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Advanced Tether Experiment Deployment Failure

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The Advanced Tether Experiment was launched into orbit aboard the National Reconnaissance Office sponsored Space Technology Experiment spacecraft on 3 October 1998. The tether experiment payload was intended to demonstrate deployment and survivability of a novel tether design as well as controlled libration maneuvers. On 16 January 1999 after deployment of only 22 m of tether, the advanced tether experiment was jettisoned from the spacecraft due to an out-of-limits condition sent by the experiment's tether angle sensor. The essential system design is reviewed, the available flight data are presented, and likely causes of the failure are suggested.

Introduction

THE Naval Research Laboratory (NRL) built the Advanced Tether Experiment (ATEx) as an experiment for the Space Technology Experiment (STEX) spacecraft. ATEx was delivered to the STEX contractor (Lockheed Martin, Denver, in April 1997) as government-furnished equipment. STEX was launched on 3 October 1998, from Vandenberg Air Force Base on a Taurus launch vehicle, eventually achieving a 751-km circular altitude at 85-deg inclination. Spacecraft checkout and orbit transfer was completed by January 1999. At this point, the ATEx mission began and was to continue for 61 days.

ATEx was a high-risk, low-cost tether flight experiment. ATEx placed the tether's lower end body on top of an active spacecraft, which permitted the opportunity to perform libration control experiments. (Librations are pendulumlike oscillations of the system both in and out the orbit plane.) To date, no tether mission has demonstrated extended control of system librations. The ability to control these motions, along with the remaining objectives, is necessary to develop more sophisticated tethered space systems. There were two ATEx mission objectives: demonstrate tether system stability and control and fly a tether designed for long-term survivability.

The ATEx system comprised an upper end body (UEB), the tether, and a lower end body (LEB), which was attached to the top of the STEX spacecraft as shown in Fig. 1. The fully deployed tether length was to be 6.05 km. The LEB was to be attached to the STEX spacecraft for about 61 days of active flight experiments. Then the LEB was to be jettisoned from STEX.

One of the mission objectives was to fly the thin, flat, tape tether (0.127 mm thick × 25 mm wide) shown in Fig. 2. The tether was made from approximately a 6.5-km continuous extrusion of low-density polyethylene (LDPE) with three Spectra® (similar to Kevlar®) reinforcing strands running lengthwise down the tether. All previously flown tethers have been ropelike and flown in both NASA's Tethered Satellite Systems (TSS) and Small Expendable Deployer Systems (SEDS),[1] the NRL Tether Physics and Survivability (TiPS) experiment,[2] and the Canadian Space Agency's Observations of Electric Field Distribution in the Ionospheric Plasma—a Unique Strategy (OEDIPUS)[3] missions A and C. Space debris models predicted that a tether of the braided rope type with a narrow cross section would last only two to three years before being severed by a micrometeoroid. A tape-type tether with a larger cross section was predicted to have a much longer life and thus would be a better choice for an operational tether system. However, because this type of tether is radically different from the rope-type tethers previously flown, the deployer design could not leverage existing deployer designs. Additionally, the tape nature of the tether made it much more difficult to manage and wind when compared to a rope-type tether. For instance, the tape tether used on ATEx had the tendency to stick to itself, and it exhibited increasing adhesion the longer it was stowed. Additionally, the tape tether had a noticeable memory effect. For instance, if the tether were wrapped around a pencil it would tend to maintain a coiled shape after the pencil was removed.[4]

ATEx failed to properly deploy. After deploying only 22 m of tether, the LEB was jettisoned, ending the experiment. Based on analysis of the telemetry, there were no software or hardware related failures. A tether departure angle sensor first detected the tether in an anomalous location 10 s prior to jettison. This initial detection was quickly followed by tether passing an out-of-bounds limit, an unacceptable risk to STEX. This sensor then produced the jettison command. Excessive slack tether was determined to have caused the out-of-bounds limit.

Two conference papers were written and presented in 1997. Reference 4 describes the deployment hardware design, evolution, and test. Reference 5 describes the structural components, onboard sensors, and planned experiments. This paper will focus on those features of the system essential for understanding the deployment concept, its mechanization, and subsequent failure.

STEX Spacecraft Description

Figure 1 illustrates the ATEx/STEX configuration and the spacecraft coordinate X, Y, and Z axes relative to an orbital frame in its nadir pointing attitude. During the initial deployment phase, the spacecraft was operated as a three-axis-stabilized momentum-bias vehicle. A momentum wheel, with its spin axis parallel to Y, had its speed modulated to control the pitch axis, and electromagnetic torque rods were used to control the roll and yaw axes. The attitude control system operated at a rate of 0.1 Hz, with an effective bandwidth of 0.01 Hz. The solar arrays were each gimbaled in elevation and azimuth with respect to the central body. The arrays were held fixed early in the deployment, though not in the null position shown in Fig. 1.

For tether deployment, the arrays were rotated 8 deg in elevation and 42 deg in azimuth. This configuration rendered the spacecraft axes nonprincipal, increasing cross-axis coupling. Relevant mass and inertial properties of ATEx and STEX are presented in Table 1.

ATEx Design Description

ATEx consisted of three main parts: the UEB, the tether, and the LEB. The UEB was a passive, unpowered body attached to one end of the tether. The LEB housed the deployer mechanisms and electronics. The LEB was to remain fixed to STEX during the deployment and libration control experiments and then was to separate for the survivability phase of the mission.

Figure 3 shows two cross-sectional views of ATEx identifying the relevant deployment mechanism components. The tether was level

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wound onto a 203-mm-long reel under a constant tension of 4.5 N. A full tether reel had an outside diameter of 363 mm. As measured in tests, the tether reel support bearings and seals developed ~0.4 Nm of running friction torque. The static friction torque was ~0.7 Nm. Unpowered horizontal and vertical guide rollers were present to ensure proper tether transport and to maintain the tether position to the lengthwise center of the pinch rollers. The horizontal roller was mounted in radial ball bearings and had a high-traction (though not sticky) polyurethane surface. The vertical roller was stationary and made from Teflon®. A motorized pinch-roller assembly was used to pull tether off the reel, around the guide rollers, and into the deployment stream. Each pinch roller was supported by radial ball bearings and had high-traction polyurethane surfaces. A 30-deg stepper motor with a 60:1 reduction gear drove one pinch roller. The other pinch roller was spring loaded (45 N) against the driven roller. To avoid the development of compression-set flat spots on the polyurethane surfaces, the pinch rollers were held apart by shims. These shims were driven out just prior to deployment.

