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A Revolute Joint with Linear Load-Displacement Response for a Deployable Lidar Telescope

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Abstract

NASA Langley Research Center is developing concepts for an advanced spacecraft, called LidarTechSat, to demonstrate key structures and mechanisms technologies necessary to deploy a segmented telescope reflector. Achieving micron-accuracy deployment requires significant advancements in deployment mechanism design, such as the revolute joint presented herein. The joint exhibits load-cycling response that is essentially linear with less than 2% hysteresis, and the joint rotates with less than 7 mN-m (1 in-oz) of resistance. A prototype reflector metering truss incorporating the joint exhibits only a few microns of kinematic error under repeated deployment and impulse loading. No other mechanically deployable structure found in the literature has been demonstrated to be this kinematically accurate.

Introduction

A continuing challenge for spacecraft designers and technology developers is to reduce significantly the cost of spacecraft and science instruments while increasing their performance. Recently, NASA's Office of Space Access and Technology initiated the development of a series of advanced sensor spacecraft, or "sensorcraft," which will be substantially cheaper than previous-generation science spacecraft because of aggressive use of advanced sensor and spacecraft technology. One of these sensorcraft is Lidar Technology Satellite (LidarTechSat), an Earth-observing sensorcraft for demonstrating advanced technologies in structures, mechanisms, materials, and electronics, while measuring upper atmospheric clouds and aerosols. Various concepts, one of which is shown in Figure 1, for LidarTechSat are being developed at the NASA Langley Research Center.

Lidar (light detection and ranging) is an active, remote-sensing technique first demonstrated in space on NASA Langley's Lidar In-space Technology Experiment, flown aboard the Space Shuttle in 1994 [1]. A typical lidar instrument includes a laser, which transmits laser light pulses into the atmosphere, and a telescope, which receives the reflected light from atmospheric constituents. Most lidar-science measurements are based on a comparison of the intensities of transmitted and reflected light. Thus, unlike an imaging telescope which must focus light coherently, a lidar telescope must only produce an incoherent focus. Hence, a lidar telescope can be less dimensionally accurate than an imaging telescope, thereby demanding micron-precision rather than sub-micron-precision.

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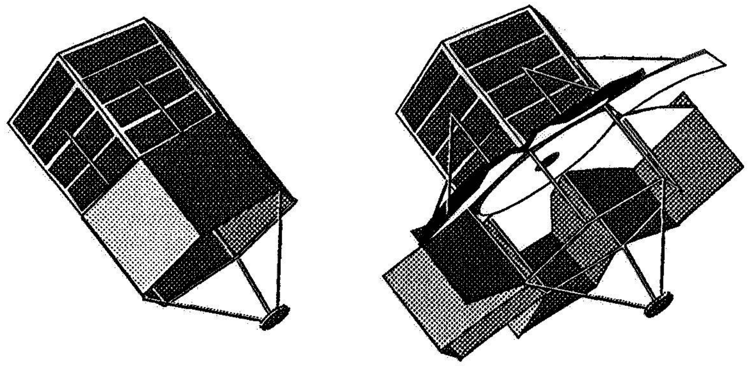


Telescope packaged

Telescope deployed
(sun shroud partially removed)

Figure 1. LidarTechSat Sensorcraft Concept.

One of the key structures and mechanisms technologies being considered for LidarTechSat is micron-precision deployment of a segmented primary reflector for the lidar telescope. The mission-science benefit of precision deployment is that, for a given launch shroud diameter, an increase in telescope aperture through deployment increases the gain (i.e., sensitivity) of the instrument. Hence, deployment allows a given instrument aperture to be packaged within a smaller and less expensive launch vehicle, thus reducing mission cost for the same science return. Cost reduction through precision deployment is a desirable technology-development objective for application to many future science missions in addition to LidarTechSat.

The LidarTechSat primary reflector will consist of multiple reflector segments that must be precisely positioned using a deployable metering truss. Nonlinearities in present state-of-the-practice deployment mechanisms limit the accuracy of deployable metering trusses to approximately 100 microns [2]. Although this accuracy provides adequate reflector-panel-positioning control for low-frequency (≤ 20 GHz) communication antennas, it is unacceptable for high-frequency (≥ 100 GHz) science instruments. The LidarTechSat laser operates at a visible-light frequency of 564 THz, which requires a few microns of accuracy in the telescope primary reflector. Improving metering-truss-deployment accuracy by two orders of magnitude requires significant advancements to be made in the design of precision deployment mechanisms and the understanding of sub-micron structural mechanics of these mechanisms.

The revolute (i.e., hinged) joint described herein has been developed at NASA Langley Research Center for the LidarTechSat deployable telescope metering truss, but it has significant potential for application in many precision deployable structures[1]. The objectives of this paper are to (1) discuss the nonlinear structural response of conventional revolute joint designs and explain how these nonlinearities affect deployment accuracy; (2) describe the features designed to eliminate nonlinearities in

[1] Invention Disclosure Case No. LAR 15300-1 has been filed with the NASA Langley Patent Counsel.

the LidarTechSat metering truss revolute joint; and (3) present test results for individual joints, as well as a prototype-metering truss incorporating multiple joints.

