SECTION 7
TETHERED OPERATIONS

The operation of separate PL's in proximity to the Orbiter has always been a RNDZ/PROX OPS operational concern. In the near future a new class of PL's will appear, those which remain physically attached to the Orbiter by tethers. Although some new flight-dynamics laws come into play, such objects are only a tether-break away from becoming classical PROX OPS subjects and many actually plan to separate rather than return to the Orbiter; furthermore, traditional monitoring and control techniques for RNDZ/PROX OPS have major applications to this new class of PL. Consequently, the flight procedures for tethered objects clearly fall within the purview of this book.

7.1 BACKGROUND

To understand tethered operations, an appreciation of the history, candidate applications, and safety concerns is required.

7.1.1 History

Tethered operations occurred in the Gemini program when the manned Gemini spacecraft was connected to the Agena booster by a 100-foot tether. Gravity gradient and artificial gravity experiments were conducted.

Current projects involve plans for both short (300 feet) tethers (on Hitchhiker G2) and long (10 to 20 n. mi.) tethers (for the Italian "TSS" or "Tethered Satellite System"). An official NASA project envisages systems that can achieve 50 n. mi. (100 km) deployment distances with new tether materials, control laws, and supporting subsystems.

7.1.2 Applications of Space Tethers

Numerous applications have been imagined for tethered objects in space. These include:

Electrodynamic -- A conducting tether moving through Earth magnetosphere generates electrical current (a 5 to 10 n. mi. tether would generate line voltage of 2 to 4 kV), or, inversely, current in a conducting tether generates thrust for orbital adjustment.

Trolling (instruments or test models) -- Instruments are lowered into normally inaccessable (in terms of longterm in situ measurements) regions of the upper atmosphere. Test models of future aerospace planes are lowered into the upper atmosphere for aerodynamic studies. Keels may be lowered into the upper atmosphere for plane changes.

Variable G -- In stable gravity gradient mode, modules moved along tethers can experience a variety of G-forces, which can be tailored to the desired applications. In dynamic, rotating systems, large accelerations can be generated for control, physical processing, or long-term human health applications.

Momentum Transfer -- Objects at the end of tethers can be released, taking momentum from a main object and imparting it to a secondary smaller object for either orbit boost or deboost. The momentum of the larger object can then be made up using high-efficiency low-thrust propulsion systems.

Constellations -- Structures can be established in stable REL positions tens or even hundreds of miles apart. For operational reasons, specialized modules (such as a docking wharf) can be separated from a main object for operations, and then retrieved, repeatedly.

7.1.3 Safety Considerations

While the theoretical applications appear to be unlimited, the key issue is whether such plans are operationally feasible. That is, can safe procedures (both AUTO and manual) be developed under which such applications can occur?

Key safety issues include (but are not limited to)

a. System dynamics stability

b. Tether failure

    (1) Structural (tether)

    (2) Attach points

    (3) Induced (e.g., collision with debris)

c. Reeling mechanism failure

    (1) Jamming

    (2) Power loss

    (3) Overtorque reel-in

    (4) Runaway

d. Deployed-object anomalies

    (1) In-line thruster fail-off

    (2) NLOS thruster fail-on

    (3) Dynamics

e. Orbiter damage

  (1) Physical impact (tiles, windows, SSME/OMS/RCS engines)

  (2) Tether mechanism stow (versus jettison)

  (3) Mechanical jam (e.g., Ku-band antenna, PLB doors)

f. Contingency procedures

  (1) Brake application

  (2) Motor unpower

  (3) Tether guillotine

  (4) Boom jettison

  (5) Separation maneuvers

Any candidate body of procedures must take into account these and other as yet undefined concerns.

7.1.4 Reference Material

A number of general reference articles are available (from which much of the material in this section has already been directly excerpted), including:

Guidebook for Analysis of Tether Applications, Joseph A. Carroll, contract RH4-394049 with Martin-Marietta (as part of NASA-MSFC contract NAS8-35499, "Study of Selected Tether Applications in Space"), March 1985.

"Controlled Tether Extends Satellite's Orbital Range," Victor Wigotsky, Aerospace America, June 1984, pp. 34-36.

"Tether Propulsion," Ivan Bekey and Paul Penzo, Aerospace America, July 1986, pp. 40-43.

"Tether Applications in Space Transportation", Joseph A. Carroll, Acta Astronautica, 1986, Vol. 13 no. 4, pp. 165-174.

Proceedings of NASA/AIAA/PSN "International Conference on Tethers in Space," September 17-19, 1986.

"Tethers in Space: The Future Nears," William J. Broad, N. Y. Times, January 7, 1986.

"Trolling the Atmosphere," Richard DeMeis, Aerospace America, June 1986, pp. 16-17.

7.2 THEORETICAL CONDITIONS

The statics and dynamics of tethered space systems involve mathematically accurate but intuitively unfamiliar features. A brief summary of the theoretical basis for such features may help in appreciating their operational implications.

7.2.1 Tension

In a weightless condition, tethered objects are unlike objects hung on cables under one g conditions, where the full weight of the object is supported by the cable. In orbit, both tethered objects are nearly in stable ballistic trajectories, and only the difference between such free trajectories and actual tethered trajectories shows up as tether tension.

Consider the example of two equal mass objects tethered 10 miles apart. Their c.m. is in a stable orbit with a known period. For a free-flying object passing 5 miles below this system c.m., relative motion would be approximately 50 miles per REV, or 50 ft/s (in accordance with the "10:1" rule of thumb for ΔH to lateral separation ratios). The lower mass, then, is moving 50 ft/s too slow for a circular orbit at its altitude, but it is still moving at nearly 25,000 ft/s anyway, so the deficit in orbit motion is a very small fraction (several tenths of one percent, in this case), and the weight "hanging" on the tether is a similarly very small fraction of the total one g weight of the lower mass (a half-ton satellite would induce only a few pounds of tether tension). A rule of thumb is that a free-hanging tethered system will experience tension equivalent to 1 percent of the one g weight of the object per 12 n. mi. of length.

Note: If the lower mass, 5 miles below the c.m., were detached, it would act exactly as if a satellite there in circular orbit suddenly performed a -55 ft/s ΔV. Then it would thus fall into an orbit with opposite end about 33 n. mi. lower while the upper mass would rise 33 miles (via the old familiar "2:1 Rule" of ΔV to ΔH ratios). This is approximately the same result discussed under "momentum exchange" applications.

Gravity gradient tension is caused by a combination of gravitational and centrifugal forces (fig. 7-1). One-third of the total force is centrifugal, due to the ROT of the LVLH system in inertial space; two-thirds is gravitational, due to the inverse square diminution of Earth gravitational attraction as distance from Earth increases.

In low Earth orbit, the magnitude of these effects depends on the size of the system. A rule of thumb specifies about 0.12 μg/ft, or 1 μg per 8 feet.

Over about a foot, the gravity gradient forces amount to a tenth of a microgee (essentially undetectable); over the length of the Orbiter (150 feet), the gravity gradient forces amount to about 10 microgees (possibly noticeable); over a tether length of 5 n. mi., gravity gradient forces amount to several thousand microgees. Objects which are located that far from the system c.m. will experience gravity gradient acceleration fields of that size.

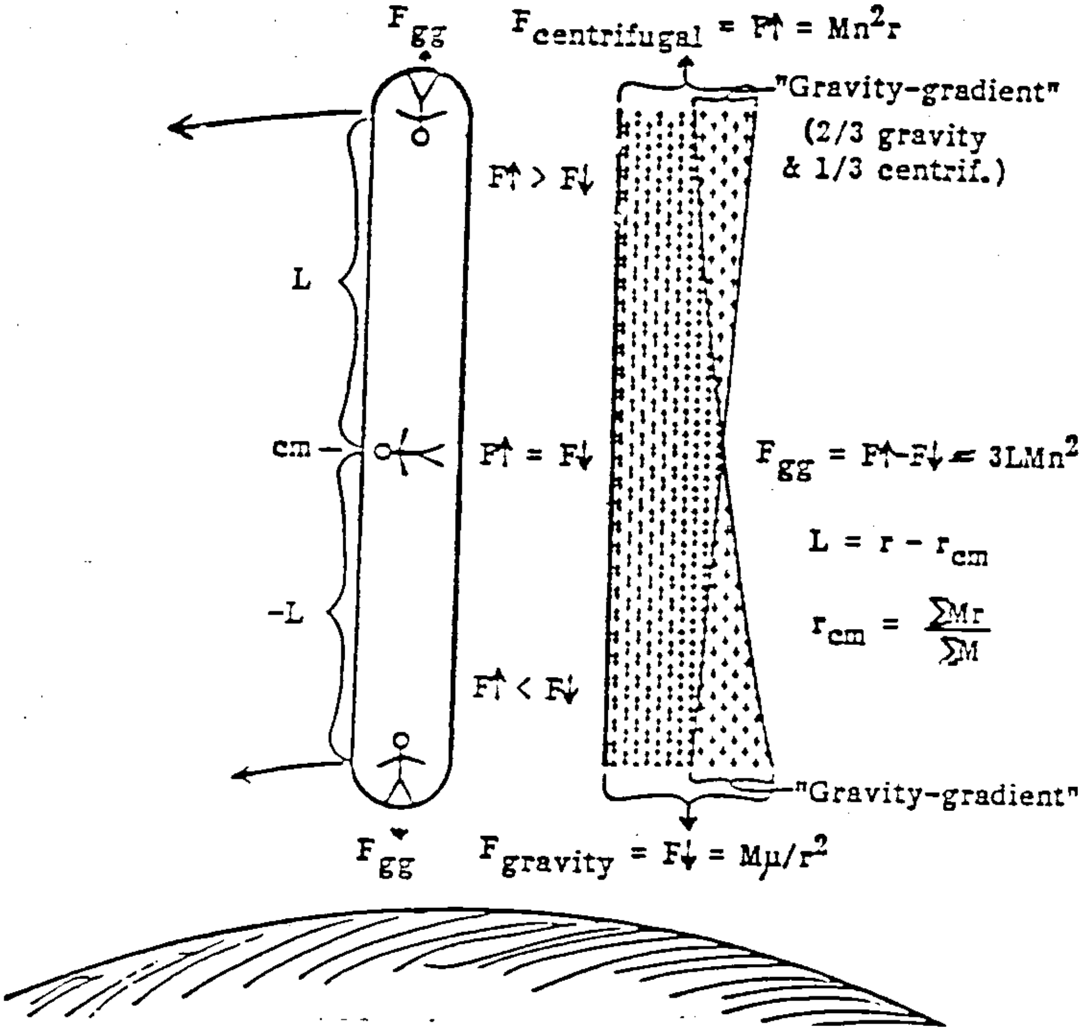


Figure 7-1.- Origin of "gravity-gradient" forces.