The UEB possessed a cantilevered structural element referred to as the initial deployment guide (IDG). The IDG was a thin (0.76-mm) sheet of aluminum 187 mm wide, which tapered down to a 0.15 mm thickness over its lower 25 mm. The bottom edge was smoothly rounded to avoid cutting or abrading the tether. As illustrated in Fig. 3, the IDG had a rectangular notch in which to accommodate the tether. The tether was attached to the IDG at the top of the notch through two belt buckle slots and a clamp. Before deployment of the UEB, the IDG rests between the pinch rollers as shown in Fig. 4. The IDG is present to allow the pinch-roller system to accelerate the UEB to the 2-cm/s tether deployment rate. The notch provides a pass through for the tether, and the taper facilitates a smooth transition between the IDG and tether material. To ensure a smooth transition between the IDG and tether, a layer of Kapton® tape was applied to each side of the tether over a 10-cm length, thereby increasing the thickness of this portion to ~0.4 mm. This Kapton-reinforced segment had substantially higher stiffness, from all aspects, than the bare tether alone. Also illustrated in Fig. 4 is a segment of tether identified as the slack loop, residing above the pinch rollers. This 12-cm length of tether allowed the IDG to move up through the pinch rollers without deploying tether from the reel. The slack-loop material was prevented

Table 1 Mass and moments of inertia of ATEx and STEX at deployment

Centroidal inertia matrices, kg-m^2		
	UEB component[a]	
0.37	0.0	0.0
0.0	0.55	0.0
0.0	0.0	0.91
	LEB and STEX components[b]	
304.9	34.0	−2.9
34.0	294.4	−4.7
−2.9	−4.7	156.4

[a]12.2 kg. [b]640.2 kg.

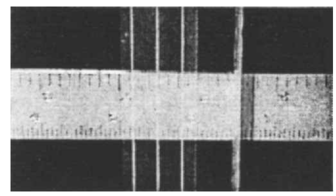

Fig. 2 ATEx tether (front and side views).

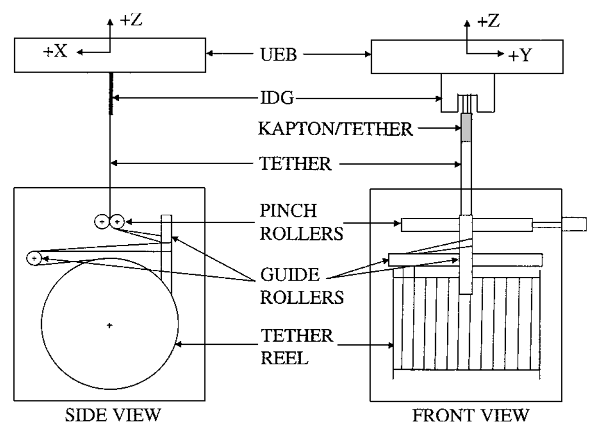

Fig. 3 ATEx deployment mechanism components.

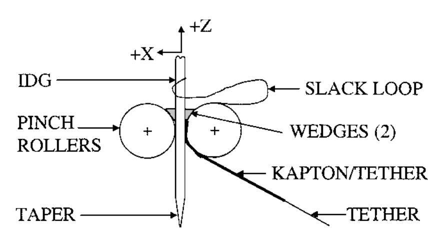

Fig. 4 Predeployment configuration of UEB/IDG, tether, and pinch rollers.

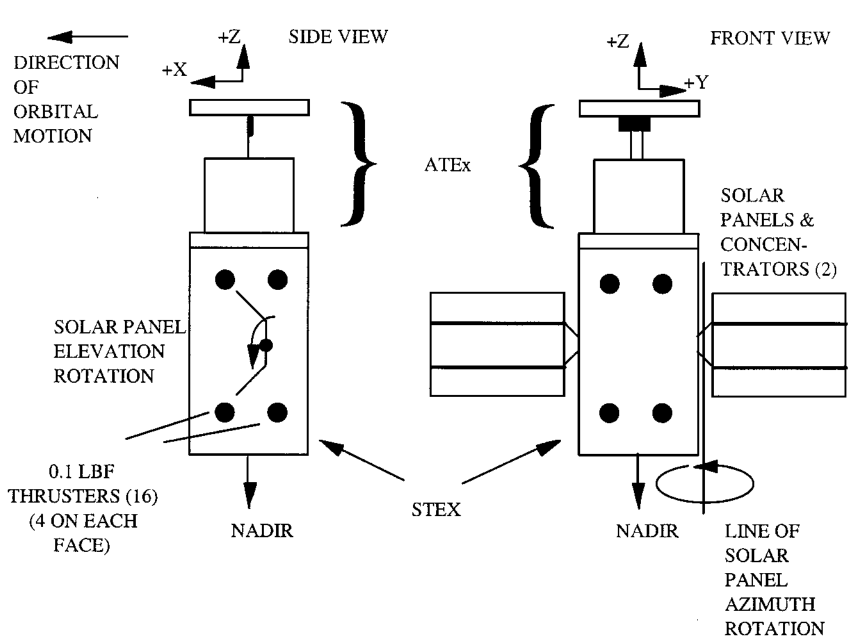

Fig. 1 ATEx/STEX with solar arrays in null position.

from being pulled inside through the pinch rollers by a pair of wedges laminated to the Kapton. This design allowed the tether between the pinch rollers and the reel to be cinched tight prior to deployment. The slack loop also contained a 10-cm segment that had the polyethylene material removed, leaving only the Spectra strands. This cutout segment reduced the stiffness of the tether, thereby reducing the transmission of nontensile forces from the tether to the UEB. The slack loop was sized such that by the time the Kapton-covered tether was fully engaged by the pinch rollers and the reel had commenced rotation there would still be ~3.2 cm of slack tether above the pinch rollers. This resulted in the deployment beginning with 3.2 cm of slack tether. The slack material was found to be necessary to eliminate an otherwise retardant impulse on the UEB as it exited the pinch rollers. This impulse was caused by slippage between the pinch rollers and tether as the tether reel was accelerated during the IDG to tether transition.

Deployment

To begin deployment, the STEX spacecraft was aligned to the local-vertical/local-horizontal (LV/LH) reference frame and the solar arrays were fixed in position. The pinch-roller stepper motor was commanded to deploy the UEB 2.5 cm and then hold this position. This kickout was performed to raise the UEB off its contact points with the LEB, reducing the possibility of recontact and tipoff perturbations. The kickout took 2.3 s. After kickout the UEB was simply supported by a thin contact patch between the pinch rollers and the IDG, with the elastic polyurethane on the rollers acting as a restoring spring. Ground-based air-bearing tests against a cantilevered base showed the UEB to have a 0.12-Hz pendular mode in this position. The kickout position was maintained for 10 min to allow the damping of any excited oscillations. After the damping period, the stepper motor was then commanded to produce a steady 2-cm/s deployment rate. This rate was to continue for the entire deployment (~3.5 days). Tests showed that the UEB would achieve this velocity in ~1.0 s, well before the IDG would clear the pinch rollers.