Background

Structural Response of Conventional Revolute Joints. Revolute joints are necessary in all deployable structures to allow the folding and unfolding of components. Conventional revolute joints involve a tang which rotates around a clearance-fit pin and clevis assembly. As shown in Figure 2, the pin-clevis assembly surrounds the tang, resulting in a geometry that is symmetric about two perpendicular planes passing through the center of the joint: one plane is perpendicular to the pin axis, and the other plane contains the pin axis. This symmetry ensures that the joint will not bend as axial tension and compression loads are applied and places the pin in a state of double shear, thereby increasing the joint stiffness and strength.

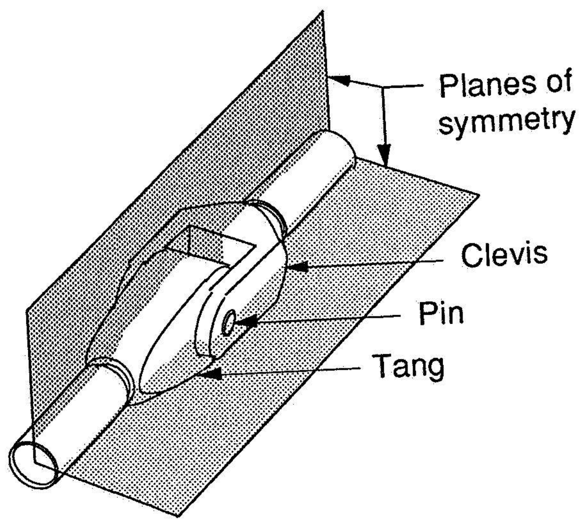


Figure 2. Conventional Pin-Clevis Revolute Joint.

Under tension-compression load cycling, conventional pin-clevis joints exhibit four types of nonlinear load-displacement response (Figure 3): (a) freeplay due to clearance fit between the pin and the tang; (b) changes in stiffness due to the nonlinear, clearance-fit boundary condition of the pin; (c) bi-linearity, or unequal tension and compression stiffnesses, associated with different tension and compression load paths through the clevis and tang; and (d) hysteresis due to friction between the joint components. Numerous studies [3-6] have shown it to be essentially impossible to predict nonlinear joint response analytically. Current mathematical models of nonlinear joint phenomena involve numerous empirical parameters whose values may change significantly with changing test conditions.

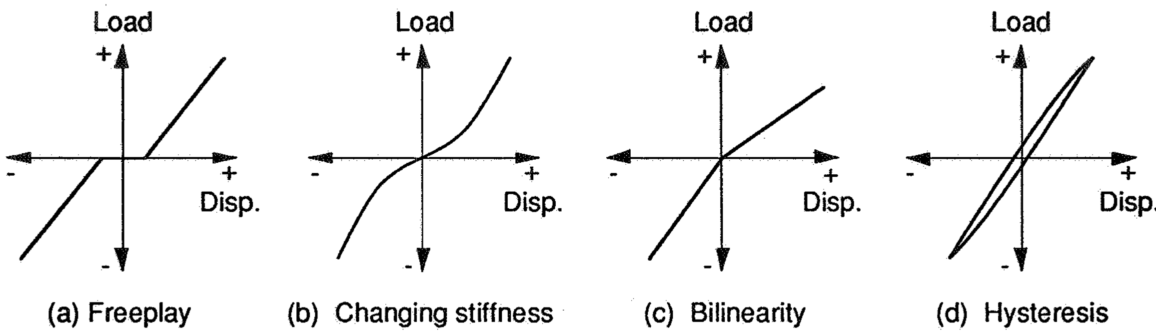


Figure 3. Nonlinear Load-Displacement Response of Conventional Pin-Clevis Revolute Joints.

Effect of Joint Nonlinearities on the Accuracy of a Deployable Reflector. In addition to introducing uncertainty in the response of a structure, nonlinearities in deployable joints can be a source of dimensional errors in the deployed structure. For example, a deployable structure with freeplay in its joints can be displaced within the freeplay deadband with minimal force. Hence, the geometric accuracy of a deployable structure is limited by the freeplay present in its joints. In a subsequent section, data are presented that indicate hysteresis within joints can also lead to dimensional errors in the deployed structure.

Dimensional errors in the deployed structure caused by joint freeplay and hysteresis are defined herein as “kinematic errors.” Kinematic errors represent a subset of all errors which define the structure's “absolute accuracy,” (i.e., the deviation from the theoretical shape). Other error types are strain-induced (mechanical, thermal, and hygroscopic) and fabrication errors. If necessary, fabrication errors (and some quasi-static strain-induced errors) can be accommodated by using a variety of quasi-static or “updating” shape-adjustment techniques. In addition, dynamic strain-induced errors can be accommodated by using a variety of active shape-control techniques. However, kinematic errors are difficult to accommodate if they involve freeplay [7]. In fact, studies have shown that freeplay-induced kinematic errors can only be compensated for by using load-carrying active devices which “artificially” stiffen the joints where freeplay is present, thereby essentially eliminating the freeplay [8].

For any segmented reflector, the primary function of the metering truss is to maintain the positional accuracy of the reflector panels. Non-deployable metering trusses, such as the ground-based Keck telescope metering truss [9], exhibit no significant kinematic errors due to the absence of deployment mechanisms. Therefore, as depicted in Figure 4(a), non-deployable metering truss dimensional errors that exceed the reflector-panel positioning requirement can be accommodated by updating- or active-control systems. However, as depicted in Figure 4(b), dimensional errors in deployable metering trusses can only be offset if the reflector-panel position requirement is not exceeded by the freeplay-induced kinematic errors.