Practical considerations help define an Orbiter-satellite range beyond which gravity gradient forces can be relied on to safely maintain tether tension. Inside that range, other techniques (such as in-line thrusters) would be required to maintain tension. For initial TSS-S studies, that range appears to be approximately 4000 feet. For other tethered payloads, analysis may produce a different range.

7.2.2 Motion

The motion of tethered systems has been analytically studied in depth.

Changing the tether length between two end masses induces a system tilt, due to Coriolis forces. This induced tilt sets up a periodic motion called libration. As will be described below, the reverse process is also possible: in-plane libration can be damped by a judicious variation in tether reel in and reel out rates.

Libration is defined as the cyclic swinging motion of a tethered system relative to the local vertical, or the system R-BAR. The following treatment and terminology is adapted from Carroll (1985).

In-plane libration is measured with an angle theta of the tether relative to the system R-BAR. Out-of-plane libration is measured with the angle phi, again measured as the tether orientation relative to local vertical. For convenience, these are referred to as theta-libration and phi-libration.

In the extreme case, libration becomes spin, as the system begins a centrifugal ROT rather than a periodic back-and-forth swing. Such dynamics have applications both to momentum transfer techniques and potentially to non-thruster retrieval techniques.

Four aspects of libration behavior deserve notice:

First, the restoring forces grow with the tether length, so libration frequencies (at low amplitudes) are independent of tether length. Thus, tether systems tend to librate "solidly," like a dumbbell, rather than with the tether trying to swing faster than the end masses (as can be seen in the chain on a child's swing). For low orbits around Earth, libration periods are roughly an hour (theta-libration period is 0.577 times orbital period; phi-libration period is 0.5 times orbital period), and increase if amplitude is very large.

Second, tethered masses would be in free-fall except for the tether, so the sensed acceleration is always along the tether.

Third, the axial force can become negative for extreme swings (phi > 60°, or near ends of retrograde in-plane swings where theta > 66°), and this may cause problems unless the tether is released, or retrieved at an adequate rate to prevent slackness (or if the objects have active in-line thrusters).

Fourth, although theta-libration is not close to resonance with any significant driving forces, phi-libration is in resonance with several, such as out-of-plane components of aerodynamic forces (in nonequatorial orbits that see different air density in northward and southward passes), or electrodynamic forces (if tether currents varying at the orbital frequency are used). There are limits to the effect of such weak but persistent forces, but these limits are, in most cases, quite high. Further, when a system is in an eccentric orbit, variations in orbital rate cause librations which in turn exert periodic torques on an initially uniformly-rotating object, and in highly eccentric orbits this can soon induce tumbling.

Besides libration, other dynamic features of tethered systems are tether oscillations ("longitudinal" or length-wise, and "transverse" or crosswise, both in plane and out of plane), and end mass attitude oscillations (pitch and roll motion is called "pendulous motion," and yaw motion is just spin-around-the-tether axis).

Six control methods have been described in the literature. They are: tension variation via reel commanding; main object thrusting; deployed object thrusters; movable mass on tether; stiff tether and movable boom; aerodynamic effects. Only the first three appear practical in the early years of STS/station tethered operations.

Libration damping is done by paying out the tether when the tension is greater than usual and retrieving it at other times. This absorbs energy from the libration. In-plane libration causes large variations in tension (due to Coriolis effect), so such "yo-yo" maneuvers can damp in-plane librations quickly. Control of out-of-plane libration with this technique is more difficult. Tether oscillations can also be damped by use of this technique. Reversal of these techniques is possible so that libration can be "pumped" rather than "damped."

Although these long-period effects may dominate tethered motion when the satellite is fully or nearly extended, and special control procedures must be defined and validated, during the more dynamic phases (initial deploy and final retrieve), the time period is brief enough that such periodic effects are entirely masked by local Orbiter-specific dynamics.

7.3 TYPICAL HARDWARE

A wide variety of candidate hardware is under development for the various tethered missions now being planned. The following discussion is only meant to describe typical hardware.

7.3.1 Orbiter-Satellite Connection

The Orbiter and the tethered satellite are connected by a physical tether (section 7.3.1.1) and possibly by one or more in-line attentuation mechanisms (section 7.3.1.2).

7.3.1.1 Tether

Both conducting and nonconducting tethers are under development, selected either for pure support or for electromagnetic experimentation.

Candidate tether configurations either have no covering or have jackets of Teflon, Kevlar, or Nomex braid. Diameters range from 0.065 to 0.100 inches. The Kevlar (aramid) tether exhibits a very high strength-to-weight ratio, a wide operating range of -148° to 392° F, and good mechanical fatigue properties.

Typical tether weights run from 2 to 6 lb per kft for breaking strength of 400 to 600 lb.

An attractive material for quick satellite deployments is SPECTRA-1000. Such a tether would be 0.030 inches in diameter, weighing 0.2 lb per kft, with a 150-lb breaking strength. It melts at 300° F and has no long-term resistance to ultraviolet radiation and atomic oxygen erosion, but for short-term missions it provides 10 times the carrying capacity per line weight as does Kevlar.

Two types of tether stretch are of concern: elastic and deformable. Elastic stretch lengthens the tether under tension, but disappears under relaxation; deformable stretch is permanent alteration of line length.

Elastic stretch causes dynamic motion of the satellite, both in attitude and longitudinally along the tether. It damps out tension excursions caused by Orbiter motion (if unintentional excursions, this is a benefit; if deliberate excursions for control, this is a drawback). As a mechanism for energy storage, it can impart energy to the satellite in undesired and unexpected ways.

Deformable stretch is of concern in terms of measured length, as the tether is being retrieved. The "deployed length" parameter computed by the deployer mechanism may reach zero while a significant amount of stretched tether is still deployed. If this parameter is to be used in computations for libration control or as a cue for crew procedures, there must be a means of calibrating it against some other range determinator (e.g., radar or CCTV triangulation) and then entering a corrective offset value.

7.3.1.2 Attenuation Mechanisms

Portions of the Orbiter/satellite connector may be shock attenuation structure, either one-time (stretchable/frangible tether) or cyclic (springy tether). A property known as "lossiness" (where deformation occurs at a cost in work done) would be a useful characteristic of boom-tether-payload correction mechanisms; "lossy" structures could absorb and soften tension jerks.

7.3.2 Deploy-Only Hardware

Simple tether systems which do not envisage retrieval can pay out the tether from the deployed satellite. One such near-term system is the PMG on Hitchhiker G2. The tether is pulled out of a deployer assembly on the satellite as the satellite departs with its own momentum. Any snag will cause the tether/Orbiter attach plug to pull; at the end of the planned deploy, the plug will also nominally pull. Science data is taken only during the reel-out period.

More advanced versions of this system envisage stable stationkeeping at full tether extension. In such cases, the Orbiter/tether connection must be deliberately cut at the end of tethered operations (several REV's). Snagged tether during deploy, or deployment mechanism jam, must still result in immediate Orbiter/tether separation and a subsequent Orbiter/satellite safe separation without Orbiter maneuver.

7.3.3 Deploy/Retrieve Hardware

When tethered objects are to be deployed and then retrieved, much more complex systems are required. These can involve unfurlable boom structures, reels and motors, and corresponding monitor/control mechanisms.

7.3.3.1 Booms

For the TSS, a lattice deployment boom was chosen, rather than a telescoping or furlable design, because of inherently greater strength and damping. This is designed as a jointed non-continuous longeron boom, and is extended and retracted through a motor-driven nut at the canister outlet.

Should the boom and canister assembly need to be jettisoned from its primary support truss, pyro nuts are released and three constant-force linear spring motors give a 60-lb push over 80 inches of travel on tracks in the support truss. There is also a redundant pyro-operated tether cutter for this contingency. A tether cutter is also installed on the upper boom mechanism for simple tether guillotine.

The satellite docking cone at the top of the boom consists of a circular support covered with 0.2-in.-thick Teflon felt, and fastened to a tubular, structurally supported frame. The boom permits docking the satellite at an angle of 20°. The entire upper boom mechanism mounts on a contact ball bearing that allows ±180° rotation, powered by a gear motor, to align the aerodynamic boom for satellite reinsertion into the PLB.

7.3.3.2 Reel Motors

The TSS reel drive, which stores the tether, is powered by a brushless, 3-phase, 5-horsepower electrically-commuted samarium cobalt dc motor. The motor operates over a dynamic range of 10 rpm to 1000 rpm at torques up to 45 ft-lb.

7.3.4 Generic Tethered Object Systems

A generic tethered object may possess a wide variety of operational capabilities, based on different types of hardware.

7.3.4.1 Line Tension Mechanisms

The most straightforward technique for maintaining short-range tether tension is for the tethered object to activate thrusters pointed down the tether. Since the plume is directly into the Orbiter payload bay, most technologies are ruled out on contamination grounds, but nitrogen gas is fully acceptable and has sufficient performance. The TSS-S has two thrusters of 2-newton force (0.45 lb) each. They are controlled over the RF link by crew inputs to a payload-specific SPEC.

Another candidate technique for maintaining satellite tension against a tether is use of another tethered object, a deployed mass at the end of a 5- to 10,000-ft tether which pulls the main payload out (like a drogue chute), and maintains tension during retrieval (fig. 7-2). Postretrieval, this mass is jettisoned. This is the so-called "space anchor."