The fundamental concept for deployment was to accelerate the UEB to a relative velocity of 2 cm/s along the local vertical direction ($+Z$). The UEB would be followed by a continuous stream of tether fed through the pinch rollers at the same rate and direction. As the UEB and tether material moved to increasing altitude, gravitational effects (orbital mechanics) would cause an apparent retrograde motion relative to STEX; that is, the UEB/tether would move upward and behind the spacecraft. Differential gravitational forces acting on the system increase tension within the tether. Eventually the gravity gradient torque acting on the system would cause the backward tilt to reverse, leading to an oscillating motion of the system relative to the local vertical.

Figure 5 shows a view of the system in the orbital plane during the deployment and indicates pertinent angular measures. Although motion perpendicular to the orbital plane is also possible, most motion during deployment occurs within the orbit plane.

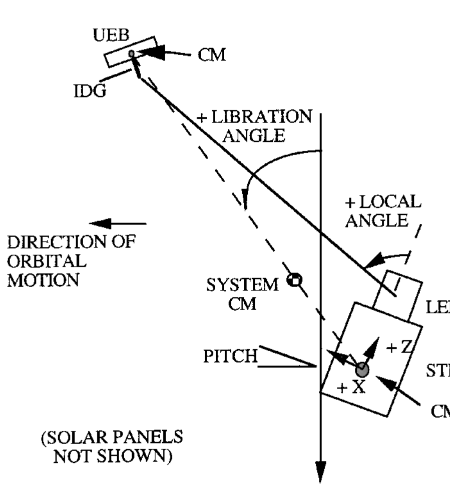

Fig. 5 In-plane angles for tethered system.

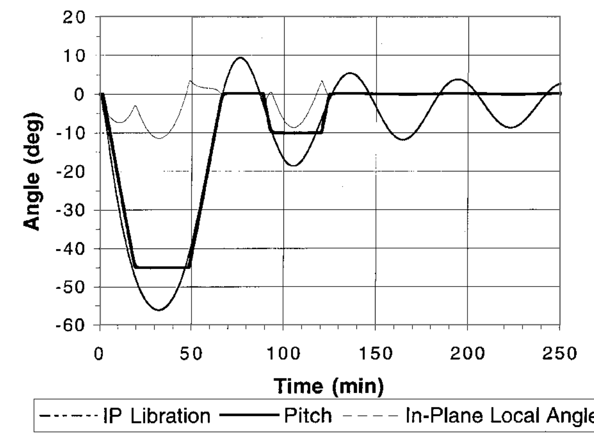

Fig. 6 In-plane libration, pitch attitude, and local angles for early deployment of ATEx.

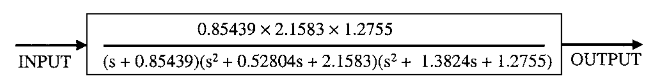

Fig. 7a Accelerometer filter transfer function.

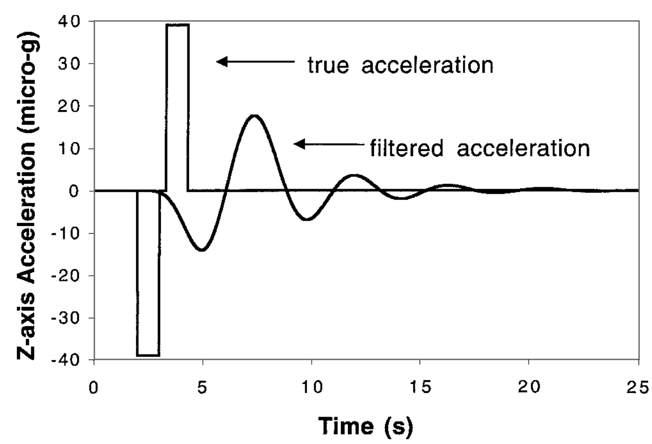

Fig. 7b Simulated spacecraft reaction to UEB kickout.

Figure 6 illustrates the predicted in-plane libration angle over the first 4 h of deployment. As deployment proceeds, the libration angle steadily diminishes. The spacecraft was commanded to execute a preplanned pitch maneuver to maintain a relatively small in-plane local angle (angle between $+Z$ and the line connecting the respective tether attach points) 1 min into the deployment. These predictions are shown in Fig. 6. Although the spacecraft's attitude control loops were closed during this maneuver, there was no measurement of the actual local or libration angles. The maneuver was conducted open loop, based solely on results predicted by preflight simulations. Additionally, extensive ground-based deployment tests were conducted to validate the deployment mechanism's performance.[1]

Instrumentation

The ATEx system used three Allied Signal QA-3000-010 accelerometers that were mounted to the STEX interface deck and aligned to the spacecraft body axes. These were placed near the Z axis and 0.85 m above the ATEx/STEX mass center (prior to deployment). With this geometry, the X and Y accelerometers sensed pitch and roll attitude motions. The accelerometers had a dynamic range of ± 1000 μg and a resolution of ± 0.5 μg. Because these instruments were intended to measure the very-low-frequency motions characteristic of the fully deployed system, each channel passed through a fifth-order low-pass Chebyshev filter with a cutoff frequency of 0.2 Hz. The filtered signals were sampled at 4 Hz for telemetry. The filter transfer function is given in Fig. 7a, where s is defined as the Laplace operator. Figure 7b shows the effect of the filter on a rectangular acceleration–coast–deceleration input signal. This corresponds closely to that experienced by the STEX vehicle

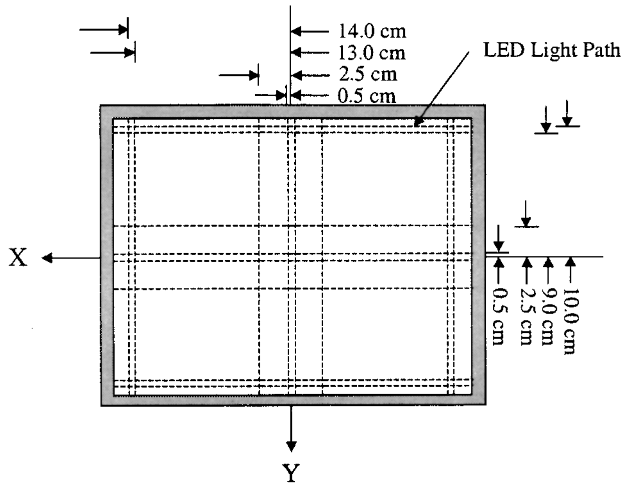

Fig. 8a Local angle sensor *X*–*Y* plane view.

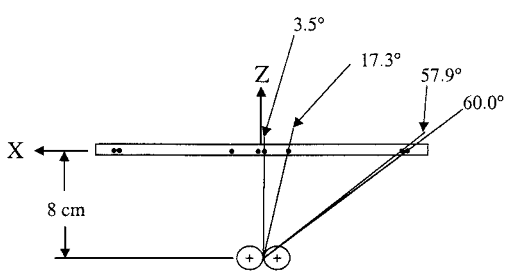

Fig. 8b Local angle sensor *X*–*Z* plane view.