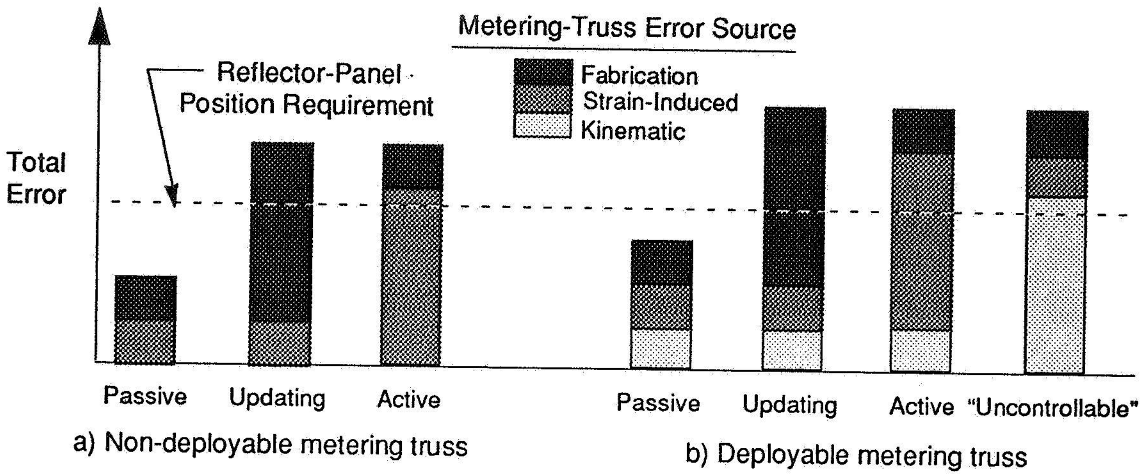


Figure 4. Metering-Truss Error Sources and Their Effect on Reflector-Panel Position Control.

Approach to Achieve Accurate Panel Positioning with Minimum Cost and Risk. Since the magnitude of freeplay represents a practical lower limit of the achievable panel-positioning accuracy in a deployable metering truss, it is imperative to develop deployable joint and mechanism designs which have little or no freeplay. Furthermore, to simplify the task of analytical modeling and to minimize the cost and complexity of correlating analysis and test results, it is highly desirable to minimize all sources of nonlinearity in the load-displacement response of joints and mechanisms. Finally, to minimize mechanism complexity and deployment risk, it is desirable to consider joint and mechanism concepts which can be preloaded locally rather than system concepts that are preloaded globally.

If it is assumed that freeplay-induced kinematic errors can be minimized through improved mechanism design, the accuracy of a deployable metering truss will be essentially determined by its fabrication and strain-induced errors. Therefore, as in the case for non-deployable metering trusses, achieving high accuracy at minimum cost requires a design trade between the costs of passive and active control of fabrication and strain-induced errors. To perform a meaningful trade, it is necessary to consider analysis and test verification costs in addition to hardware and software costs [10]. In general, the lowest cost and risk shape control system is passive. However, there is a precision limit below which passive shape control is not possible due to the lower bounds on fabrication tolerances and material thermal and hygroscopic stability. Although the quantitative relationship between cost or risk and absolute accuracy is different for each application, some general principles can be applied to achieve minimum cost and risk:

- Active shape control of any type is substantially less costly and risky if the structural response of the metering truss is predictable — kinematic error sources should be eliminated, and the structure should be linear.

- Panel-positioning accuracy is maximized, and cost and risk of adaptive adjustment is minimized if strain-induced errors are minimized. Thus, one should use high-stiffness, stable materials, along with efficient (high stiffness-to-mass ratio) structural architectures.

- Total cost may be reduced by relaxing fabrication tolerances and compensating for these effects with one-time shape adjustment after assembly.

Design Features of the LidarTechSat Revolute Joint

Conventional deployable structures either have significant joint freeplay and other nonlinearities, or they incorporate post-deployment preloading devices to minimize the nonlinearities. Inevitably, these devices add complexity, mass, and cost to the structure. Generally, these devices also increase deployment risk because they substantially increase deployment forces and complicate or prohibit re-stowage or re-configuration after initial deployment. In addition, post-deployment preloading induces global mechanical strains and deformations that are difficult to predict, especially if the structure is indeterminate.

The revolute joint developed at the NASA Langley Research Center for application to the LidarTechSat telescope is designed to exhibit minimal nonlinear behavior and high kinematic precision through local preloading of the joint components rather than global preloading of the assembled structure.

Components of the LidarTechSat Revolute Joint. The design concept, illustrated in Figure 5, represents a substantial departure from conventional pin-clevis joints, since the rotational element is a set of preloaded angular-contact bearings instead of the traditional pin. With only four fairly simple machined parts (the clevis, the tang, and two bearing-assembly pieces), the LidarTechSat revolute joint is also relatively inexpensive and easy to manufacture.