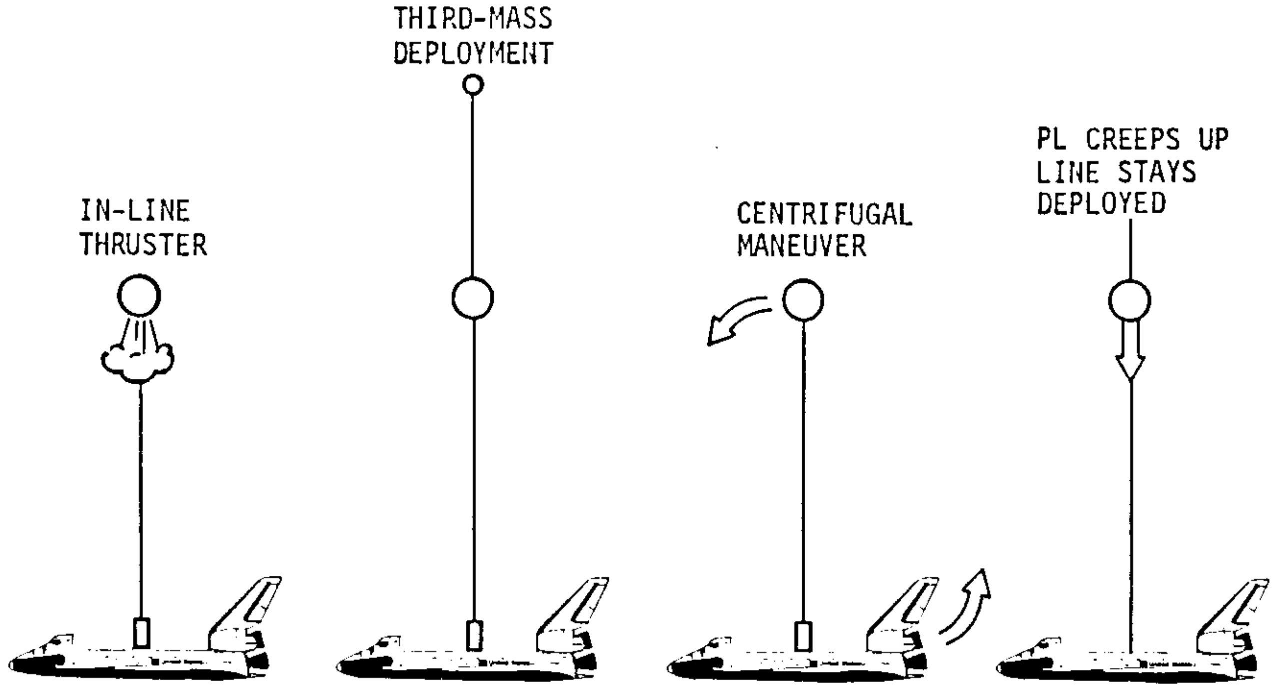


Figure 7-2.- Line-tension techniques.

7.3.4.2 Other Attitude/Translation Capability

Tension on the tether attach point on the satellite can be counted on to maintain satellite roll and pitch angles within small deadbands. However, the tether exerts no force in the satellite yaw axis (roll about the Orbiter-satellite line), so some means of active yaw control may be required both for satellite pointing and to prevent excessive tether twisting.

To assist in maintaining Orbiter-satellite relative stability, a tethered satellite may also possess translation thrusters for both in-plane (parallel to Orbiter X axis) and out-of-plane (parallel to Orbiter Y axis) maneuvers. In the event of significant satellite roll/pitch deviations, however, use of such satellite thrusters can significantly impact tether tension. While translating the satellite is a much more economical technique than translating the Orbiter, there remain operational and training concerns about the practicality of such a technique.

7.3.4.3 Radar/Optical Visibility Enhancement

Due to potential tether-induced radar degradation (in the case of electrically conducting tethers), the placement of radar enhancement devices on tethered objects may be highly desirable. If radar TRK throughout the deployed phase is deemed mandatory, use of an active transponder may be considered.

Visibility of the satellite, especially at night, may be a safety issue for close operations, especially within the range where gravity gradient forces can no longer be relied on to maintain tension. At night and with radar failed, if there are no other sensors capable of verifying safe Orbiter-satellite separation and rates, tether guillotine and Orbiter separation may be the only safe option. Hence, either high-performance reflectors or satellite-mounted lights (even long-period strobes) may be at least highly desirable.

Although volume XIV of the Payload Accomodations Document only specifies PL visibility to 1000 feet, an unresolved issue with tethered systems is whether the tether itself be considered part of the PL. If so, volume XIV lays out the requirement that the first 1000 feet of the deployed tether be visible, no matter how far out the actual satellite is. This issue must be resolved on a case-by-case basis.

Techniques to enhance visibility of the tether itself (particularly the segment closest to the satellite, for several hundred feet, either in entirety or pointwise) may be examined; such visibility may significantly enhance the ease and confidence of crew procedures during initial deploy and final retrieve operations.

7.3.4.4 Reels

Although the most common design involves a tethered satellite attached permanently to the far end of the tether, there are concepts in which the satellite itself may reel in the tether, either to store it onboard or to deploy it out the other end (i.e., the satellite "crawls" up the tether leaving it hanging free beneath it).

7.3.4.5 Grounding Device

For electro-dynamic applications, the electrical circuit must be closed by "grounding" the ends of the tether into the ionosphere, both at the Orbiter end and at the satellite end. This can be done with an electron gun or a hollow cathode.

7.3.5 Typical Tethered Payloads

A wide variety of tethered objects is already under development or advanced design. These are typical:

a. Tethered Satellite System (TSS)

The TSS is a 1100-pound, 5-ft-diameter spacecraft built by Aeritalia in Italy, under management of the Italian Council for National Research.

b. Plasma Motor-Generator (PMG)

Planned for use with the Hitchhiker G2 payload. Details TBS.
Has 200-meter tether, not retrieved.

c. Kinetic Isolation Tether Experiment (KITE)

Involves 1-ton payload (SPARTAN-class or actual modified SPARTAN spacecraft) to range of 1 to 5 kilometers (0.5 to 2.5 n. mi., or 3000 to 15,000 ft), in stable gravity-gradient attitude. In study phase only.

d. Small Expendable Deployment System (SEDS)

This demonstration experiment involves a basketball-size deployer and an 0.030-inch tether, 10 n. mi. long, weighing about 20 lb. The system is designed to deploy a payload of up to 1 to 1-1/2 tons; after deployment, the tether is jettisoned.

7.4 INTERFACE/IMPACTS TO STS

Operating a tethered object from the Orbiter can be expected to have significant impacts on many normal operating procedures, sometimes requiring major procedural changes or additions.

The primary impact of tethered objects will probably be from the enforced attitude holds required during the deployed phase; these attitudes will probably be either -Z toward or away from center of Earth. Impacts may include the following:

7.4.1 DAP

The constant torque from the tether tension can have significant impacts on attitude control, even if the Orbiter is allowed to reach an equilibrium attitude with the deployed tether. The system moments of inertia will be changed in several axes. The TSS-D torque will exert a controlling force in roll, and to a less extent in pitch, while yaw DB must also be maintained. Examination of this issue by appropriate guidance, NAV, and control analysts has not yet been undertaken.

7.4.2 Ku-Band Radar

Testing at White Sands in 1986 indicated that electrically-conducting tethers have a significant negative impact on RR TRK ability (this was anticipated on theoretical grounds). Forward scattering of the radar pulse down the tether seems to sufficiently defocus the pulse so that the return echo is weakened; the effect reduces the apparent radar cross section of the tethered object. This may have impacts for initial RR acquisition during retrieval.

7.4.3 Flight Dynamics

As a tethered satellite object is deployed to great range, the Orbiter/satellite system continues to orbit Earth in a path essentially determined by the c.m. of the whole system. However, both ground and onboard NAV will be TRK the Orbiter only, and can be offset from the true "(whole-system) Orbiter" by a significant amount. For the TSS at 20-mile range, this c.m. offset can amount to several hundred feet, which corresponds to several thousand feet downtrack error per REV. SV management must take this c.m. offset effect into account.

7.4.4 IMU Alignments

Restricted attitudes will require use of TGT's of opportunity. Further complications arise from the specific nature of the required attitude: down-deploys place the -Z STRK toward Earth and up-deploys may still have the satellite continuously in the -Z STRK FOV (at a range of 20 n. mi. the TSS-S brightness in terms of stellar magnitude should be between 0 and -2, in daylight); in either case, the -Y STRK is pointed nearly horizontal, although there should be a narrow safe-operating range for its use. Two stars of opportunity should be available through the -Y STRK for such alignments.

7.4.5 Microgravity Effects

At maximum extension of a substantially-sized tethered object, significant microgravity acceleration will be experienced in the Orbiter in the +Z ("down") direction. The TSS at 20 n. mi. will move the Orbiter/satellite system c.g. out above the Orbiter by several hundred feet, inducing a microgravity field of several tens of microgees inside the Orbiter. While not immediately noticeable, such a field would cause any free-floating objects to "fall" to the floor within a minute or two (this may impact crew habitability), will cause all fluids to settle, and can induce convective currents in the atmosphere and other fluids (depending on differential heating). This field can last on the order of a full day, under current plans. Proper fluid feed in OMS/RCS, fuel cells, and other systems may be affected; the induced weak convective effects in the cabin atmosphere may impact cooling. As a first approximation, no serious malfunctioning might be expected since the acceleration is in the same direction as during entry and landing; however, the very long time interval of the acceleration may introduce unexpected effects. Serious systems analysis of this issue is yet to be undertaken. It should be noted that such forces already exist within the Orbiter due to its large dimensions (the crew compartment is about 50 feet from the Orbiter c.g.), but the tether-induced forces will be several times as large and in another axis.