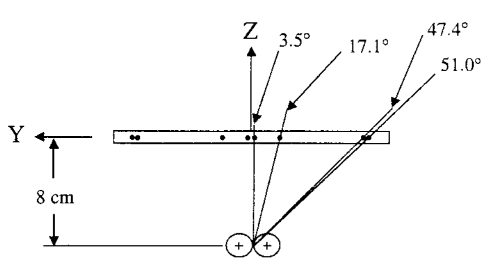

Fig. 8c Local angle sensor *Y*–*Z* plane view.

in reaction to the 2.5-cm kickout of the UEB. The amplitude attenuation and phase distortion of the higher frequency content of the input signal is evident.

The local angle sensor (LAS) was an electro-optical instrument designed to locate and track tether position in a plane near the top of the LEB. This sensor comprised 16 light emitting diode (LED)/detector pairs forming a planar rectilinear grid located 8 cm above the pinch rollers. The arrangement is shown in Figs. 8a–8c. Intended primarily as a safety system to protect the STEX spacecraft from errant tether, it did also provide information, albeit coarse, on tether position in the neighborhood of the deployer. Flight software tracked the tether motion across the light beams. If material moved progressively through the beams and crossed the outer edge, it was deemed out of limits and the ATEx LEB would be automatically jettisoned. Note from Fig. 8a that such a condition would be reached if the tether were to move laterally only 10 cm off the Z axis. LAS data were sampled at 500 Hz onboard STEX and telemetered at 2 Hz.

The tether supply reel contained a turns counter that triggered once per revolution. During tether winding the turns-to-length conversion was recorded. The turns counter and conversion provided a means to determine the length of tether deployed separate from simple multiplication of elapsed time and constant motor speed.

The STEX spacecraft attitude determination system (ADS) was active during the tether deployment. However, the ADS was neither intended nor configured to make detailed measurements of the deployment dynamics. Nevertheless, the ADS did provide some information. Employing a star camera and three-axis gyro system, the ADS telemetry provided spacecraft attitude relative to the LV/LH frame, which was in turn established from onboard propagation of the orbit ephemeris. These attitude data were recorded onboard at a 10-Hz sample rate. Gyro measurements were also available. Unfortunately, these data were recorded for telemetry at only 0.5 Hz and, consequently, contained no useful information.

Table 2 Deployment timeline

16 Jan. 1999 (universal time)	Event
22:22:57	STEX locks solar arrays
22:53:24	Contact at first ground station begins
22:54:00	STEX enters eclipse
22:54:30	Mission data collection begins
22:55:31	IDG begins 2.5-cm kickout
22:55:33	IDG completes 2.5-cm kickout, begin 10-min damping of system
23:05:59	Pinch-roller motor reenergized
23:06:00.8	Motor begins to turn again
23:06:04.4	IDG leaves pinch rollers
23:06:08.4	IDG clears LAS
23:06:42	Contact at first ground station ends
23:07:00	STEX begins pitch slew
23:23:30	STEX returns to sunlight
23:23:39	Contact at second ground station begins
23:24:06	First off-nominal LAS data
23:24:16.1	Off-nominal tether location at extreme trigger point, LAS issues jettison command
23:24:17	Jettison action
23:24:40	Pitch slew pauses at −45 deg
01:25:00 (17 Jan.)	Visual observations of ATEx over Maui

Deployment Flight Data

Deployment Sequence of Events

Approximately one month prior to ATEx deployment, the STEX orbit was propagated to the first opportunity to begin the sun orbit geometry limited mission. ATEx was restricted to operate at beta angles within ±50 deg. Beta angle is the angle that the orbit plane makes with the sun. On 11 January, the beta angle was −50 deg, and this angle increased to +50 deg by 18 March. During ATEx operations, STEX maintained a nadir pointing attitude with the solar arrays restricted in azimuth rotation to ±50 deg.

Contacts with the Air Force Space Command Network ground stations assigned to this mission were computed. Contacts were selected that provided nearly continuous coverage during the critical very early deployment. The best coverage left a 17-min gap within a 55-min set of three contacts. ATEx deployment was scheduled to start within this series of consecutive ground contacts, which would begin on 16 January. A discussion of the telemetry from deployment will follow, starting with Table 2, which shows the deployment sequence of events.

Accelerometers

Figure 9 shows the time histories of the accelerometers and the spacecraft attitude, (expressed as 2–1–3 Euler angles from LV/LH to body) from 60 s before UEB kickout through the LEB jettison. Note that the accelerometer data have not been corrected for nonzero bias, which is present in each channel, and that those instruments remained aboard STEX after jettison. The kickout, deployment start, STEX pitch maneuver, and jettison events are all indicated. Although not clear at the scale shown, careful review of the attitude data revealed no anomalous perturbations. Examination of the accelerometer signals between the start of deployment and jettison shows some variation about the mean (excepting the STEX pitch event appearing in the X channel). These variations are, however, near the resolution limits of the instrument and appear to be noise. Minor tension spikes were expected to occur in this interval as the tether became taught, then recoiled, and became slack again. However, the magnitude and duration of these forces were so small that they were rendered undetectable by the low-pass filters.

In the search for anomalies, the kickout, deployment start, and jettison events were scrutinized. Figure 10 shows the accelerometer data near kickout. The Z-channel response when compared with the simulated response (run through the 0.2-Hz filter) of Fig. 7b

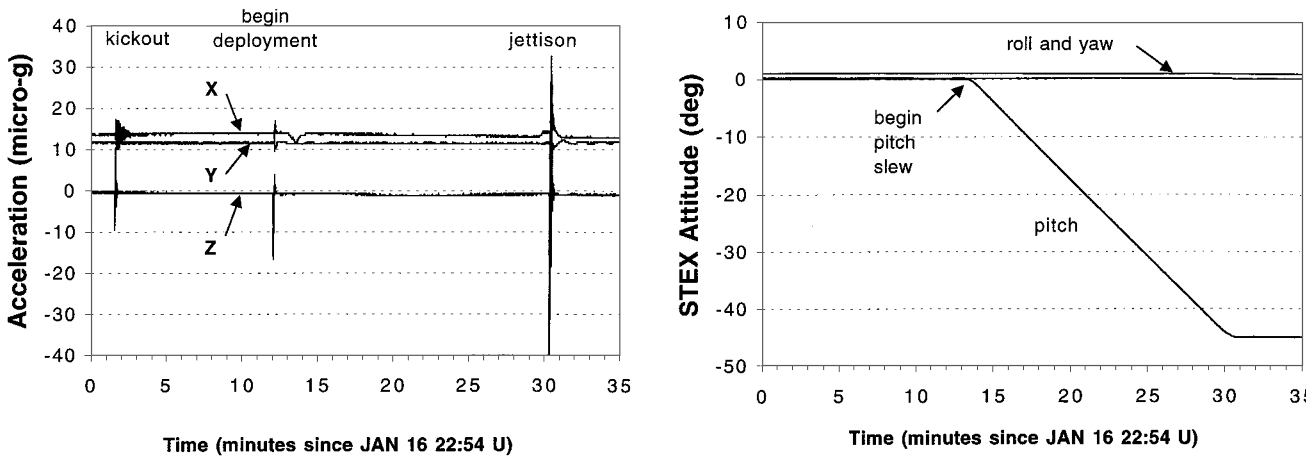

Fig. 9 Accelerometer and STEX attitude data.

