TETHER FUNDAMENTALS

Joe Carroll
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PLENARY SESSION -- TETHER FUNDAMENTALS PRESENTATION

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Buongiorno.

When I was finishing college 15 years ago, I had an interest in some space-tether concepts which I guess I had first heard of through science fiction. But I decided not to pursue them at that time because I thought that there was simply no way that anybody would ever take them seriously, even though they seemed to be physically possible. And then I found out several years ago that tethers were beginning to be taken seriously.

We are indebted to Professor Colombo for many things, but I think the greatest of them is that he spent the last nine years of his life convincing people that tethers are indeed something worth taking seriously. Many of his analyses on tether dynamics may have been difficult to do, but his greatest accomplishment really seems to be simply this: that he got the aerospace community to look seriously at tethers as something not just for science fiction authors but also for engineers and even for national space programs. It is amazing.

I have just one very basic overall point to make on the subject of tether fundamentals. A simple slogan or way of putting it is that tethers may be one-dimensional physically, but analytically they are very, very multi-dimensional. For example, I have a new tether material here--Spectra 900 fiber--which has a higher strength-to-weight ratio than Kevlar. But it has two idiosyncrasies that limit its applications: it rapidly loses strength above room temperature, and it is very sensitive to atomic oxygen. These limitations may seem extraneous, but they are real--and may be crucial in some applications.

So the point of this presentation is going to be that in order to make these tether applications work, we have to "lose our technological innocence" or "engineering innocence"--and not just in one particular area, but in at least a dozen different areas. All the things that I'm going to say in the rest of the talk are just examples, one after another, of the many different ways in which we have to lose our innocence technologically, in order to find out which tether applications are truly practical.

We are here in the city of Venice which has an illustrious history that is highly tied to its accomplishments in maritime technology and sailing. Tethers, ropes, cables, hausers--and ways of using them well--are intimately tied to the history of Venice. We at this workshop are basically where Venice was over a thousand years ago: 90% or maybe even 99% of the things that we are going to consider or try to do are not going to work. But that doesn't matter because there are so many possibilities that, even if only 1% of them work out, we can end up with a technology which is as rich as sailing technology, and which perhaps will have as many effective applications for ropes, strings, tethers, cables, and so forth, as sailing technology found for them over a 1,000 year period in Venice.
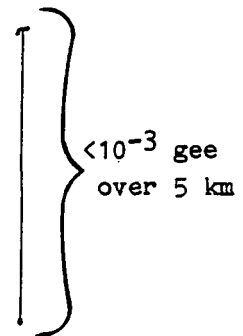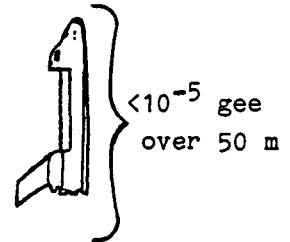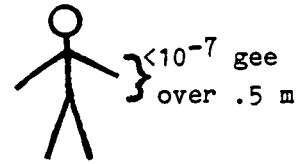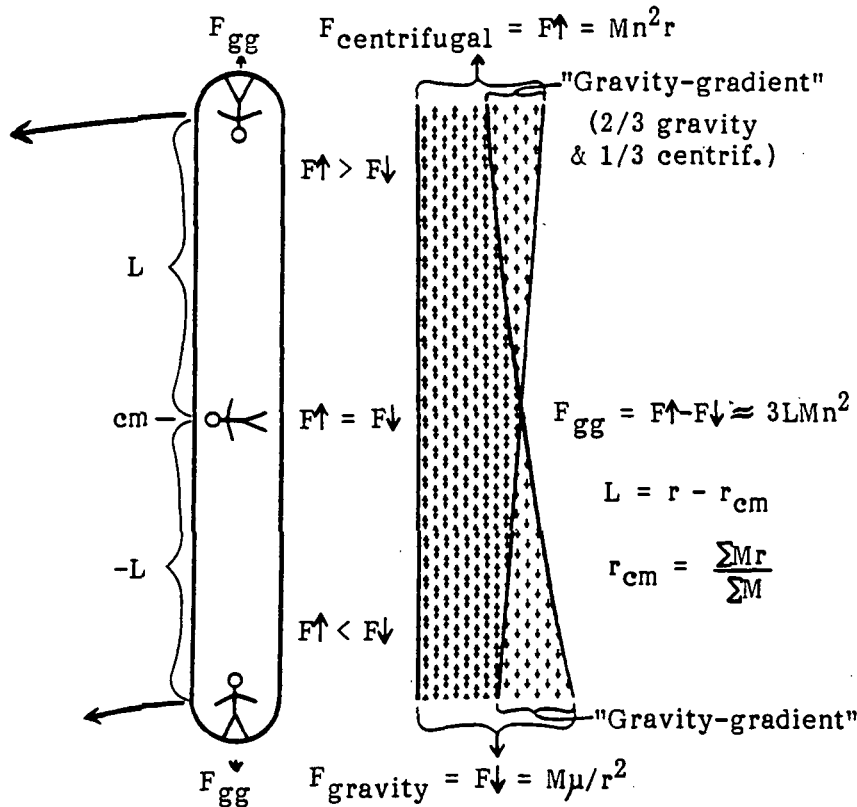
Now as my first example, look at gravity-gradient effects. We find that they are there whether we want them or not. We may want a micro-gee facility in low earth orbit. We find that, for example, if we want less than one ten-millionth of a gee, the maximum vertical dimension over which we can have that is quite small: about .5 meters, or .25 meter above and below the CG of a space station. If you relax the requirements to 1E-5 gee, you still can't meet that requirement over a vertical distance greater than about 50 meters, or something less than half the height of the planned space station. This is an idiosyncracy of being in a low orbit. It may turn out to be crucial in some applications, and may be entirely irrelevant in others.