7.5 GROUNDRULES, ASSUMPTIONS, AND CONSTRAINTS

7.5.1 Dedicated Crew Size - Initial OPS

Analysis by CB indicates that four dedicated crewmembers are needed for initial dynamic tether mission phases: one MS is at the PLT station operating SPEC's; another MS is performing photodocumentation at the aft right station; the PLT is at the aft left station performing the actual flying; the CDR is at the CDR station coordinating, and preparing for contingency operations such as guillotine and separation. Conceivably, a TSS PS could also be present as an observer.

7.5.2 Dedicated Crew Size - Mature OPS

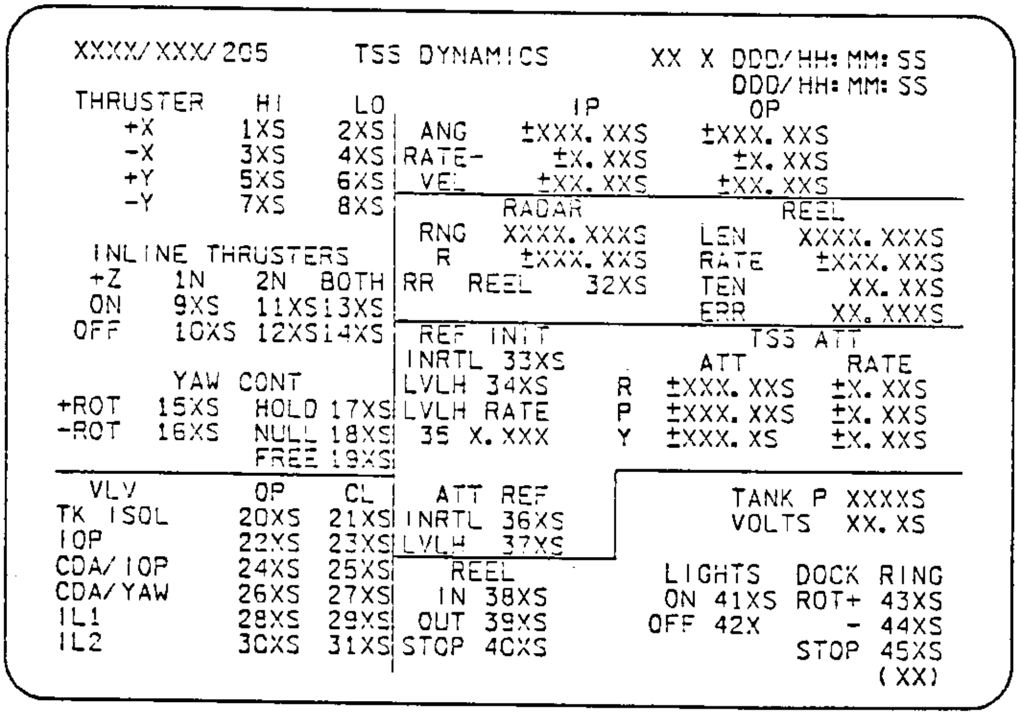
Regular tether operations, once sufficient experience has been accumulated, may be performed with three or even two dedicated crewmembers.

7.6 SPECIAL DISPLAYS/CONTROLS

Unique features of tethered operations require specially-designed monitoring tools and techniques. These can involve standard RNDZ items such as SPEC functions, CCTV systems, and cabin tools such as ranging rulers.

7.6.1 Crew Displays

During 1986 SES TSS runs, a unique pseudo-SPEC function was designed for "TSS Control," and it was arbitrarily designated "SPEC 50"; this number and the entire display definition was unique to the SES. Parameters available on the SPEC 50 display included RR range and range rate, in-plane and out-of-plane angles and angle rates, and NLOS ft/s rates, tether length and length rate (measured by the TSS-D mechanism), etc. The displayed radar range was approximately 75 feet higher than the tether length because of geometric factors. Significant insights were obtained into the desirable features of the real, still-to-be-defined "TSS Control" SPEC. Two displays, one for systems and one for dynamics, were eventually developed (fig. 7-3).



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XXXX/XXX/205        TSS DYNAMICS          XX X DDD/HH:MM:SS
                                               DDD/HH:MM:SS
THRUSTER     HI      LO              IP           OP
   +X        1XS     2XS| ANG    ±XXX.XXS    ±XXX.XXS
   -X        3XS     4XS|RATE-      ±X.XXS      ±X.XXS
   +Y        5XS     6XS| VEL      ±XX.XXS     ±XX.XXS
   -Y        7XS     8XS|------------------------------------------
                        |      RADAR                 REEL
                        | RNG   XXXX.XXXS    LEN    XXXX.XXXS
  INLINE THRUSTERS      |  R     ±XXX.XXS    RATE    ±XXX.XXS
 +Z     1N    2N   BOTH |RR  REEL    32XS    TEN        XX.XXS
 ON     9XS   11XS13XS  |                    ERR       XX.XXXS
 OFF    10XS  12XS14XS  |------------------------------------------
                        | REF INIT                 TSS ATT
                        |INRTL 33XS             ATT       RATE
        YAW CONT        |LVLH 34XS       R  ±XXX.XXS   ±X.XXS
+ROT   15XS   HOLD 17XS |LVLH RATE       P  ±XXX.XXS   ±X.XXS
-ROT   16XS   NULL 18XS | 35 X.XXX       Y  ±XXX.XS    ±X.XXS
              FREE 19XS |
------------------------|               ---------------------------
  VLV        OP    CL   |  ATT REF     |      TANK P XXXXS
TK ISOL      20XS  21XS |INRTL 36XS    |      VOLTS   XX.XS
IOP          22XS  23XS |LVLH   37XS   |
CDA/IOP      24XS  25XS |--------------
CDA/YAW      26XS  27XS |    REEL          LIGHTS   DOCK RING
IL1          28XS  29XS |  IN 38XS         ON 41XS  ROT+ 43XS
IL2          30XS  31XS | OUT 39XS        OFF 42X      - 44XS
                        |STOP 40XS                  STOP 45XS
                                                         (XX)
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Figure 7-3.- Tethered OPS control display.

CAUTION: This is not a draft SPEC and in fact may contain parameters not available for on-board display.

Enough requirements were developed to raise the issue of creating two TSS crew displays, one for TSS-S/D systems and the other devoted to TSS dynamics. The former would include a substantial body of still-undefined TSS-D parameters, as well as TSS-S systems monitoring and reel controls.

The latter would display data needed immediately at the aft crew station by the crewmember performing the flying and would be the basis for design of a generic tether dynamics SPEC for any application to tethered operations.

On the TSS DYNAMICS display, the crew should have the option of entering a length bias to correct for tether stretch during deploy; at a set range measured both by radar and by TSS-S angular size in the CCTV, the measured length should be observed, and the necessary bias consequently computed and entered.

With a correct length and length rate, time-to-berthing should be computed and displayed in MM:SS. This was simulated at the SES by setting a countdown clock based on known run duration, and it was found to be extremely useful during the terminal phase in estimating corrective firings required and in avoiding overcorrection.

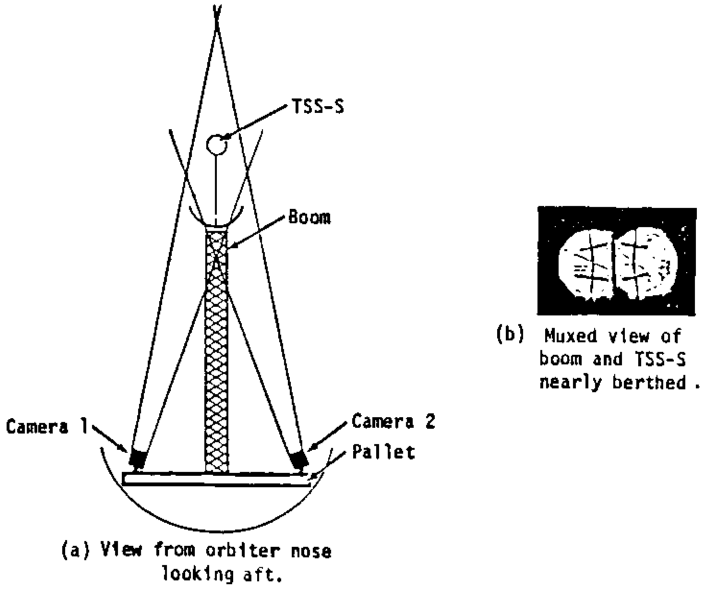
TSS-S attitudes must be displayable in an Orbiter relative frame as well as LVLH, so that proper berthing alignment can be noted.

7.6.2 Special CCTV Arrangement

For 1986 SES TSS runs, a special CCTV arrangement specified that two CCTV's be placed on the TSS-D pallet, near the PLB attachment points on the right and left side. Each camera was aligned to look up past the boom tip towards the TSS-S, and the two views were multiplexed onto monitor 1 at the aft crew station to provide a pseudo-stereo representation (fig. 7-4). This technique provided superb cues to TSS-S/boom relative position and rates, especially in the final stages of the retrieval.

7.6.3 Ranging Rulers

The symmetry of the TSS-S lends itself well to use of CCTV image size subtended angle as a backup range determinator, as done on other PROX OPS missions. Traditional "ranging rulers" (which when placed over the max-zoom image of the TSS-S on the aft flight deck monitor provide a usable range indication) have been produced and utilized successfully; a special stereo ranging ruler, used to measure the center-to-center distance on the muxed view, was also tested and proved to be useful in ranges of under 200 feet. Both of these range determinator techniques are highly desirable because of nominal loss of RR range at close ranges and an unpredictable bias on the tether length measurement (as measured by the deployer mechanism) due to tether stretch during the deploy period (at final berthing, the "length" measurement may be reading negative by tens, if not hundreds of feet).



(a) View from orbiter nose looking aft.

(b) Muxed view of boom and TSS-S nearly berthed.

Figure 7-4.- CCTV arrangement/TSS-D boom/pallet.

7.7 CANDIDATE PROCEDURES

Early theoretical considerations and feasibility assessment have generated several candidate procedures for tethered operations. No verified procedures exist for any mission phase at this time.