The bearing assembly, shown in Figure 6, consists of a hub and preload plate which retain and preload a commercially manufactured pair of precision angular-contact bearings. The hub is machined with an outer diameter that makes a slip-fit with the inner race of the angular-contact bearing. A raised lip is machined on the outer surface of the hub to retain the inner race of one bearing and react the preloading force applied by the preload plate, through the other bearing. The preload plate is attached to the hub using four small machine screws. As these screws are tightened,

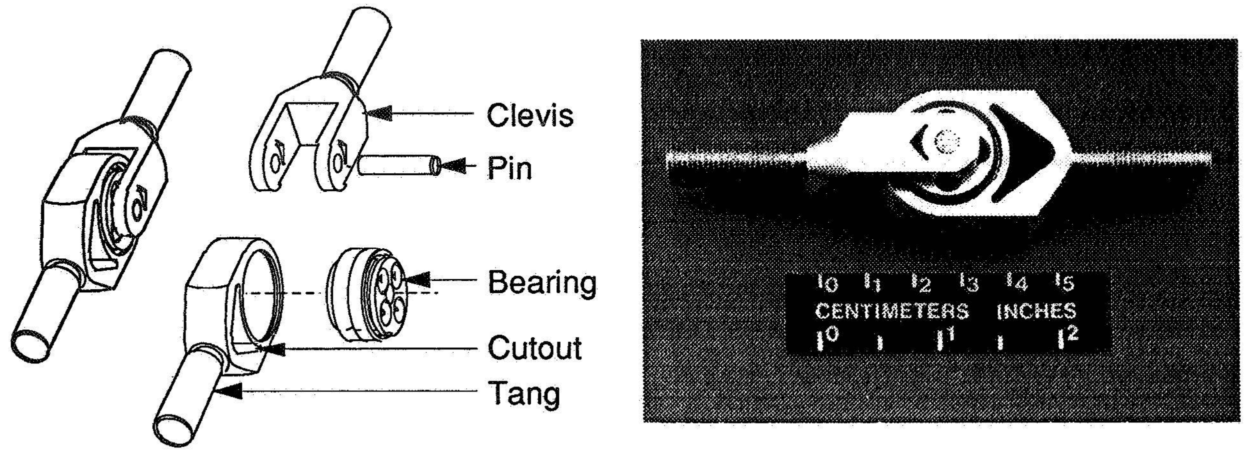


Figure 5. LidarTechSat Revolute Joint.

the outer lip of the preload plate makes contact with the inner race of one angular-contact bearing. The clamping force generated by the four machine screws is applied solely to the inner races of the angular-contact bearings, thus preloading the bearings according to bearing manufacturer specifications. Prior to preloading the bearings onto the hub, a thin-film liquid adhesive is applied between the inner bearing races and the hub to ensure intimate contact and to eliminate any potential for freeplay. Once completed, the bearing assembly is bonded into the cylindrical cavity of the tang with the same thin-film liquid adhesive.

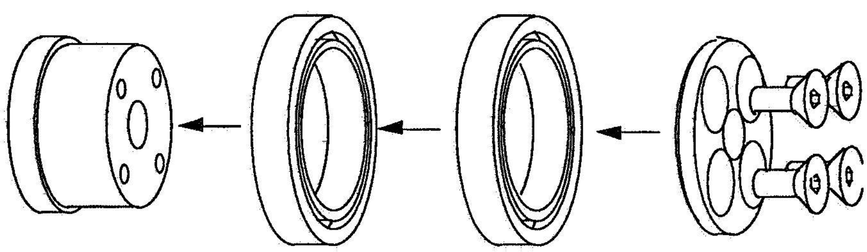


Figure 6. Bearing Assembly.

The tang incorporates a threaded shaft for attachment to other structural components. A cutout is provided in the body of the tang to divide the joint axial load into two paths. The load path is divided in this manner to ensure that the tension stiffness and the compression stiffness of the tang are equal. Details of the cutout design are provided in a subsequent section.

The clevis is a traditional split fork which surrounds and attaches to the bearing assembly and incorporates a threaded shaft for attachment to other structural components. The hole through the clevis arms is sized for a press-fit with the pin, and final assembly of the joint is achieved by simultaneously pressing the pin through these clevis arms and the central hole of the bearing carrier. The clevis arms also incorporate cutouts that have been designed to separate the axial load through the joint and to ensure equal stiffnesses in tension and compression.

Preloaded Bearings. The source of most nonlinearities in conventional pin-clevis revolute joints is the pin and pin-clevis interface [3]. As mentioned previously, traditional pin-clevis joints require freeplay between the pin and clevis (i.e., the pin diameter is less than the clevis-hole diameter) to allow free rotation of the joint. Unfortunately, this freeplay introduces both the response deadband and the changing stiffness (Figure 3) associated with nonlinear pin-hole Hertzian contact stress. To minimize these nonlinear effects, the preloaded pair of angular-contact bearings were selected for use in the LidarTechSat revolute joint in place of a simple pin.

Angular-contact bearings are often referred to as “duplex” bearings because they are manufactured in matched pairs and installed back-to-back, so that a known preload is developed between the races and the balls as the inner races of the bearings are clamped together. Because of this preloading process, all clearance (freeplay) is eliminated between the balls and the races. However, the Hertzian contact stress between the balls and the races introduces the possibility of nonlinearity in the load-displacement response of the bearing [11]. To minimize this effect, the bearing set incorporated in the LidarTechSat revolute joint has a relatively large diameter (approximately 1.9 cm or 0.75 in), which maximizes both the size of the balls and the number of balls which carry load. Preloaded angular-contact bearings are commonly used in high-precision articulating mechanisms [12]; however, no examples of angular-contact bearing use in the design of mechanical deployable structures have been found in the literature.