As shown in the figure, gravity-gradient forces are simply the difference between centrifugal force, which increases linearly as you go out along the structure, and the gravity force, which increases as you go inward. These two forces cancel out precisely only at one place, which is very nearly the CG of the structure. Above or below that point you have a force which very nearly scales with the vertical distance from the CG. So at the bottom of the long cylinder shown in the figure, you can stand up, with your feet oriented down; at the middle, you can float; and at the top, "down" happens to be outward. This can be put much more simply to highlight the counter-intuitive aspects of tethers: you can only climb halfway up a tether; beyond that you are "really" going down--and you can prove it by sliding the rest of the way!

When I say "counter-intuitive," I really mean "counter to the untrained intuition." One of the really remarkable things about human beings is the extent to which they can--and do--train their intuitions. A good experienced pilot knows what to do in ordinary cases and in emergencies because his intuition is trained. He has a feeling or image of what is going to happen when he does a certain thing to the plane. And part of what we are going to be doing in the next three days, and in the next ten years, is training our intuitions in this new area, just as a pilot trains his by practice in a new plane.
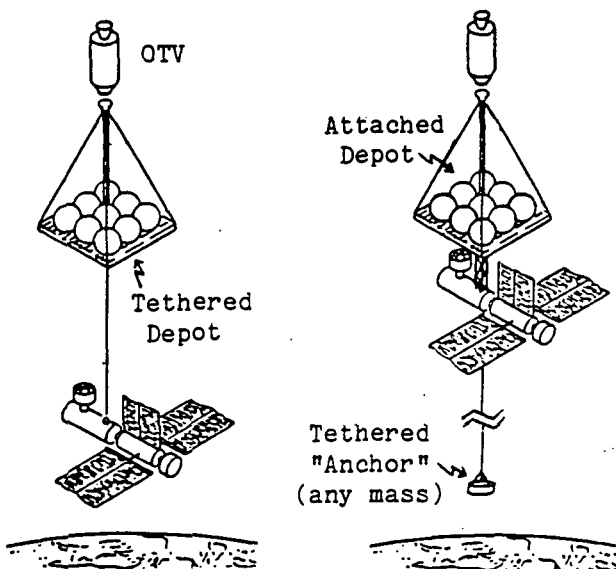
Note: Most of the following viewgraphs are from the
      Guidebook for Analysis of Tether Applications
      (prepared by the speaker for Martin Marietta)