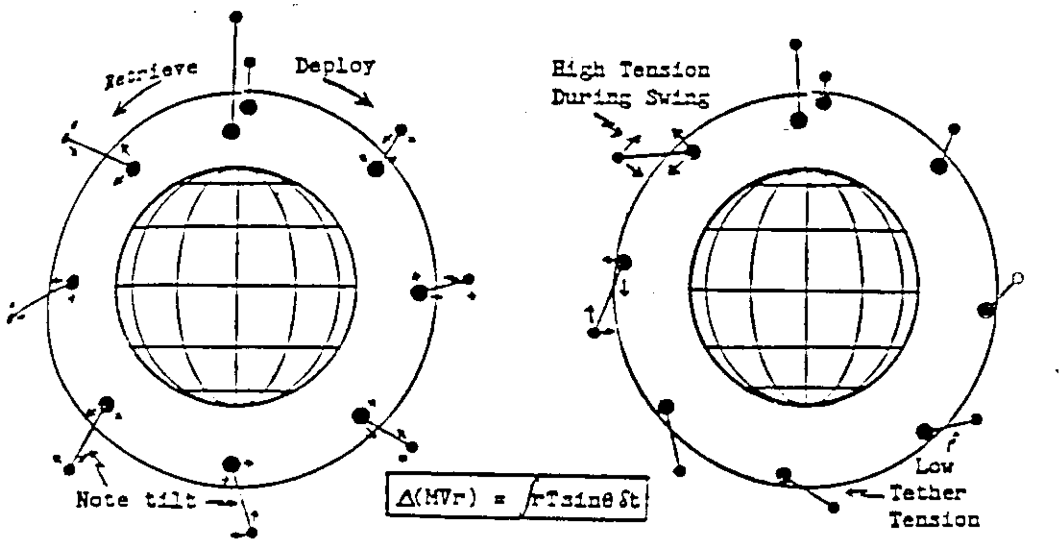
7.7.1 Deploy

As discussed by Carroll (1985), there are several different theoretical deployment techniques. Two are shown in figure 7-5.

In both cases, the initial deployment is done with thrusting or a large boom.

In the first case (left), the tether is paid out under tension slightly less than the equilibrium tension level for that tether length. The tether is slightly tilted away from vertical during deployment (upper object trailing along V-BAR) and librates slightly after deployment is complete.

In the other case, after the initial near-vertical separation (to about 2 percent of the full tether length), the two end masses are allowed to drift apart in near-free-fall, with very low but controlled tension on the tether. Just under one orbit later, the tether is almost all deployed and the range rate decreases to a minimum due to orbital mechanics effects. Thrusting or tether braking is used to cushion the end of deployment and prevent end mass recoil. Then the tether system begins a large-amplitude prograde swing towards the vertical, during which high tether tension occurs.



Momentum Transfer During Deployment & Retrieval

Momentum Transfer During Libration (after low-tension deployment)

Figure 7-5.- Deployment technique

In both cases, the angular momentum transferred from one mass to the other is simply the integral over time of the radius times the horizontal component of tether tension. In one case, transfer occurs mainly during deployment; in the other case, it occurs mainly during the libration after deployment.

An intermediate strategy, deployment under moderate tension, has also been investigated. However, this technique results in very high deployment velocities and large rotating masses. It also requires powerful brakes and a more massive tether than required by the other two techniques.

Coriolis forces can cause a large bowing of the tether during deployment of light payloads. At low altitudes, aerodynamic drag can have a similar effect.

7.7.2 Stationkeeping

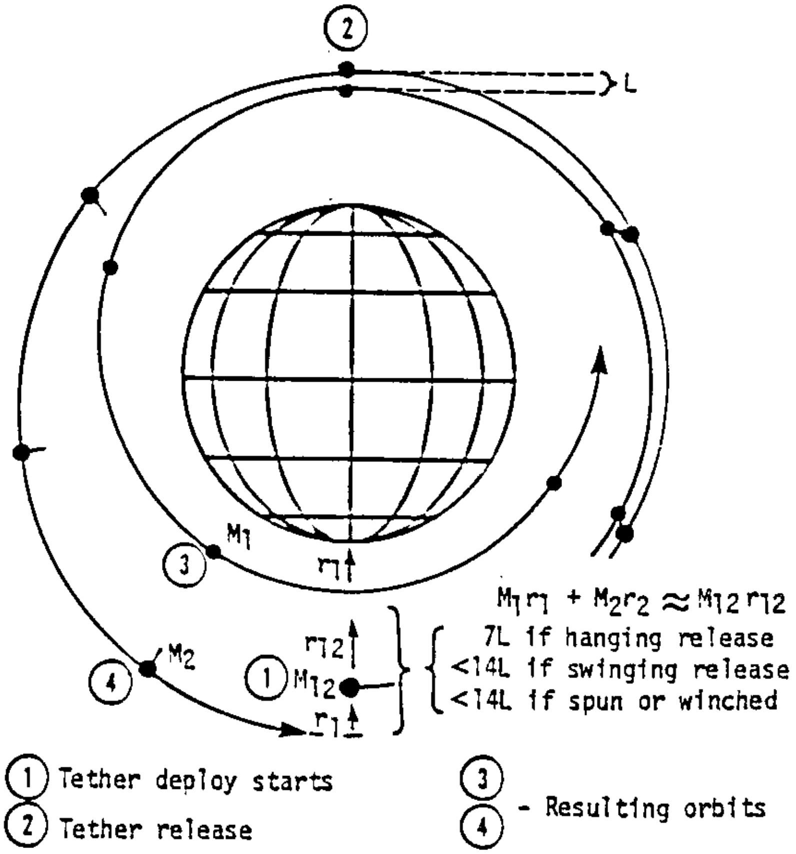
The primary control mechanism for distant tethered objects will probably be reel in/out operations, supplemented by thrusters on the object and on the Orbiter. Secondary effects can be generated by use of the moment arm provided by a long boom (such as the TSS-D).

Details remain undefined until more realistic analysis and simulations are completed.

7.7.3 Nominal Detach

Many interesting applications involve performing a hanging release of a tethered object (fig. 7-6) in order to transfer momentum from a primary body to a smaller one (resulting in transfer to a higher or lower orbit, as desired). The tether (and reel) may either be on the primary body and be retrieved for reuse or on the released body.

For two tethered objects at distance L, release of the tether causes a growing separation. After half an orbit, that separation of orbits reaches a distance of 7 times L (physical separation will be greater since the lower object will also be substantially further ahead due to orbital motion, by about 20 times L).



Effects of tether deployment and release

Figure 7-6.- Hanging release.

Under conditions of swinging release (fig. 7-7), that orbit separation can be any value less than 14 L; for spun or winched releases, it can be greater than 14 L.

Carroll (1986) gives an approximation for achievable hanging release ΔV (in LEO, with the deployed object mass much less than the main object mass) as:

ΔV = k Vc SQRT (tether mass x end masses sum / end masses product)

where Vc = 2300 ft/s for Kevlar, 3300 to 3800 ft/s for advanced materials
and k = 1 for spinning operations
1.15 for hanging releases
1.2 for swinging releases
1.4 for winching operations

Note that the ΔV is a function of tether mass, not length (a more massive tether can support more energetic releases). For payloads very light in comparison to launching object, the SQRT reduces to SQRT (tether mass / payload mass). For breaking strength of 10,000 pounds, Kevlar weighs 40 to 100 lb per kft, and Spectra-1000 weighs 12 to 15 lb per kft.

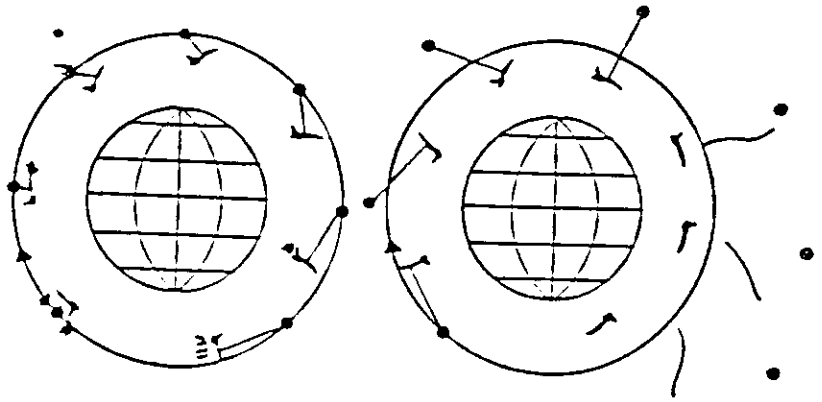


Figure 7-7.- Low-tension deployment, swing and release.

Of course, momentum given to one object is taken from another. If the momentum can later be restored by a high-efficiency propulsion system, this is tolerable. In some cases this may even be useful: if a space station uses a tether to deboost an Orbiter at the end of its resupply mission, space station orbital decay makeup needs and Orbiter deorbit burn propellant needs are both reduced.

7.7.4 Retrieve (Active)

Retrieval of tethered objects is the most difficult phase of tethered operations.

7.7.4.1 Theoretical Basis

The theoretical basis of retrieval stability contains a large, but as yet unvalidated, body of mathematical analysis.

7.7.4.2 Simulator Basis for Procedures

In 1986, a series of TSS retrievals was made on the SES, with variations in Orbiter DB's and in allowable TSS-S out-of-plane and in-plane excursions. A "best technique" was subsequently selected for follow-on contingency runs, but this cannot be construed as being any sort of standard, validated procedure. This technique is offered only as a viable candidate, which may illustrate many of the characteristics the final procedure should be expected to have.

7.7.4.3 Procedure Setup

The DAP was in LVLH, with nominal RNDZ/PROX OPS deadbands (2° NORM, 1° VERN for both DAP A,B), and small translation impulses (0.05 ft/s A, 0.01 ft/s B).

The approach was guided along a funnel with sides proportionately narrowing as tether length decreased: at 500 feet, a 5° dispersion was acceptable in either in plane or out of plane, in the 400's it was 4°, in the 300's it was 3°, and in the 200's it was 2°. The angles and rates of the satellite are observed on SPEC 50.

