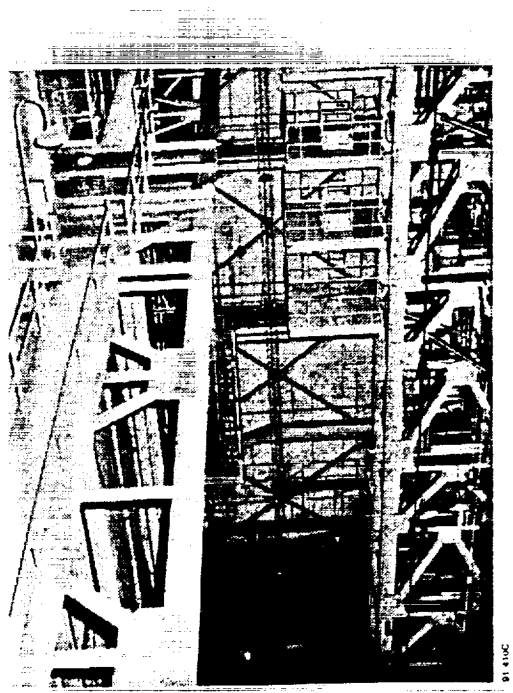
CASES Ground Test Facility (GTF)

CASES
(Controls, Astrophysics, and Structures Experiment in Space)



CASES Flight Experiment

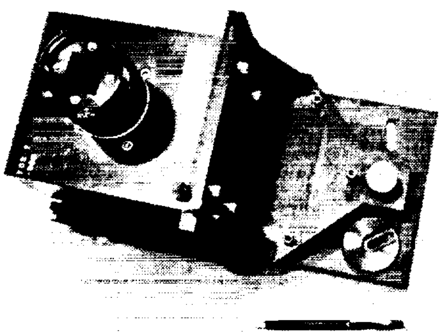
- CASES is a proposed space experiment to conduct x-ray science and CSI research
- The science portion provides x-ray imaging of the galactic center and the Sun with unprecedented resolution
- Requires precision pointing and suppression of vibrations in the x-ray telescope comprised of a 32-m flexible boom, an occulter plate at the tip, and proportional counters at the base
- The CSI mission provides stabilization for precise telescope pointing plus an on-orbit testbed for demonstrating alternative control methods
- Variations under consideration include a free-flyer version or a CASES without the x-ray devices



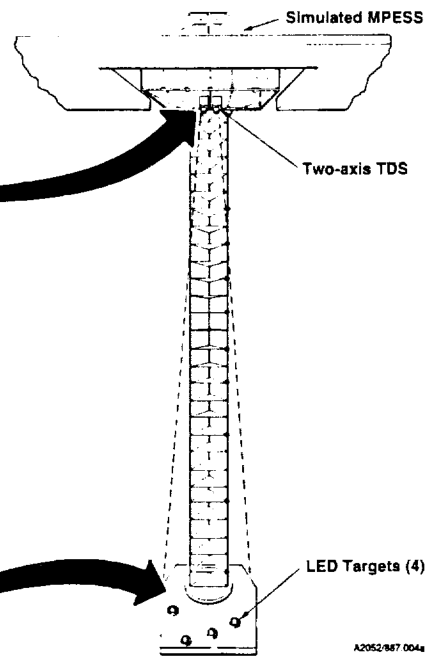
CASES Ground Test Facility (GTF)

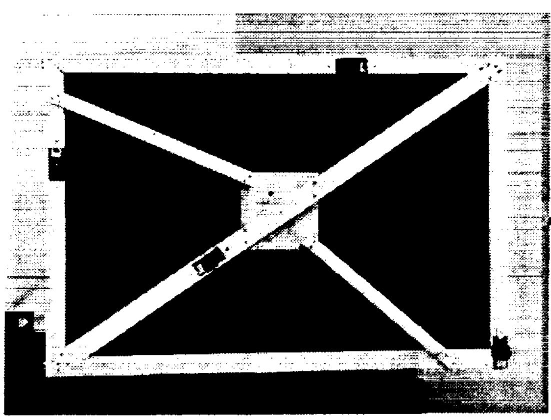
- GTF baseline configuration is modelled after the CASES flight experiment
- GTF development will support verification and validation of flight hardware and software:
  - Advanced control laws
  - System identification techniques
  - Failure detection/compensation
  - Real-time flight software
  - Experiment data handling methods
  - Prototype sensors and actuators
  - Prototype flight computers
  - Actual flight hardware
- Structural dynamics investigations planned:
  - Modal behavior of the boom
  - Boom deployment/retraction
  - Disturbance characteristics and effects

Tip Displacement Sensor (TDS)