Elastic Tailoring of the Tang and Clevis. In a conventional pin-clevis revolute joint, bi-linearity is caused by differences between the tension and compression load paths as a results of pin-clevis and pin-tang interfaces. In general, these joints have a more direct load path in compression than in tension and, as a result, exhibit a higher compressive stiffness than tensile stiffness.

The cutout shown in Figure 7 divides the load paths through the tang to ensure equal tension and compression stiffnesses (similar features apply to the clevis arms). The cutouts effectively reduce the compression stiffness of the joint by forcing the compression load path to divide, rather than pass in a straight line to, the bearing. To eliminate bi-linearity, the cutouts are sized such that the compression stiffness of the tang equals the tension stiffness of the tang *assuming that the bearing-tang interface carries no radial tension.* This assumption virtually ensures equal tension and compression stiffnesses, independent of the radial stiffness of the bearing-tang interface adhesive.

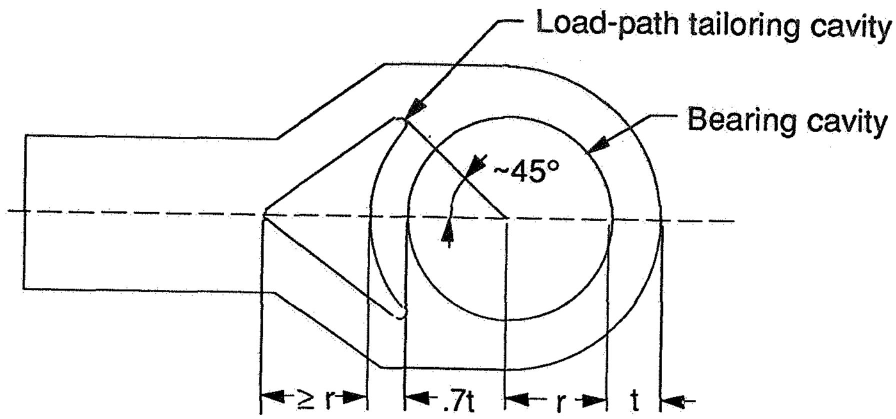


Figure 7. Tang Cutout for Equal Tension and Compression Stiffness.

A preliminary parametric study was conducted using a two-dimensional finite element model of a generic tang in which tension and compression loads were applied to the free end of the tang and reacted by radial *compressive* pressure on the inner boundary of the annulus. These finite element analysis results demonstrated that nearly equal tension and compression stiffnesses would result if the cutout was sized and shaped as shown in Figure 7. As indicated in Figure 7, the cutout should extend approximately 45° in each direction from the centerline of the joint, and it should be at least as deep along the axis of the joint as the inner radius of the annulus. Also, the annulus within the cutout should be thinned to approximately 70% of its nominal thickness outside of the cutout. While other cutout shapes may be tailored to eliminate bi-linearity, this cutout shape was selected because it is relatively compact.

Preliminary Tests and Results

Component-Level Joint Tests. A few prototype joints, such as the one shown in Figure 6, were fabricated for quasi-static axial load-cycle testing. The setup used in these tests is shown in Figure 8. The joint specimen was threaded into adapter fittings and installed in a 222-kN- (50,000-lb) capacity hydraulic tension/compression test machine. A high-sensitivity 2200-N- (500-lb) capacity load cell was installed between the joint and the test-machine crosshead to measure the total axial load applied to the specimen. Centerline axial displacement within the specimen was determined by averaging displacement measurements from three high-sensitivity Linear Voltage Displacement Transducers positioned equidistantly around the specimen. Tests were performed such that the load was quasi-statically cycled between 222 N (50 lb) of tension and compression loads and between 444 N (100 lb) of tension and compression loads. Similar tests were conducted on joints incorporating two different bearing-preload values.

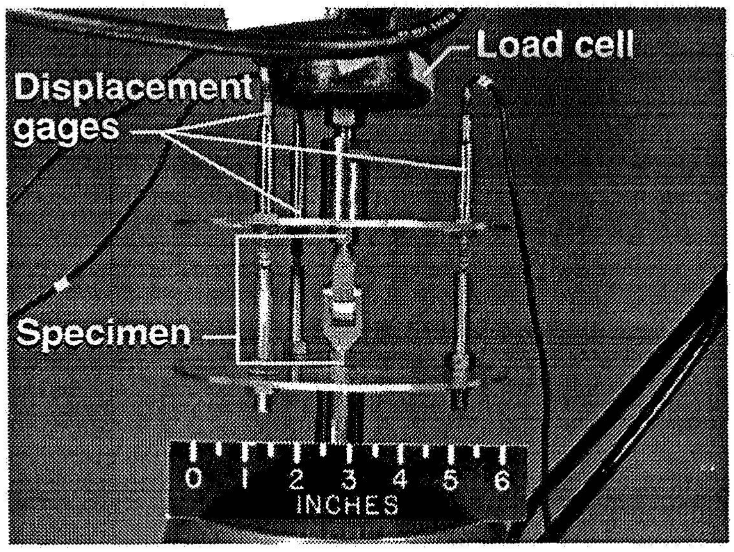


Figure 8. Axial Load-Cycle Test Setup.