7.7.4.4 Initial Retrieval

Control can be accomplished by Orbiter translation, performing ±X and ±Y burns with the THC to fly the boom tip back towards the satellite image (in the case of the TSS-S, it is also possible to fly the satellite itself by use of its onboard thrusters, but this has not been thoroughly evaluated, and it may be more reasonable to make use of piloting techniques with which the crewmembers are already familiar). Small Orbiter DB's have been (not surprisingly) found to be best for allowing use of this satellite LOS as a cue to corrective maneuvering.

One significant effect of Orbiter RCS cross-coupling has been noted and deserves mention. When observing a target out the overhead window, the crewmember commands RCS translation maneuvers perpendicular to the LOS in order to control Orbiter/target relative position (in a "fly to" mode). However, because translations induce some cross-coupled rotation, the initial LOS motion of the target may be momentarily misleading. This effect is discussed in detail in section 6.2.1.2 and figure 6-7, and accentuates the need for the crewmember to be patient after performing translation pulses, to see the LOS motion after deadbanding, and not be misled by the initial LOS rates (which contain deceptive rotation-induced components). This also underlines the need for tight DB's.

To repeat, these translations are performed to keep the satellite LOS (as displayed on a SPEC) under control in the progressively narrowing funnel. Corrections must be made when the satellite LOS angles exceed the allowable limits; corrections can also be made as it passes through the zero angle(s) to null out the angle rates.

7.7.4.5 Close-in Procedure

Prior to radar losing lock inside 80 to 100 feet, the control scheme must change. Since RR angles are already becoming biased due to the geometric offset of the Ku-band antenna compared to the boom tip, and since RR lock is soon to be lost anyway, it is desirable to switch to another "fly-to" technique. Criteria for translation firings is therefore changed from RR angles to the television monitor, where the multiplexed stereo image of the boom tip is "flown to" a spot directly between the twin images of the satellite. This new piloting technique also appears to be "common sense" with easily understood criteria for corrections.

To prevent automatic deadbanding from unexpectedly disturbing the LOS, at this changeover point, DAP is moded to MAN and RPY to PULSE/PULSE/PULSE (i.e., free drift). During this final phase, the Orbiter attitudes may drift up to 5° from initial, but this should be acceptable.

A typical tension time history is shown in figure 7-8 (two examples). While the in-line thruster constant value is apparent, wide excursions also occur. This includes momentary zero-tension intervals.

7.7.4.6 Alternative Procedures

An alternate control technique during the terminal phase (defined as the close range where RR lock has broken, through contact) is to use vernier attitude control to move the boom tip. There appear to be two arguments against this technique. First, the crewmember is already accustomed to flying by translation and has become well versed in predicting LOS reactions to controllable inputs, so a new control technique would require a new period of adaptation during a very brief and dynamic phase. Secondly, since the boom probably does not extend through the Orbiter c.g., Orbiter rotations (particularly pitch) will induce substantial boom tip translations in the Z axis, complicating the piloting. For this reason, candidate procedures so far use translation control all the way through contact.

7.7.4.7 Failure-Mode Procedures

Several SES runs were made with RR failed, with VRCS failed, or with one of the two TSS-D boom pallet CCTV's failed. Prop usage more than doubled, primarily due to difficulty in correcting subtle angle rate dispersions (in sensor fail cases), or to overcorrections (in VRCS fail case). Higher tether tension excursions and longer periods of zero tension were also experienced. Nevertheless, retrievals seem to have been accomplished successfully.

7.7.4.8 Satellite-in-Motion Procedures

Pendulous motion of the satellite was another area of concern. This consists of the satellite rocking in pitch/roll from the tether attach point. We induced large pitch/roll angle rates, up to 5 to 10 deg/s (any higher, and the tether wrapped around the satellite), and noted how they quickly coupled

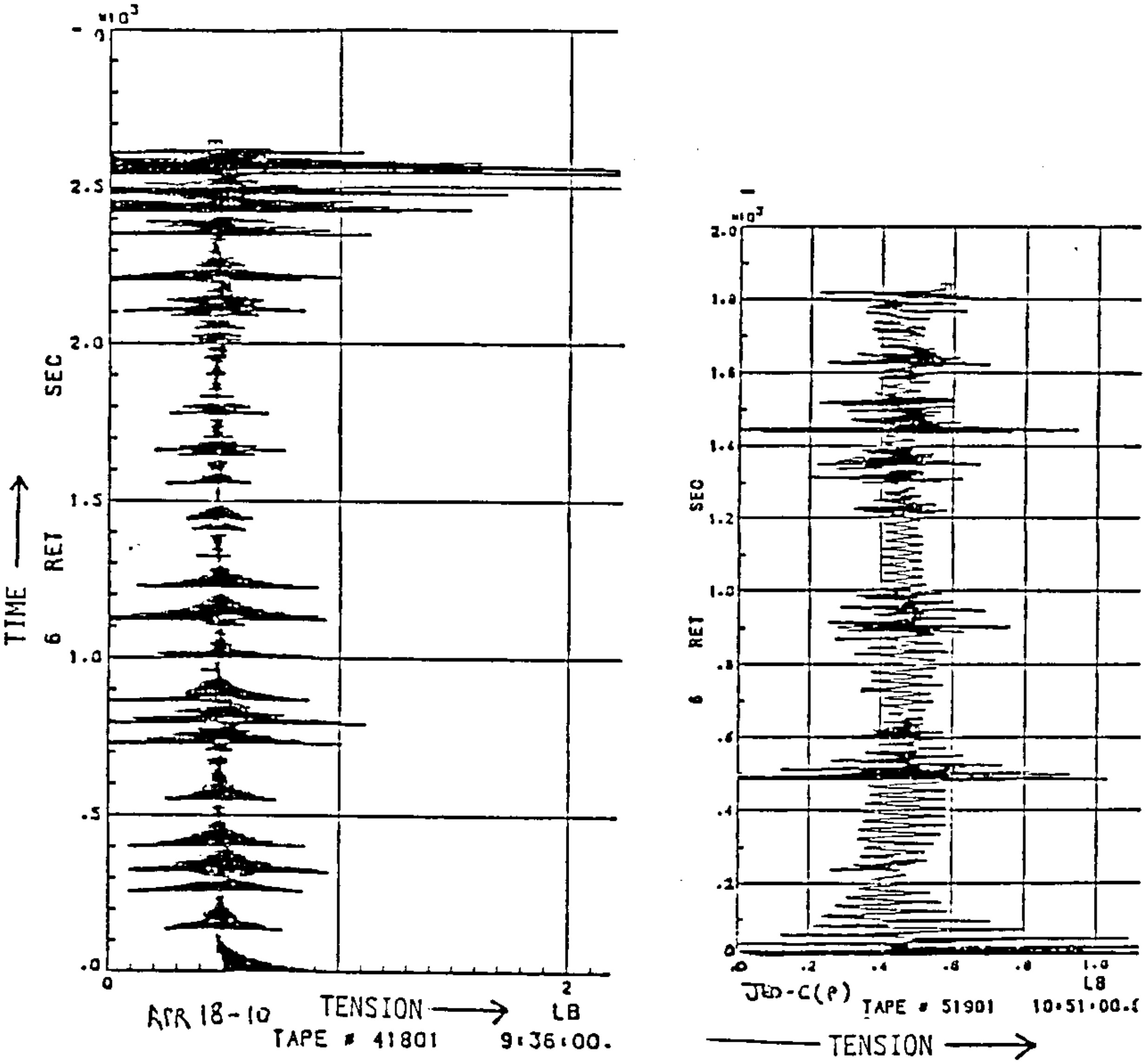


Figure 7-8.- Tension history plots with inlines, various control techniques (illustrates occurrence of zero tension).

into other axes and were continuously excited by subsequent RCS firings. While the rates never damped out, contact with boom tip was usually made well within acceptable angle ranges. Whether the contact range rate was safe could not be determined (this is a hardware issue for the deployer mechanism contractor to judge), but it did not appear to be all that much worse than in nominal cases.

7.7.5 Retrieve (Passive)

Retrieval without in-line thrusters may be performed either entirely without line tension, or with some alternate means of maintaining line tension. Both were performed on the SES in 1986, under many variations. In the absence of vigorous off-line validation, these candidate procedures must be considered very preliminary.

7.7.5.1 No-Tension Retrieval

The no-tension retrieval was performed in several variations, designed to create a known Orbiter/satellite REL position for final approach (and thus allow use of a canned preverified separation maneuver in the event of guillotine). In one, the Orbiter went to inertial hold and performed an inertial flyaround of the satellite until it reached the V-BAR (120° of orbit travel, in about 30 minutes); in another, the Orbiter went only to the satellite R-BAR, in an attempt to use gravity gradient forces to provide a small tension; in another, the approach was made in LVLH mode directly from the initial condition.

In all cases it was found possible to fly the boom tip up to the satellite while monitoring tether slack (comparing RR to tether length) and keeping it small. It was noticed that tether jerks which did occur did not seem to induce worrisome closing rates; instead, due to random satellite attitude, they mostly imparted random attitude rates to the satellite rather than inducing translations.

The major unknown in this class of procedures was how the system would respond at final boom contact. The satellite attitude was essentially random during final approach, although tether jerks tended to pull the attach point toward the center of the visible hemisphere. The SES model was of low fidelity here since it did not simulate "wrap" of the tether around the surface of the satellite; instead, the tether always ran from the attach point straight to the boom, even through the body of the satellite, if the attach point was passing across the hidden hemisphere (the "back side" of the satellite). It is conceivable that with the real hardware the satellite could nestle into the boom tip and then, through a series of final jerks as the tether continues to be reeled in, become properly aligned for latch capture (assuming no snags on satellite structure).

Even so, however, a procedure which allows tether wrap around the satellite appears to be highly undesirable. Since the satellite attitudes and rates go essentially random early in all of these scenarios, and do not appear to be controllable by any crew procedures, this option appears unacceptable.