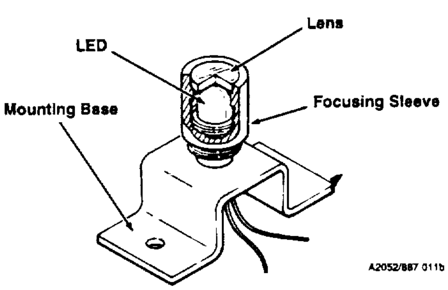


TDS Sensor Head





Test Fixture With TDS Illuminators (Targets)

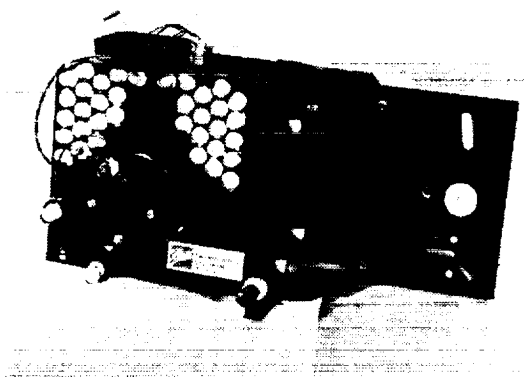


TDS Illuminator/Target

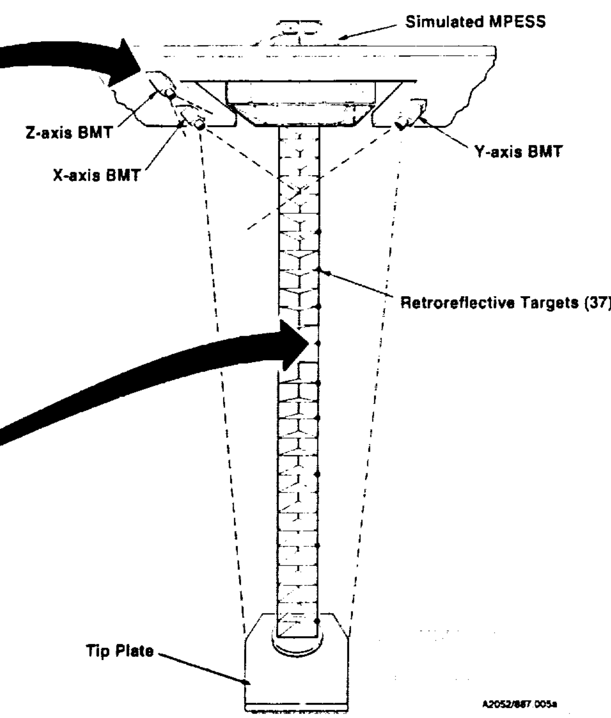
- Illuminator/Target:
  - Four (4) separate active targets
  - Each uses one HP 15-candela LED
  - Adjustable lens expands LED beam to 15 deg

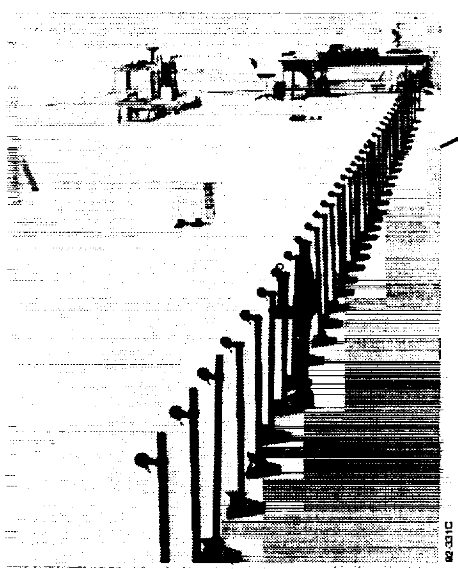
- Two single-axis electro-optical sensors mounted at the base of the boom
- TDS sensors view 4 active (LED) targets on the tip plate (32.3 m range)
- TDS sensors measure motions in two orthogonal directions (X, Y) to an accuracy of 0.60 mm
- Update rate for target position is selectable between 25 and 500 Hz
- Data output in analog form (±10 V) on eight (8) dedicated circuits to the CASES control computer
- System Characteristics:
  - Field of view: 2.3 deg (required)
  - Target range: 32.3 m
  - Update rate: 25 to 500 Hz (selectable)
- Sensor Head Description:
  - Nikon 105 mm f/2.5 lens
  - Cylindrical lens: -425 mm
  - Same detector and filter as BMT design
  - Detector is mounted normal to optical axis

Boom Motion Tracker (BMT)



BMT Sensor Head





Test Array of Retroreflective Targets

- System Characteristics:
  - Field of view: 20 deg (Approx.)
  - Target range: 3.6 to 31.3 m
  - Update rate: 100 Hz

- Sensor Head Description:
  - Nikon 85 mm f/1.8 lens (X,Y sensor)
  - Nikon 70 mm f/1.8 lens (Z sensor)
  - Kodak KLI-2103 CCD detector (tilted)
  - Cylindrical lens: -425 mm (X/Y)
-300 mm (Z)
  - Long pass glass filter (0.59 to 3 μm)