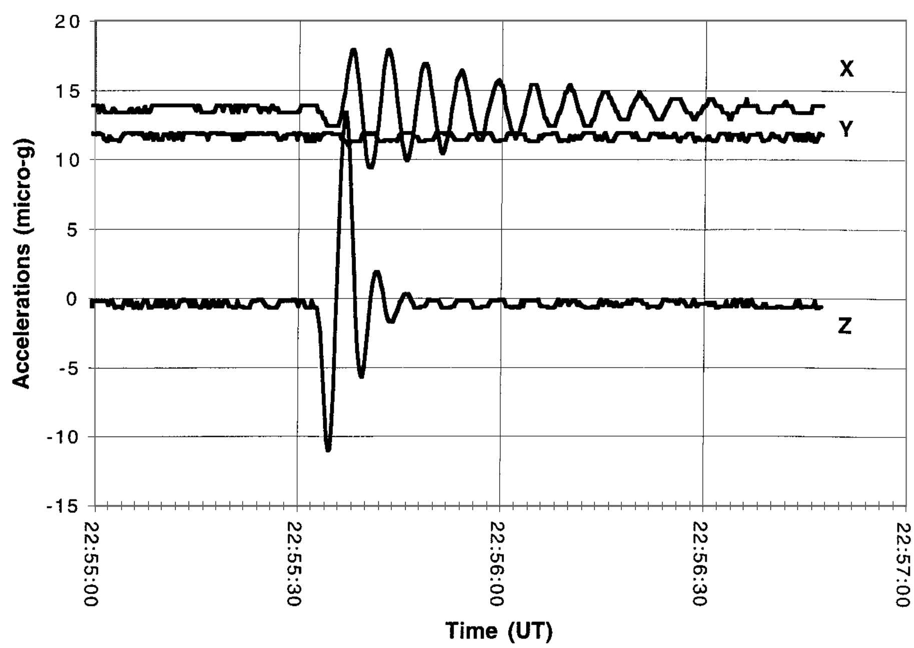

Fig. 10 Accelerometer data near kickout.

is seen to be nominal. The X channel shows a damped oscillation at 0.19 Hz. This signal is believed to have been produced by pitch oscillations of the spacecraft in reaction to the UEB rocking back and forth in the pinch rollers in the X–Z plane. This signal was anticipated. The higher frequency observed on-orbit vs ground-test data is consistent with the vehicle being unconstrained.

The UEB deployment is shown in Fig. 11. The UEB is accelerated to 2 cm/s in the Z direction in approximately 1 s. The response of the Z-axis accelerometer is simply the filtered vehicle reaction to the acceleration pulse and is considered nominal. The response in the X axis is, however, more complicated. Note that the start of the X-axis response is markedly delayed from that of the Z axis, by approximately 2.5 s, indicating an excitation in the X direction and/or pitch axis after acceleration of the UEB.

To understand these results, we must take a detailed look at the first few seconds of the deployment startup. As described in the deployment section, initially only the IDG is engaged by the pinch rollers, the tether passing between them in the IDG notch. After approximately 2.5 cm of IDG deployment, the Kapton-over-tether segment is engaged by the pinch rollers as the tapered portion of the IDG moves into the rollers. The slack loop above the rollers allows this movement without motion of the reel. Once the tether is engaged by the pinch rollers, it begins to stretch, developing a torque on the tether reel. The reel torque increases until its static friction level is reached, at which point the resistance drops precipitously to its lesser constant running friction value. The reel experiences a near impulsive acceleration and begins rotating, feeding out tether and reducing the tension. After a brief transient, the reel achieves a steady rotation rate. Reaction of the spacecraft to the reel motion produces a counter-rotation (about the $-Y$ axis), which is sensed by the X-axis accelerometer as a negative acceleration pulse. This hypothesis has been corroborated by analysis. This pitch torque impulse to the spacecraft occurred just as the IDG was departing the pinch rollers, and it is possible that this produced an excessive tipoff rate for the UEB. The design requirement for the UEB pitch axis tipoff rate was $<\pm 0.2$ deg/s. A number of simulations and laboratory air-bearing tests indicated that, within the parameter uncertainties, this tipoff would not occur. However, study showed that if excessive tipoff were to occur, it could cause the UEB to recontact the tether with unforeseen consequences.

The final segment of accelerometer data pertains to the LEB jettison and is shown in Fig. 12. Both the reel turns counter and the duration times deployment rate calculation indicate that jettison occurred after approximately 22 m of tether had deployed. Note from Fig. 12 that no unusual accelerations are apparent immediately before this event. Jettison was accomplished by the release of a latching mechanism connecting the LEB to the STEX vehicle, which allowed four compressed spring cartridges to impulsively separate the two bodies along the Z axis, with a relative velocity of 0.6 m/s. The Z-axis accelerometer records the principal component. The spring

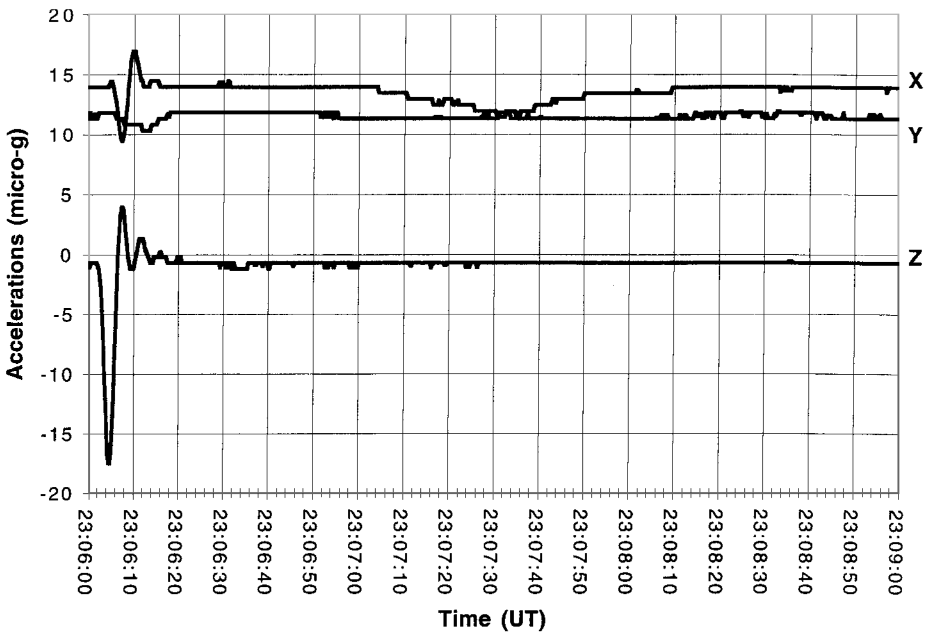

Fig. 11 Accelerometer data near deployment start.