Representative load and total displacement responses for three load cycles are plotted in Figures 9 and 10 for joints with bearing preloads of 44 to 66 N (10 to 15 lb) and 111 to 142 N (25 to 32 lb), respectively (the range in the preload is a bearing manufacturer specification). Also shown in these figures are the load-displacement response after a best-fit straight line has been subtracted from the measured total displacement. The remaining displacement is the joint hysteresis. The displacement gages used are only sensitive to about 0.1 micron, hence the noise seen in the hysteresis plots of Figures 9 and 10 is likely due to instrumentation rather than to joint response.

The results in Figure 9, for the test joint with a 44- to 66-N (10- to 15-lb) preload bearing, include load cycles of ±222 N and ±444 N (±50 lb and ±100 lb). For each load range, the joint was cycled three times, and the results from all load cycles are presented to demonstrate the load-displacement repeatability. The load-displacement response is essentially linear with less than 2% hysteresis. The hysteresis loop is approximately one micron wide for the ±444-N (±100-lb) load cycle and somewhat narrower for the ±222-N (±50-lb) load cycle. The shape of these hysteresis loops and their scaling with load-cycle magnitude are consistent with the occurrence of localized Coulombic micro-slippage between the balls and races as a result of the tangential load carried by the ball-race interface under load cycling [13]. Similar load-cycle tests conducted with a prismatic aluminum rod yielded approximately an order of magnitude less material-induced hysteresis. These results reinforce the assumption that the hysteresis in the load-displacement response of the joint is due to friction between the balls and races within the bearings.

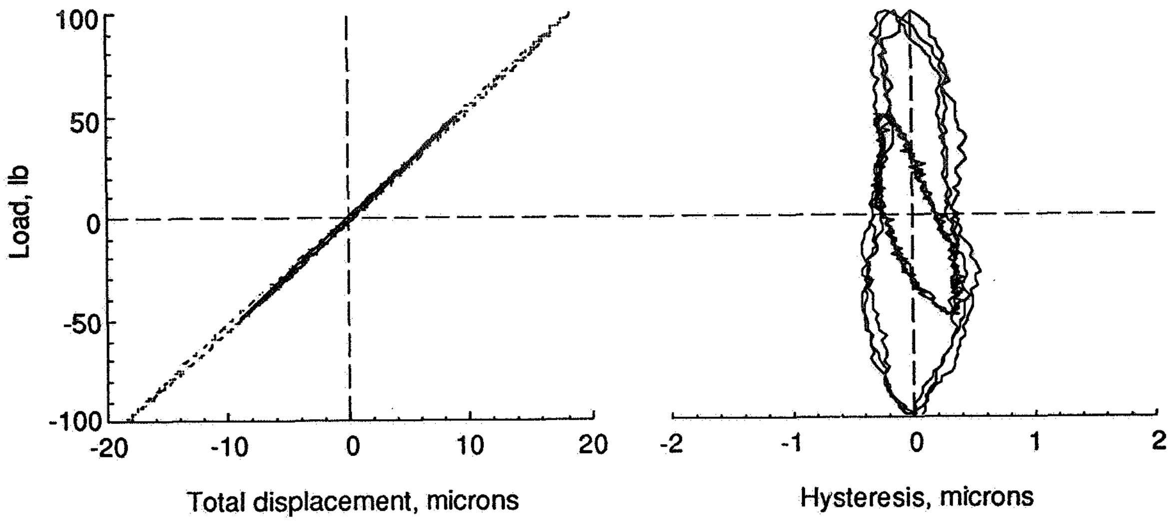


Figure 9. Load-Displacement Response and Hysteresis Loops for a Joint With 44- to 66-N (10 to 15 lb) Preload Bearings.