Gravity Gradient Effects

$F_{centrifugal} = F\uparrow = Mn^2r$

"Gravity-gradient"
(2/3 gravity
& 1/3 centrif.)

$F\uparrow > F\downarrow$

$F\uparrow = F\downarrow$

$F_{gg} = F\uparrow - F\downarrow \approx 3LMn^2$

$L = r - r_{cm}$

$r_{cm} = \dfrac{\sum Mr}{\sum M}$

$F\uparrow < F\downarrow$

"Gravity-gradient"

$F_{gravity} = F\downarrow = M\mu/r^2$

Origin of "Gravity-Gradient" Forces

$< 10^{-7}$ gee
over .5 m

$< 10^{-5}$ gee
over 50 m

$< 10^{-3}$ gee
over 5 km

Magnitude of
Gravity Gradient
Effects in LEO

OTV

Attached
Depot

Tethered
Depot

Tethered
"Anchor"
(any mass)

Two Propellant-Settling Options

Crystal Growth	→?		? ←	Calcium Retention
Latex Reactors	→?		?←	Walking
Electrophoresis	→?		?←	"Desktop" work
LSS Assembly	→?		?←	Eating, Hygiene
			?←	Fluid Settling

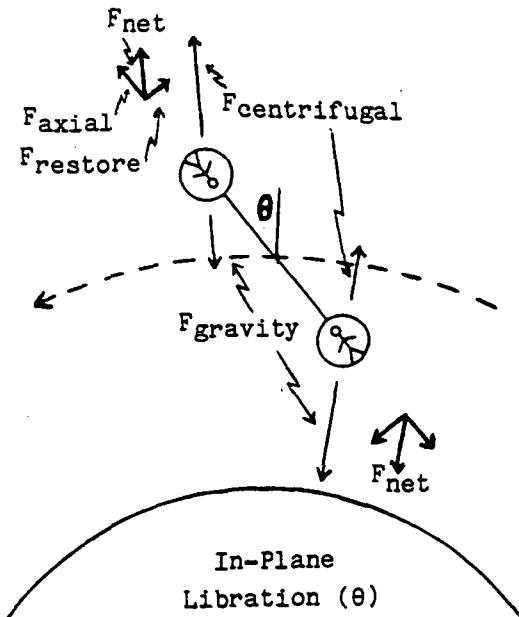Microgravity 10^{-3} G   Full Gravity

Potential Overlap of Regions for
Low-Gee & Gee-Dependent Operations

This viewgraph shows what is involved in libration. I could spend half an hour on each of these figures. But the basic point is that you can draw the vectors for the gravity and centrifugal forces at each end of a dumbbell. When you compute what they are, and the directions in which they act, then you find that there is a net force at each end of the dumbbell. This force has a component aligned with the tether that causes tether tension, and a restoring component which tends to swing you back towards the vertical.

The forces are very small, and so the resulting pendulum dynamics are, well, not very exciting. If you want excitement, look at the minute hand of a clock, because it rotates faster than a gravity-gradient pendulum does. It's good to keep in mind this image--that in a local-vertical, local-horizontal reference frame, the rotation of a gravity-gradient pendulum is slower than the rotation of the minute hand of a clock.