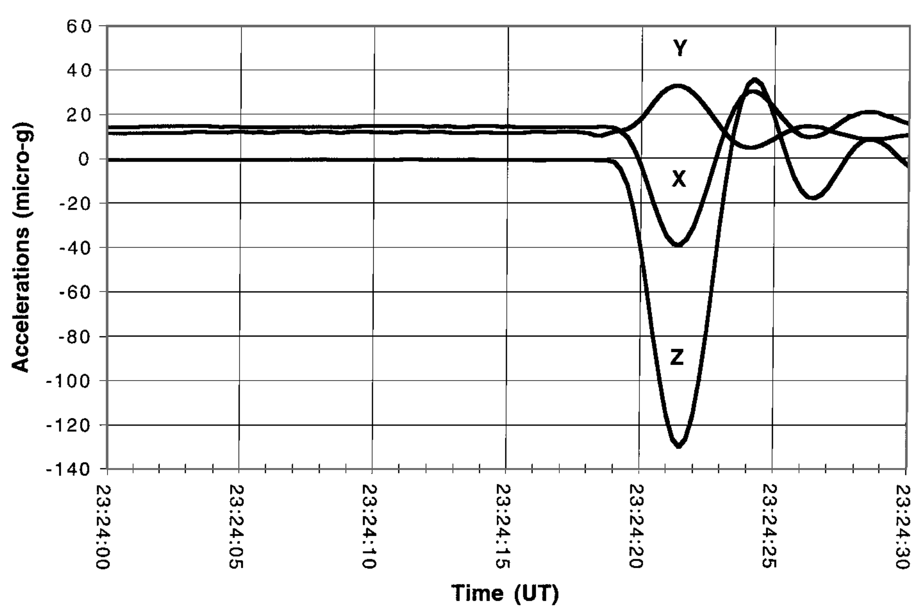

Fig. 12 Accelerometer data at jettison.

cartridges were located along the perimeter of the LEB, offset from the Z-axis centerline. The small mass center offset accounts for the nonzero X and Y accelerations apparent in the data.

Local Angle Sensor

Figures 13–16 show the time history of the LAS telemetry during ATEx deployment. Figures 13 and 14 show the data throughout the deployment, and Figs. 15 and 16 zoom in on the area after ATEx enters sunlight and off-nominal telemetry starts. When interpreting the plots, one has to understand that if the LAS state reads +17 deg in-plane, then the tether has passed the +17-deg in-plane LED and is somewhere between it and its adjacent LEDs. In this example, the tether is somewhere between the +4-deg and +57-deg in-plane LEDs. Thus, only very coarse resolution in the LAS telemetry exists. Furthermore, the +17-deg LEDs are only 2.5 cm from the 0-deg, straight out, tether exit point. The tether itself is 2.5 cm wide; thus, if the tether is nearly straight but twisting as it exits the pinch rollers, the LAS would register ±17 deg. Thus, all but the last 10 s of deployment were considered to exhibit nominal telemetry because the tether only blocked the ±17-deg in-plane LAS sensors and the ±4-deg out-of-plane LAS sensors during this period. Significantly, all but the last 46 s of deployment were conducted in eclipse, at which point ATEx and the tether entered sunlight. The significance of this will be discussed in the next section.

Possible Failure Causes

The premature jettison was almost definitely caused by excessive slack tether present in the plane of the LAS. All four $-Y$-axis LAS LEDs were simultaneously blocked, and the jettison command was sent. Because of limited telemetry, the cause of the slack tether will never be certain. Additionally, the telemetry that was available was rather coarse and not suited toward the dynamics of early deployment or anomaly resolution. Therefore, although the telemetry appears nominal up until the last 10 s before jettison, the deployment may have been off nominal but still within the coarse telemetry bounds for a nominal deployment. The potential failure modes that were ruled out are listed in Table 3.

The possible failure modes will be discussed in the order of increasing likelihood, based on the authors' opinions. Although nothing is certain, it is highly likely that thermal expansion of the tether caused the excess slack tether and jettison of ATEx. The deployment was begun in eclipse with all telemetry nominal until the tether came into the sunlight. The first off nominal tether position LAS telemetry occurred 36 s later and 46 s after entering sunlight jettison occurred.

Electrostatic Effects

The polyethylene tether material is capable of building up a static charge. No evidence of a static charge buildup was ever seen during testing. Although no static charge buildup was seen during test, it is unknown whether the charged particle space environment could have built up static charge on the tether. It is possible that static cling of the tether to the LEB might manifest itself as an apparent slack tether condition in the LAS telemetry.

Table 3 Failure modes ruled out

Possible cause	Mitigation of cause	Probability
STEX structural interaction	Simulation and test	None
STEX ADS	Telemetry nominal	None
Local angle sensor	Telemetry nominal	None
Tether cut	Observation	None
Inadvertent tensiometer arm deployment	Telemetry nominal	None
Solar glint on LAS	Tested	Low
Thermal blanket hangup	Tested	Low
Software glitch	Health check, no single event upset	Low
Deployment mechanism malfunction	Telemetry nominal	Low

Excessive Tipoff and Deployment Dynamics

The tipoff requirement for the UEB deployment was <0.2 deg/s. This requirement was established to avoid UEB recontact with the tether due to rotation. Such an inadvertent contact could disrupt the tether deployment stream, perhaps leading to the development of excessive slack. The pitching action of the spacecraft in response to the reel acceleration, noted earlier, could have contributed to such a state. As a cause of the deployment failure, excessive tipoff rates would be expected to manifest themselves early in the deployment, a situation for which there was no evidence.

Shape Memory and Strain Relief

Ground-based deployment tests (both in air and thermal vacuum) showed the tether to take a sinusoidal shape on exiting the pinch rollers. These sine waves had a wavelength of approximately 38 mm and an amplitude of 3 mm. The presence of this shape memory condition effectively changed the unstrained length of tether deployed at any instant, as well as its effective deployment rate.