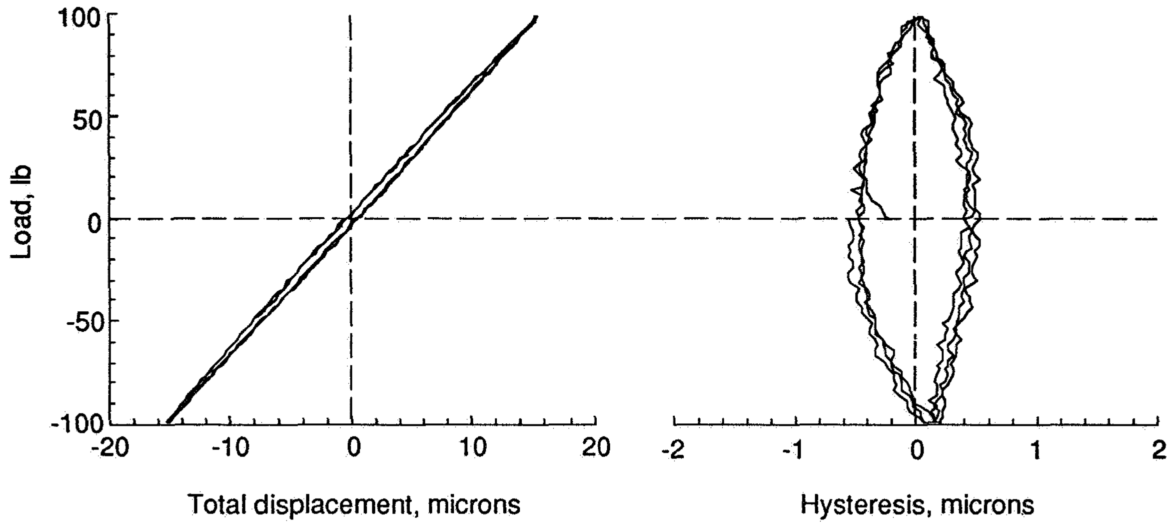


Figure 10. Load-Displacement Response and Hysteresis Loop for a Joint With 111 to 142 N (25 to 32 lb) Preload Bearings.

The results for the test joint with a 111- to 142-N (25- to 32-lb) preload bearing (Figure 10) also include three load cycles. Comparing the data presented in Figures 9 and 10 shows that both the stiffness and the amount of hysteresis in the joint increase slightly with increasing bearing preload. This result is consistent with the nonlinear Hertzian contact condition that exists between the balls and the races: as the normal force increases at this interface, the stiffness and tangential frictional forces increase as well.

It was noted previously that the bearing-clevis and bearing-tang interfaces within the joint have the potential to carry tensile load due to the use of a thin-film adhesive and that this interface effect could cause the joints to exhibit a significant difference in tensile and compressive stiffnesses. However, the linearity of the results suggests that the cutouts in the tang and clevis arms are effective in eliminating bi-linearity in the linear revolute joints without regard to the tensile stiffness at the bearing-tang interface.

The angular-contact bearing incorporated in the test joints requires only about 0.5 in-oz of applied torque to overcome the operating friction, thus minimal force would be required to deploy a structure using these joints [14].

Telescope Reflector Metering Truss Tests. To evaluate the LidarTechSat revolute joint in a structural assembly, a portion of a deployable metering truss for a segmented reflector (like the LidarTechSat telescope primary mirror) was fabricated. A photograph of the deployable metering truss test article is shown in Figure 11. This test article represents the portion of the metering truss that supports one reflector panel (one of the six perimeter panels shown in Figure 1). The metering truss test article incorporates four of the revolute joints shown in Figure 6: two of these joints are at the base of the truss, and two are at the tip to allow the truss to fold vertically into a narrow package. The test article also incorporates a latch joint that locks the truss in position at the end of deployment. To date, no component-level testing has been performed on the end-of-deployment latch joint.

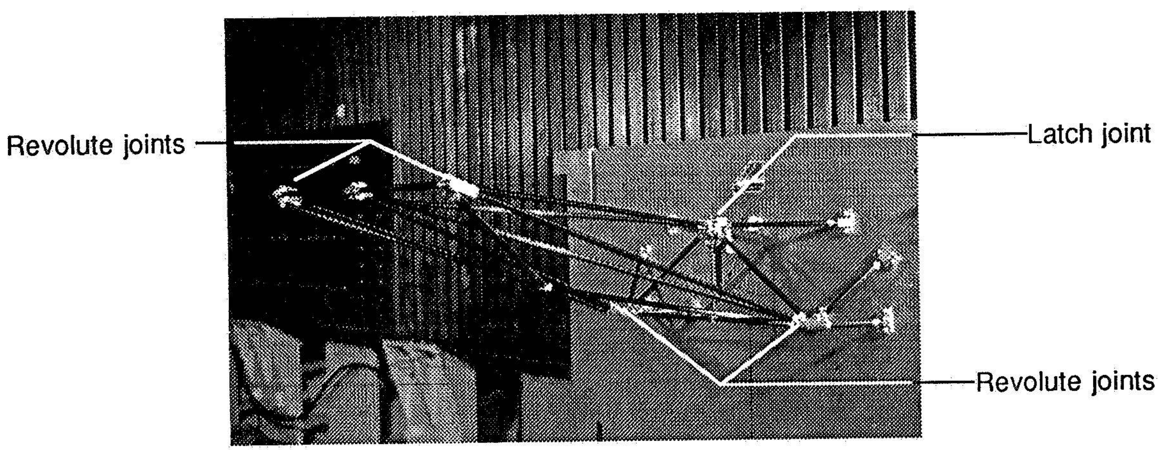
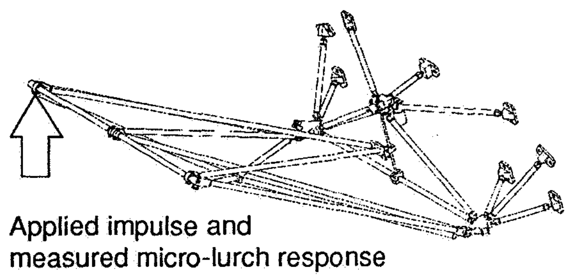


Figure 11. Precision Reflector Metering Truss Fabricated With LidarTechSat Revolute Joints.

A significant amount of testing has been performed to characterize the structural response and kinematic accuracy of the deployable metering truss test article. In these tests, the positions of key points on the structure were tracked under dynamic loading using an innovative new videographic metrology system with approximately 10-nm resolution [15]. Results from these tests indicate that the structural response of the test article is linear within a few microns under both static and dynamic loading, and the test article exhibits only a few microns of kinematic error after successive deployments and impulse loading.