One subtle effect that turns out to be important for several reasons is that the tension in an elongated object varies during libration. As shown at bottom left, the tension can go up by a factor of three (compared to a hanging dumbbell) during the middle of a wide prograde swing. But during the return (retrograde) swing, the tension on a dumbbell beam can go negative. If the dumbbell beam is a tether, the tether will go slack. This ends up being a problem with some applications. In others, it may never be a problem--either the libration isn't wide enough, or you retrieve the tether to take in slack, or you convert the swing into a spin before you ever start to go retrograde. So there are constraints, and there are sometimes work-arounds, and sometimes these work-arounds suggest new ideas, and you go on from there.
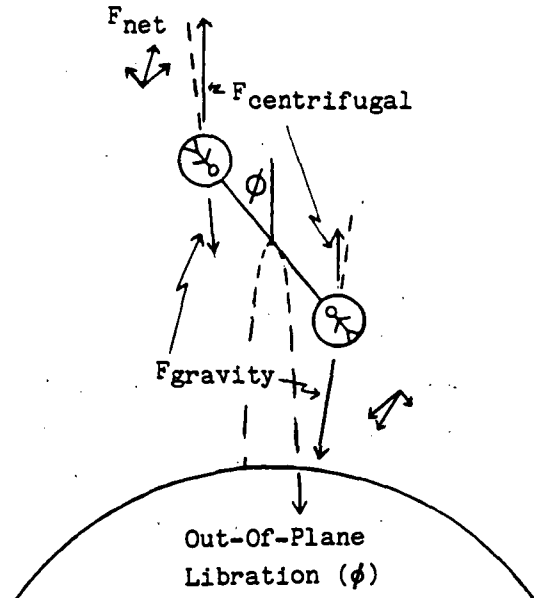
Dumbbell Libration in Circular Orbit

In-Plane
Libration (θ)

Out-Of-Plane
Libration (ϕ)

$\ddot{\theta} \approx -3n^2\sin\theta\cos\theta = -1.5n^2\sin(2\theta)$

$\dot{\theta} \approx \pm\sqrt{3}\ n\sqrt{\sin^2\theta max - \sin^2\theta}$

$(\dot{\theta} \approx \pm\sqrt{3}\ n\sin\theta max$ when $\theta=0)$
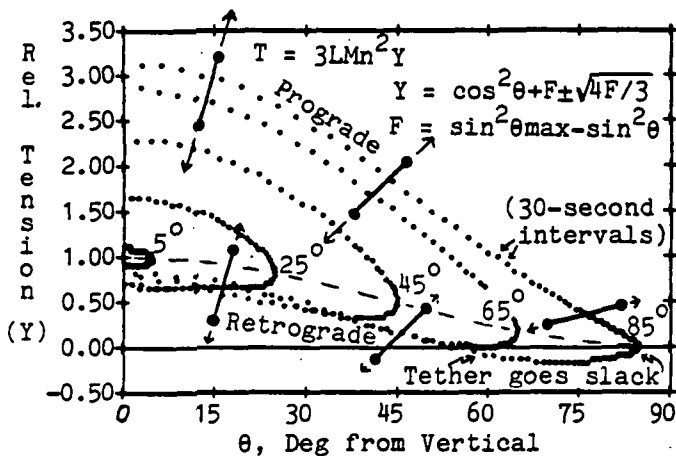
$n_\theta \approx n\sqrt{3\cos\theta max}$

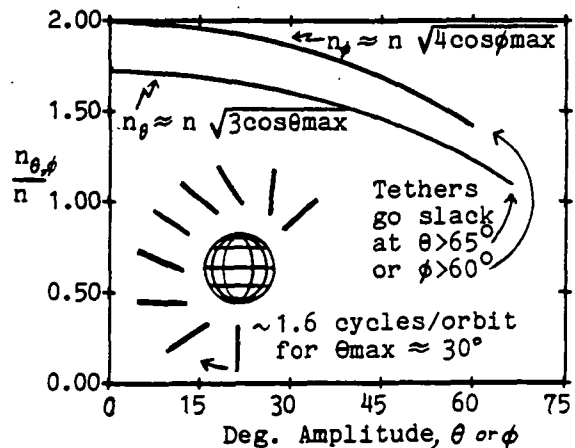$\ddot{\phi} \approx -4n^2\sin\phi\cos\phi = -2n^2\sin(2\phi)$