The pinch rollers issued material at 2 cm/s as measured along the arc length. Clearly, while in this state, the straight-line distance between any two material points was less than the arc length. The presence of the curvature also effectively reduced the longitudinal stiffness of the tether. Under load as the waviness was drawn out, the apparent stiffness would increase to that of the tether material itself. Efforts to measure the effective stiffness were avoided in favor of a parametric study of this condition. Analysis showed that the net effect of this shape memory was to slow the velocity of the deployment stream to less than 2 cm/s. The relative velocity could drop below the effective deployment rate, thereby generating

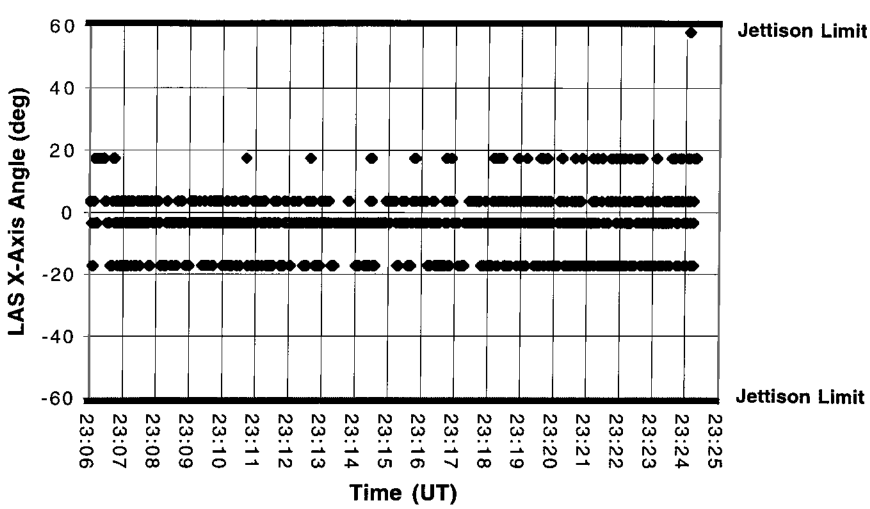

Fig. 13 LAS deployment data (along *X* axis), entire deployment from post-IDG exit to jettison.

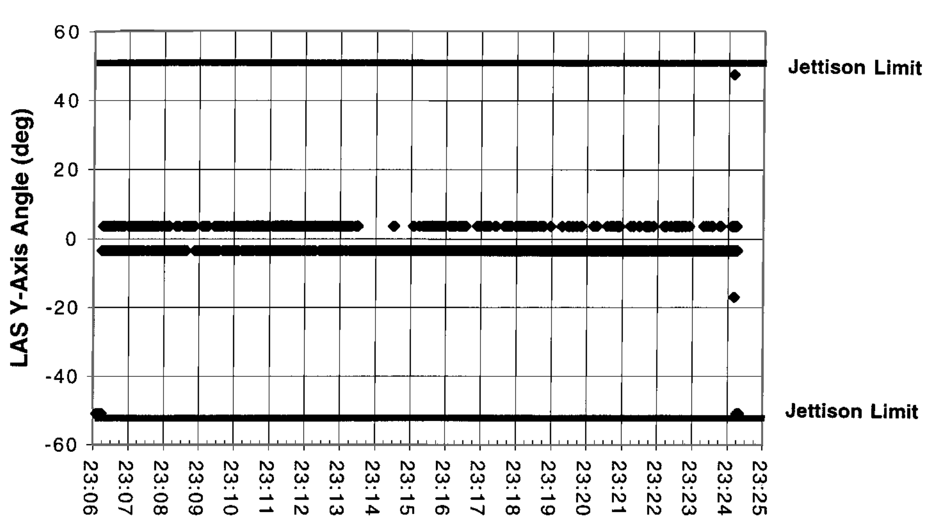

Fig. 14 LAS deployment data (along *Y* axis), entire deployment from post-IDG exit to jettison.

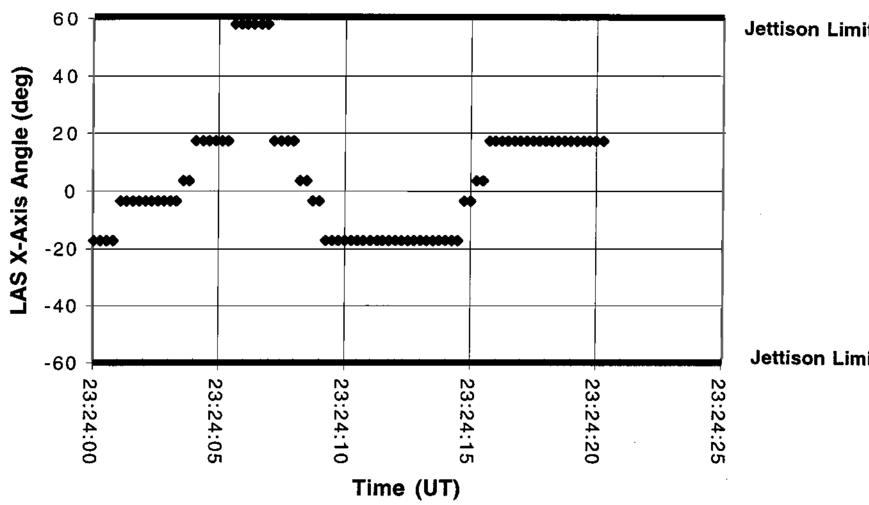

Fig. 15 LAS jettison data (along *X* axis) showing first indication of slack tether.

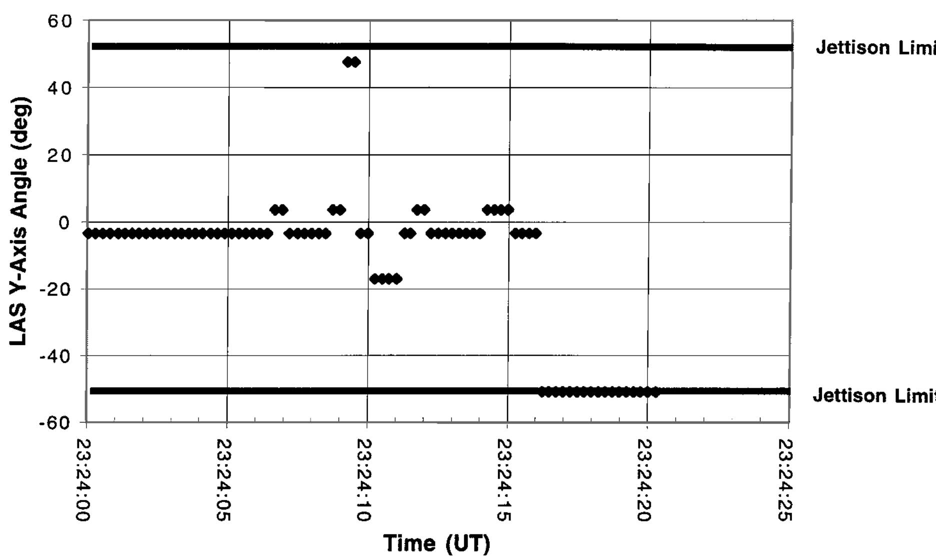

Fig. 16 LAS jettison data (along *Y* axis) showing first indication of slack tether.

slack. Additional shape memory curvature that may have occurred from the tether having been stored on the reel (38-cm diam with complete supply of tether) for almost 24 months would be expected to exacerbate the problem noted. Although no evidence was seen for the 38-cm-diam memory, it is unknown whether the curvature might exist in a 0-*g* environment.