- Three single-axis electro-optical sensors mounted at the base of the boom and offset by approximately 1 meter

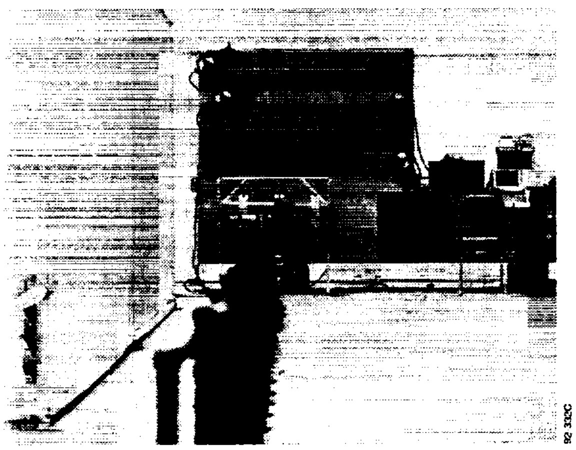
- BMT sensors view 37 retroreflective tape targets distributed along the length of the boom

- BMT measures 3-axis translational motions (X,Y,Z) to an accuracy of 0.40 mm (7 mm for Z axis)

- Update rate for each target is 100 Hz

- Output data is multiplexed for all 37 targets and all three sensors; output is in digital form

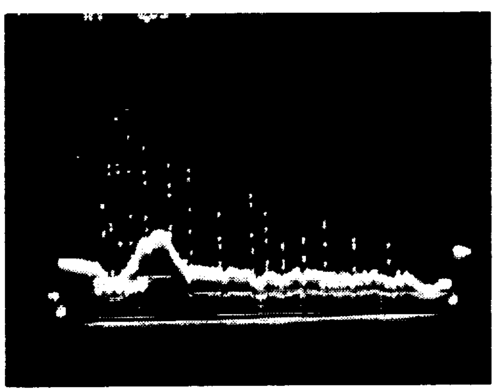
Verification Methods & Results



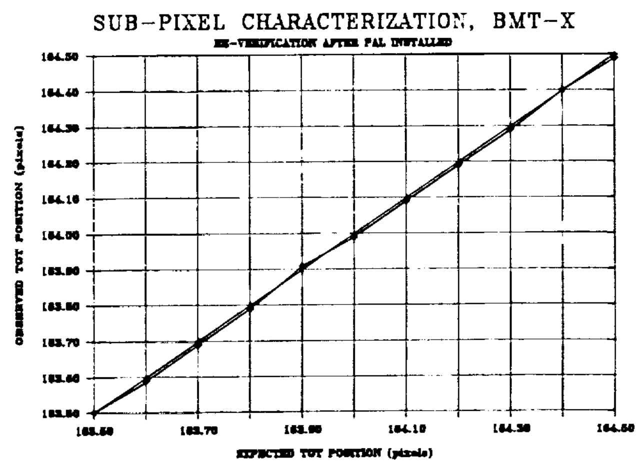
ADF RAMS Test Facility

Test Results

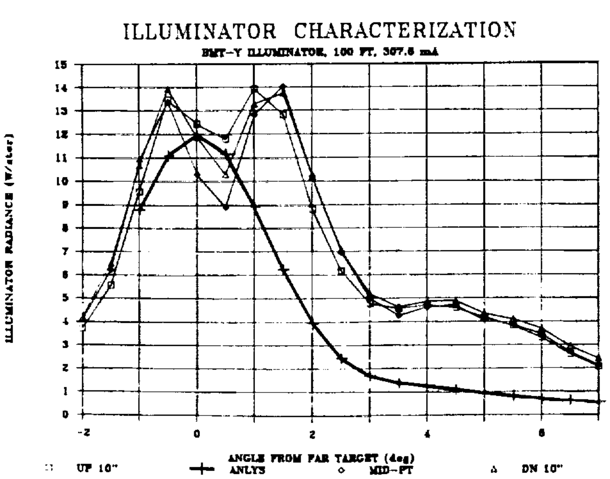
- BMT Accuracy:
  - X and Y Sensors: <0.015 in. @ 102 ft
  - Z Sensor: <0.270 in. @ 102 ft
- BMT FOV: 20 deg x 4 deg
- BMT Update Rate: 100 Hz
- TDS Accuracy: <0.024 in. @ 105 ft
- TDS FOV: 5 deg x 5 deg
- TDS Update Rate: 25 Hz to 500 Hz



Oscilloscope Picture of BMT X-sensor Showing 15 Targets



Demonstrated *high degree of linearity* across a pixel



Photometer measurements of the BMT illuminator showed *good agreement* with predictions