7.7.5.2 Centrifugal Tension Procedures

The LVLH frame of reference is noninertial. The LVLH is rotating at orbital rate of 4° per minute, or 0.067 deg/s. Under initial conditions for these runs, the Orbiter is moving in a body vector -X direction relative to the Orbiter/TSS system. This system rotation will generate some centrifugal force between the Orbiter and the satellite as they rotate about their mutual center of mass. This induced tension can be enhanced by deliberately creating a higher rotation rate. We chose to rotate in the -X direction (versus +X), because we were already moving in that direction and because later control maneuvers induced less cross-coupling.

At a range of 500 to 600 feet, a -X ΔV of about 0.3 ft/s is performed with THC (monitored on AVG G in SPEC 33), followed by establishment of a -0.150 deg/s pitch rate via RHC input (monitored on OPS 201 display). In the LVLH frame this was one full turn in 40 minutes. The boom tip television image is "flown to" the satellite image using VERN pitch and B NORM out-of-plane translation. DAP is manual, with ROT in DISC-PULSE-DISC (i.e., free in pitch only), and pulse sizes (deg/s) of A NORM 0.1, B NORM 0.04, A VERN 0.01, B VERN 0.002. Turning off in-line thrusters results in the tether elasticity's pulling the satellite inwards, creating a loss of tension for several minutes. However, after a series of gentle jerks, the satellite settles into a reasonable stability with a tension of 20 to 30 percent of that generated by in-line thrusters (several tension history plots are shown in figure 7-9).

If thruster fail is known at long range, and if there is manual control over the reel-in rate, the centrifugal maneuver can be initiated merely by increasing this reel-in rate, without need for thruster firing.

Since this tension is so weak, it can easily be lost entirely by small Orbiter (actually, boom tip) Z translations, even those induced by cross-couplings from translations in other axes or from rotations (translation cross-couplings or just geometric results). Thus, extremely delicate maneuvering is mandatory: pitch in A/MAN/VERN, and translate in B/MAN/NORM with 0.01 ft/s pulses. When maneuvers were made accidentally in higher rates, tension went to zero for long periods and sometimes never restabilized. Several plots of tension-versus-time are shown in figure 7-9.

Using higher rates to create stronger centrifugal force does not solve this problem. The SES reel rate model reacts badly to strong tether tension jerks by slowing or even stopping the reel-in rate. This occurs even if the average centrifugal line tension remains far below the nominal in-line thruster-induced tension, since tension spikes continuously occur due to RCS firings and these short spikes can freeze the reel-in for several seconds or longer. It is an open question whether this model is correct (are the gains simply set too low?), and if the reel-in rate is actually much more robust than a higher system spin rate might be feasible. However, in that case, other limiting factors appear.

As the satellite is reeled in during this 0.15 deg/s system spin rate, angular momentum is transferred into the Orbiter and the spin rate increases. A more important impact on the spin rate is the tendency of the satellite to pull up (+X) in the television field of view, requiring more "-pitch" ("pitch up" in -Z mode) to force the boom tip to chase it. This drives the pitch

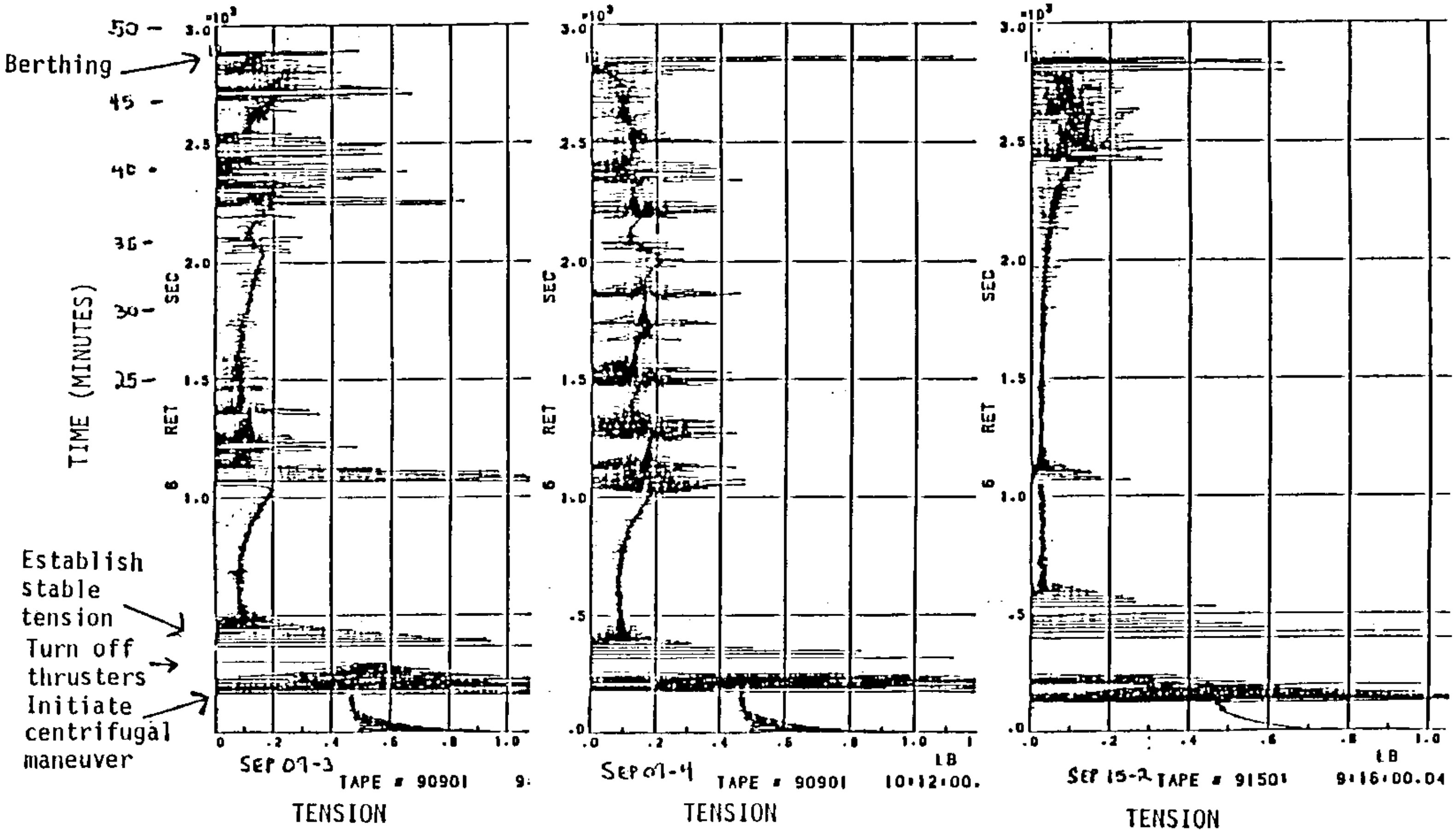


Figure 7-9.- Tension history plots. No in-lines. Centrifugal tension only.

rate from the original -0.150 deg/s to a higher rate (up to -0.400 deg/s), increasing centrifugal force and ultimately causing the satellite reel motor to jam.

To avoid this, a different "fly to" scheme must be used within about 400 feet (when tether centrifugal tension reaches about 35 percent of nominal thruster tension). This is to perform small (0.01 ft/s) +X translations, usually in bursts of 10 or 20 per minute for several minutes (the use of fewer but larger pulses does not work because of the excessive impulsive disturbances of such larger pulses on tether tension). These are sufficiently low and "pure" so as not to induce excessive pitch motion, or in any other way cause loss of the very fragile tension forces (-X pulses, it seems, are too "dirty" in terms of cross-coupling, and they do induce excessive jerks which destroy the constant non-zero tension induced by the system ROT). With such a scheme, if performed patiently and carefully, tension and length rates can both be maintained at reasonable levels throughout this interval. Care must be taken to perform these pulses randomly rather than in a regular pattern, since the longitudinal bobbing resonent frequency of a 300 to 500 foot tether would be on the order of several seconds, and it would not be good if the firings excited that motion.

Once length has dropped below 200 feet, the pitch control option can be resumed. The Orbiter, at its current rotation rate, at this point already possesses enough angular momentum that further reeling in of the satellite does not significantly add to it. These rates may climb to 0.350 to 0.400 deg/s at contact, a high but not unreasonable rate. Meanwhile, induced centrifugal tension drops as the tether length decreases.

The tension maintained constantly on the tether also maintains satellite attitudes to within proper ranges for berthing. This can be crucial to a successful retrieval. During the final few feet (as satellite body radius becomes large in proportion to remaining tether length), tension excursions become high and tension is sporadically lost; however, contact rates and attitudes appear well within acceptable ranges.

7.7.5.3 Open Issues

This passive centrifugal retrieval technique requires substantially more study, both in simulators and analytically. What are visibility considerations (for example, the Sun crossing the FOV at least once)? What are control impacts of finishing retrieval with a pitch rate as high as half a deg/s? What kind of separation maneuvers can be validated for use if a guillotine is required from a random Orbiter/TSS-S pitch orientation? How can this retrieval mode be initiated from any arbitrary range, since the in-line thrusters may fail at any range? These questions were uncovered by the current effort (answers will take substantially more effort); it is prudent to assume that additional questions await discovery.

In conclusion, initial feasibility assessment does suggest that this centrifugal procedure is a viable candidate for consideration in the no-thrusters contingency case, but it can in no way be considered verified since unconsidered factors (or different models) may provide hidden showstoppers.

7.7.6 Reel Stop/Start

The 1986 TSS SES runs indicated that there may be serious problems associated with reel motor brake/jam/lock cases. The TSS-S possesses yaw control thrusters (roll about the axis of the tether), and has ±X and ±Y translation thrusters (they work well on the SES; we found no surprises) but it has no roll/pitch attitude control. As long as there is tension on the tether, restoring torques are generated against all roll or pitch dispersions. This feature, this lack of positive roll/pitch attitude control, severely impacted the passive no-tension techniques described above since it led to random satellite attitudes and consequently probable tether wrap; for the motor stop case, it is even worse.