A similar effect could arise from tether strain relaxation. The tether material undergoes a change in its strain state as it is removed from the reel, traverses the guide rollers, passes through the pinch rollers, and exits into the deployment stream. As the tether transitions off the reel (where its tension is 4.5 N) its tension decreases to equal the reel drag torque of 1.8 N. As the tether passes across the contact patch within the pinch rollers and exits the deployer, the tension relaxes to that of material just beyond the deployer, a tension value that is virtually zero early in deployment. If complete relaxation of the tether tension did not take place over the pinch-roller contact patch, but rather occurred outboard of the pinch rollers, then the tether would experience an effective contraction in length.

Another form of tether shape memory was found in the Kapton tape portion of the tether. This 10-cm length of Kapton taped tether was stored wrapped around the pinch rollers for almost two years prior to deployment. Ground tests after 15 months of storage in this condition showed that this section retained the wrapped curvature of storage as it exited the pinch rollers. This resulted in this section of the tether deploying from the pinch rollers at a 60-deg in-plane local angle and potentially creating a disturbance on the UEB. Schedule and cost constraints prevented modeling or testing the effect that this curved section of the tether might have on the initial deployment, and so its impact remains unknown.

Tether Thermal Expansion

The tether was made from LDPE tape with three strands of Spectra coextruded integrally along its length in a continuous process. During manufacture, as the tether cools leaving the extrusion dies, the LDPE contracts at a rate of 100×10^{-6} mm/mm/K, whereas the Spectra strands expand at a rate of 20×10^{-6} mm/mm/K. This differential coefficient of thermal expansion gives the tether a crinkled appearance along its length; that is, the LDPE takes on a slight accordion shape analogous to an extension spring. Thus, the tether is never really flat or perfectly straight unless put under a 5-N tensile load. The tether would never see this much tension during deployment. At the full 6.05-km length only a 0.4-N gravity-gradient tension would have been created.

Because the tether deployment was started in full eclipse, the tether left the deployment mechanism at a temperature of 10°C. On being exposed to the cold of space, it would rapidly cool to −100°C. The temperature decrease would cause the deployed tether to contract at the 100×10^{-6} mm/mm/K rate of the LDPE as it exited the deployer. This contraction would tend to slow down the UEB because the effective length of tether being deployed was less than 2 cm/s. Still, the deployment telemetry was nominal during the 17.5 min of deployment conducted in eclipse. At this point, however, the tether and ATEx came into sunlight. Then the tether would have rapidly warmed from −100 to −30°C due to the absorptive and emissive properties of the tether. This 70°C change would have caused the 22 m of deployed tether to expand 15.5 cm. This expansion was followed by the first off-nominal LAS data 36 s later. ATEx was jettisoned due to a blockage of all four $-Y$ axis out-of-plane LEDs on the LAS 46 s after entering sunlight. That all four LEDs were blocked simultaneously indicates a horizontal length of tether 10-cm long in the plane of the LAS. It seems highly unlikely that the timing of these events was a mere coincidence. The critical importance of the thermal expansion rate of the tether, however, was not included in the tether deployment simulations.

Conclusions

ATEx was jettisoned from the STEX spacecraft 18 min and 16 s after the start of deployment. Approximately 22 m of tether had deployed at that time. The cause of jettison was tether blockage of four LED/sensor pairs in the plane of the LAS. This condition suggests the accumulation of at least 10 cm of slack tether at that location. The generation of such excessive slack could have resulted from a number of possible causes, any of which, either singly or in combination, may have occurred. The deployer possessed no direct means for ensuring that tether material would depart the pinch rollers with the desired velocity vector. If, for any reason, tether material farther out in the deployment stream were to slow relative to that of material behind it, then the tether could be expected to backup onto itself. Such a condition would disrupt the smooth steady laminar flow of material, leading to a turbulentlike state of highly complex nonlinear motion.

Significantly, all telemetry appeared nominal prior to ATEx entering sunlight. At this point the tether temperature increased 70°C. This change would have caused the 22 m of deployed tether to expand 15.5 cm. This expansion was followed by the first off-nominal LAS data 36 s later. ATEx was jettisoned due to a blockage of all four $-Y$ axis out-of-plane LEDs on the LAS 46 s after entering sunlight. That all four LEDs were blocked simultaneously indicates a horizontal or slack length of tether 10 cm long in the plane of the LAS. Because it seems highly unlikely that the timing of these events was a mere coincidence, thermal expansion is likely to have played a critical role in the failure of ATEx to fully deploy. The tether's coefficient of thermal expansion was seen as an aside in the thermal vacuum modulus of elasticity tests conducted on the tether just before launch. However, the tether thermal expansion was never considered in any of the simulations of tether deployment, and its impact was not realized until postjettison failure analysis.

The ATEx system employed a low-speed, open-loop motorized deployment. The design was driven primarily by two opposing requirements, one of needing to exert very small forces and torques on the host spacecraft during the deployment and the other of ensuring that no entanglement occurred between the tether and spacecraft. Although the former precluded the use of energetic (impulsive) deployment schemes (such as SEDS, TiPS, and OEDIPUS), the latter restricted allowable tether motions to a narrow corridor. The implemented design ultimately proved to be extremely sensitive to the perturbations to which it was subject. Because of the large-scale (several kilometers) and zero-gravity environment, space-based tethered systems cannot be fully tested on Earth. Tether testing is limited to short lengths in a gravitational field. Their designs rely heavily on mathematical models that also cannot hope to capture all of the physics involved in their complex implementations.

Experiments (especially tethers) need large design margins. The final ATEx design had very little margin for error. The analysis of the deployment by simulation methods drove precise deployment hardware performance requirements. Because of the constraints placed on the ATEx experiment toward minimizing its impact on the STEX spacecraft, however, there were no other viable deployment options found by NRL as described in Ref. 4.

The tether used on ATEx was selected for long-term survivability. The handling features (such as friction, stiction, and shape memory) of this tether, however, made it very difficult to deploy. To this end, a new deployment mechanism had to be designed to accommodate the difficulties in handling and deploying this tether. When selecting a tether, due consideration needs to be given to the deployability of the tether. Tether deployability was never considered for this experiment, and ironically the deployment ended in failure.

ATEx and STEX illustrate the point that tethers need to be better understood before they become a bolt-on addition to spacecraft. Any tether design places stringent requirements on spacecraft system design and performance, and its integration within a spacecraft is not a trivial matter.

Both the National Reconnaissance Office sponsor and NRL had recognized that the approach taken was one of both low cost and high risk. Robustness of deployment was exchanged early in the development to meet challenging technical requirements, as well as those of cost and schedule.

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