From these tests, a new nonlinear response phenomenon, called "micro-lurching," has been discovered. This response is a change in the equilibrium position of points on the structure following a transient disturbance. In each series of tests, the structure was deployed and then impulsed by a light tap on one of the outboard nodes, as shown in the sketch in Figure 12. The vertical location of the node was determined before impulsing and after the impulse-response decayed out. A typical set of results from these tests (Figure 12) shows the changes in node location (i.e., micro-lurches) that occur after successive impulses are applied to the test article. The first five impulses after deployment cause a total of about seven microns of micro-lurching in one direction, and the remaining impulses cause random micro-lurches of no more than a few microns each.



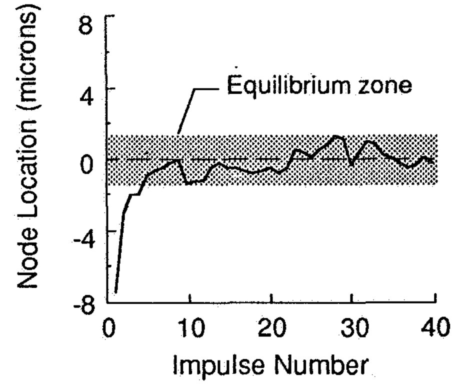


Figure 12. Typical Micro-Lurching Response of Metering Truss.

Preliminary analyses using simple two-degree-of-freedom dynamic models suggest that micro-lurching is a typical nonlinear response in structures that transmit load through Coulombic friction that is schematically parallel to the elastic deformation. Since both the revolute joints and the end-of-deployment latch joint transmit load in this manner, it is believed that these mechanisms are responsible for micro-lurching. However, additional analyses and tests are necessary to fully characterize the relationship between micro-lurching and friction-induced hysteresis in the revolute joints or nonlinearities (as of yet uncharacterized) in the end-of-deployment latch joint. Furthermore, additional analyses and tests are necessary to determine if micro-lurching is affected by gravity-induced preloading in the structure. These investigations are very important because the stochastic nature of micro-lurching might ultimately prove it to be the response parameter that defines the kinematic accuracy of a precision mechanically deployable structure.

Currently, it is believed that the initial net micro-lurch response of seven microns results from the latch and/or revolute joints which release internal strain energy and seek a lower total energy state than that present at the end of deployment. The random micro-lurches after the fifth impulse define an "equilibrium zone" within which the test article tends to remain quasi-stable over time. The width of this equilibrium zone is about 3 μ, and is a measure of the kinematic accuracy of the metering truss test article. No other mechanically deployable structure found in the literature has been demonstrated to be this kinematically accurate. This accuracy is close to the absolute precision requirement for the LidarTechSat telescope, thus making such a concept feasible at this preliminary stage of development. However, a practical design for the telescope might require active or updating shape control to compensate for fabrication and strain-induced errors.

Concluding Remarks

To date, dimensional uncertainties associated with nonlinearities in deployment mechanisms have limited the accuracy of deployable reflectors to approximately 100 microns. Although this accuracy is acceptable for low-frequency ($\leq$ 20 GHz) communication antennas, it is unacceptable for high-frequency ($\geq$ 100 GHz) science instruments. Achieving substantial improvement in deployment accuracy requires significant advancements to be made in the load-cycle linearity of precision deployment mechanisms and the understanding of sub-micron-level load-cycle nonlinearities of these mechanisms.

The revolute joint described in the present paper was designed to minimize all forms of load-cycle nonlinearity, especially freeplay, which cannot be compensated for through active control. Component-level test results prove that the concept is sound; exhibits no freeplay, bi-linearity, or changing stiffness; and has only about 2% hysteresis in the load-cycle response. These results prove the joint to be substantially more linear, as presently designed, than any joint found in the literature to date.

A deployable reflector metering truss that incorporates four of these high-precision revolute joints was fabricated and tested. These tests identified a new nonlinear response phenomenon, called "micro-lurching," which is a micron-level change in the equilibrium shape of a structure following a transient dynamic disturbance. At present, it is believed that micro-lurching is caused by load transmission through contact friction within the revolute joints and/or the end-of-deployment latch joint. However, additional analyses and tests are necessary to fully characterize these relationships as well as the effect of gravity on micro-lurching. These investigations are very important because the stochastic nature of micro-lurching might ultimately prove it to be the response parameter that defines the kinematic accuracy of a precision mechanically deployable structure. Although friction-induced hysteresis and micro-lurching in deployable structures are probably unavoidable due to the complex load paths within the mechanical joints, it may be possible to reduce these undesirable effects to an acceptable level by minimizing load transfer through friction.

The present results indicate that it is both possible and practical to design a deployable reflector metering truss that has a kinematic accuracy of a few microns for the LidarTechSat telescope. No other mechanically deployable structure found in the literature has been demonstrated to be this kinematically accurate. This accuracy is close to the absolute precision requirement for the LidarTechSat telescope, thus making such a deployable concept feasible at this preliminary stage of development. However, a practical design for the telescope might require active or updating shape control to compensate for fabrication and strain-induced errors.

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