The problem is this: the TSS-S has its initial approach rate of several tenths of a foot per second, and only the weak in-line thruster is repelling it from the Orbiter. From several runs and from back-of-envelope calculations, it is clear that even after reel lock the TSS-S will continue inward (toward the Orbiter) from 20 to 40 seconds, then come to a stop, then fall back out (accelerated by the in-line thrusters) and suddenly run into a jerk when the tether goes taut. At this point, small attitude dispersions which are always present will be translated by the attach-point jerk (a moment arm offset from the satellite c.g.) into roll/pitch rates of up to several deg/s. Even if the rates are low after this first jerk, the second jerk a minute or so later drives them out of control; usually one jerk is enough. Within a minute, the tether is wrapping around the TSS-S.

This could possibly be avoided if the motor stop were extended over a long period of time, say 30 to 60 seconds, while the weak in-line thrusters maintain tension. However, under the current design the reel brake will probably bring the reel to full stop within 5 to 10 seconds, and the TSS-S will then surge upwards in free-flight before falling back against its tether and going into an uncontrolled tumble. Guillotine follows.

[Intuitively there may also be problems with where the slack tether collects during this particular sequence. When the reel-in ceases, the TSS-S and tether will continue towards the Orbiter under their own momentum, and the excess tether immediately above the TSS-D boom may collect at the boom tip and even spill over. The boom is high enough to prevent contact within the PLB unless the slack amounts to more than 100 feet; however, snagging on the outside of the boom tip may occur, especially if the slackened tether forms loops.]

A wide variation of techniques was tried to counter this disastrous consequence of engaging the reel brake. The in-line thruster was cycled on and off to force the TSS-S back against a taut tether; Orbiter +Z translations were used to reduce slack, and -Z translations were made to soften the full-length tautness jerk; centrifugal forces were induced by system ROT's to try to push the bouncing TSS-S against a taut tether. None worked; in all cases, each jerk pulled the TSS-S back inwards in preparation for a subsequent jerk, and no sign of TSS-S angle excursion damping could be detected. This was most likely because the greatest force of the jerks came from the high random attitude rates (which never damped), with random disturbances from variations in absolute Orbiter/TSS-S range.

Even at system spin rates of up to 1.0 deg/s, the bouncing would not damp out. The bouncing was controllable in that the satellite appeared to be bouncing around the radius of the tether, never approaching more than 10 to 20 feet from full extension (and thus not threatening to contact the Orbiter). But TSS-S attitudes were out of control, and tether wrap was almost certainly unavoidable. By the criterion of safe TSS-D retrieval, this situation was absolutely unacceptable and guillotine would be mandatory.

An attempt to spin-stabilize the TSS-S by deliberately inducing a yaw rate in it also seems to be ineffective. Hopefully this would have restrained pitch/yaw excursions and allow the bouncing to damp out. However, the control system as modeled only allowed a ±5 deg/s rate and this was not enough: angle rates quickly became just as bad as with no "spin-stabilization." Perhaps a TSS-S yaw (spin) rate of 20 to 30 deg/s would be more effective, but it may not be achievable with current TSS control laws. Also, fluid damping in the satellite (e.g., vanes in the N2 tank) may promise sufficient stability.

If the fall-back jerk is not too strong (either at a close range when the closing rate is low, or if the Orbiter performs some -Z in anticipation of the tether going taut), then some control scheme may be effective. Although we were never successful in several runs (some up to a full orbit in duration) in establishing stability (defined as continuous non-zero tension and attach point remaining on visible hemisphere of TSS-S), we cannot rule out the possibility that some technique may be developed. Nevertheless, it looks unlikely.

The implications of this discovery seem to be that it is unacceptable to brake the reel at all, at least during retrievals and at the close ranges we were examining. Any situation requiring braking the reel should be serious enough to accept consequent TSS-S guillotine. This is an extremely severe constraint and needs to be widely discussed in the dynamics and operations groups. Preliminary analysis has suggested that merely unpowering the motor would allow a sufficiently gentle stop for tension to be maintained.

Furthermore, planning must anticipate an unintentional reel jam at ANY range, with subsequent loss of TSS-S attitude control. Procedures must be developed to accomodate such failure modes.

7.7.7 Jettison/Separation

In the tether guillotine case, two features were accentuated. First, the TSS-S becomes a free-flier with an initial closing rate, and secondly, if the in-line thrusters are still firing, they begin to impart an unpredictable ΔV to the TSS-S as the attitude of the satellite wanders out of control. Neither of these features is at all comforting. A prompt and powerful (1 ft/s) Orbiter +Z separation seemed called for (alternately, a strong TSS-S X/Y translation may be initiated before guillotining). Much more PROX OPS and separation analysis and simulations are required here before we can be comfortable about having a reliable procedure.

7.7.8 RNDZ With Tethered Object

There are attractive scenarios which involve a RNDZ (perhaps by the Orbiter or an Orbiter transfer vehicle (OTV) with a tethered object (a docking wharf deployed perhaps from a space station or an Orbiter). These concepts may appear ambitious, but with precise NAV data (e.g., GPS) may actually not be difficult. A sample profile is shown in figure 7-10.

Tethered capture has large benefits in safety (remoteness from primary object) and operations (no plume impingement on primary object; large fuel savings). The main hazard is collision due to undetected NAV errors or tether failure.

The tethered object itself may actually be active and perform the major MNVR's for docking.

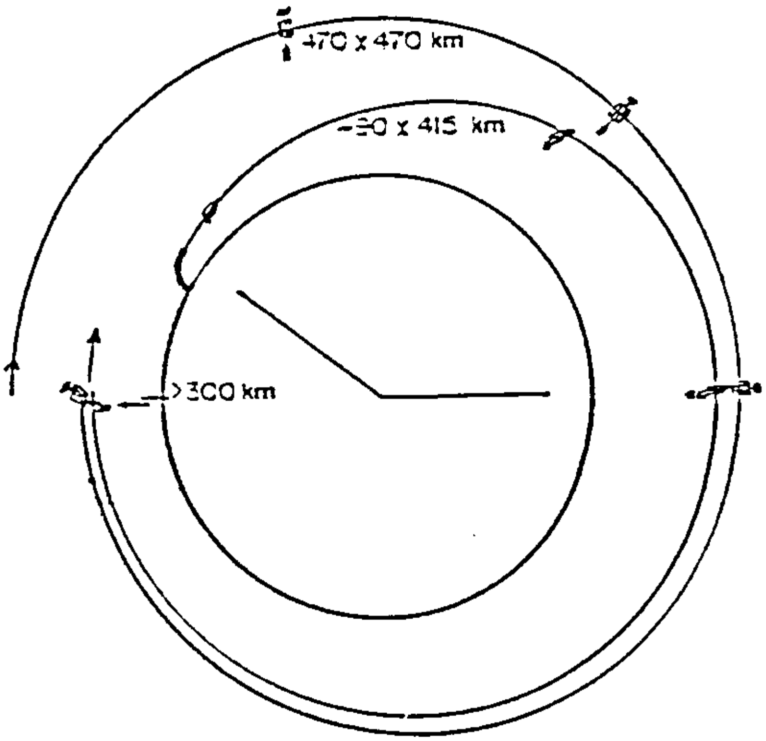


Figure 7-10.- Tether-mediated RNDZ.

Carroll (1986) points out that with experience, much longer tethers might be used to allow vehicle capture at significantly suborbital velocities. This could radically increase PL's delivered to the main object (e.g., a space station facility). Since launch trajectories do not approach the main object, vehicles of uncertain reliability can service the facility and unconventionally boosted PL's can be captured safely.

7.7.9 Loose Tether

7.7.9.1 Jettisoned From Orbiter

Due to the low mass-to-area ratio of typical tether materials, in LEO the tether should depart from the Orbiter extremely rapidly due to differential drag. Natural drag effects dominate all reasonable Orbiter ΔV maneuvers except at very low range.

7.7.9.2 Broken Tether

A loose tether attached to the Orbiter, especially one with a closing velocity induced by continued reel-in (and to a lessor degree by suddenly-released tension), must be of operational concern due to the potential for structural contact.

At very long ranges (> several miles), analysis indicates that differential drag and gravity gradient effects should overcome all reasonable initial closing rates and pull the tether out away from the Orbiter, restoring tautness in a safe and stable configuration.

At medium ranges (1000 feet to several miles) the tether momentum would probably carry it back toward the Orbiter. However, for reasonable return times (several minutes) and stable initial conditions (typical of known deployment/retrieval scenarios), the main segment of the tether will be carried down the V-BAR by Coriolis forces, sufficient to assure Orbiter structure avoidance. If the Orbiter end of the tether is cut in a reasonable reaction time (3 to 5 minutes), the tether segment in this case will entirely miss the Orbiter.

At short ranges (less than 1000 feet from Orbiter to break point) the tether will probably recontact the Orbiter at a speed of 10 to 20 ft/s. Time from break to recontact is on the order of 1 minute.

Since the tether segment is short and light, RCS plume ward-off techniques (perform +Z translation, fly away from tether) appear promising in this case. The technique seems to have the advantage of not being harmful in the event a break is perceived, but does not in fact exist; taking such precautionary steps can be done without impacting successful tethered operations. The tether would become taut again quickly.

7.8 OPEN ISSUES

Through use of the excellent SES model in the 1986 studies, significant new insights into the TSS-S terminal phase retrieval process were gained. Although no operational procedures have yet been designed, much less verified, nevertheless, a number of promising candidate techniques were made available as a starting point for downstream procedures development work.

Deployment jam can cause high stresses and recoil velocities. One proposed fix is to add a section of yieldable tether material which might prevent a fast recoil in this eventuality.

A severed thruster could recoil and foul Orbiter mechanisms. Can the RCS thrusters be used to blow away or deflect a recoiling tether (at low recoil velocities) before it piles up around the Orbiter?