$\dot{\phi} \approx \pm2n\sqrt{\sin^2\phi max - \sin^2\phi}$

$(\dot{\phi} \approx \pm2n\sin\phi max$ when $\phi=0)$

$n_\phi \approx 2n\sqrt{\cos\phi max}$

$T = 3LMn^2Y$

$Y = \cos^2\theta + F\pm\sqrt{4F/3}$

$F = \sin^2\theta max - \sin^2\theta$

(30-second intervals)

Prograde

Retrograde

Tether goes slack

θ, Deg from Vertical

Tension Variations in Librating Dumbbells
(compared to tension in hanging dumbbells)

$n_\phi \approx n\sqrt{4\cos\phi max}$

$n_\theta \approx n\sqrt{3\cos\theta max}$

Tethers
go slack
at $\theta>65°$
or $\phi>60°$

~1.6 cycles/orbit
for $\theta max \approx 30°$

Deg. Amplitude, θ or ϕ
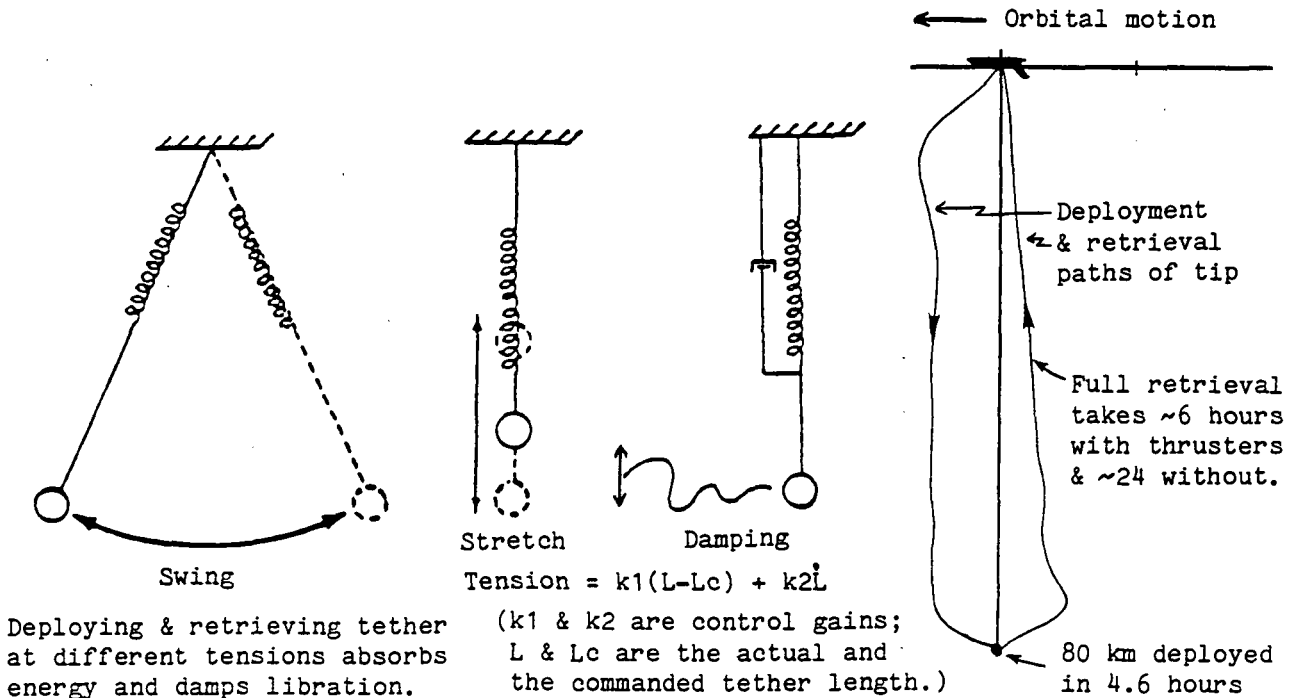
Libration Freq. vs Amplitude

Now we can start thinking about how to control these tether dynamics. The early work on the TSS emphasized tension control, and since then there has also been work on thruster-aided controls. But there also at least four other tools available to use in controlling the behavior of tethers. And even this viewgraph leaves one out: you can retrieve tether fast enough near the end to cause the whole TSS-orbiter system to go into a slow spin. This replaces the gravity-gradient environment (which involves very weak forces when the tether is short) with an artificial-gee environment. The control laws are different, and they may be easier to deal with in some cases. But that gets into shuttle operational issues, and questions like: Is it permissable to make the shuttle spin at a rate of five or six times per hour? This is an example of controls and operational issues that we have to lose our innocence on before we ever find out whether we have a good idea.

Now, as several examples of the importance of operational issues, I have some cartoons which really require no explanation...

Tether Control Strategies

EFFECTIVENESS OF VARIOUS CONTROL CONCEPTS

APPLICATION / CONTROL OUTPUT	Libration		Tether Oscillations		Endmass Attitude Osc.	
	In-plane	Out-of-plane	Longitudinal	Transverse	Pitch & Roll	Yaw
Tension	Strong	Weak	Strong	Strong	Strong	None
	(Note: tension control is weak when tether is short)					
El. Thrust	Only if M1 ≠ M2		None	Only odd harmonics	None	None
Thruster	Strong, but costly if prolonged			None	Strong, but costly if prolonged	
Movable mass	Good w/short tether		Possible but awkward		None	None
Stiff tether, Movable boom	Strong if tether is very short; weak otherwise					
Aerodynamic	High drag—use only if low altitude needed for other reasons.					

← Orbital motion

Deployment & retrieval paths of tip

Full retrieval takes ~6 hours with thrusters & ~24 without.

80 km deployed in 4.6 hours

Swing

Deploying & retrieving tether at different tensions absorbs energy and damps libration.

Stretch   Damping

Tension = k1(L-Lc) + k2L̇

(k1 & k2 are control gains; L & Lc are the actual and the commanded tether length.)

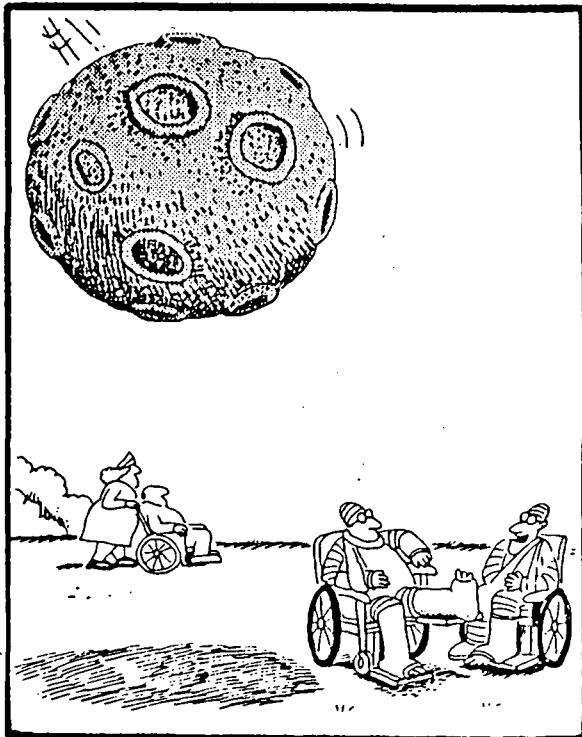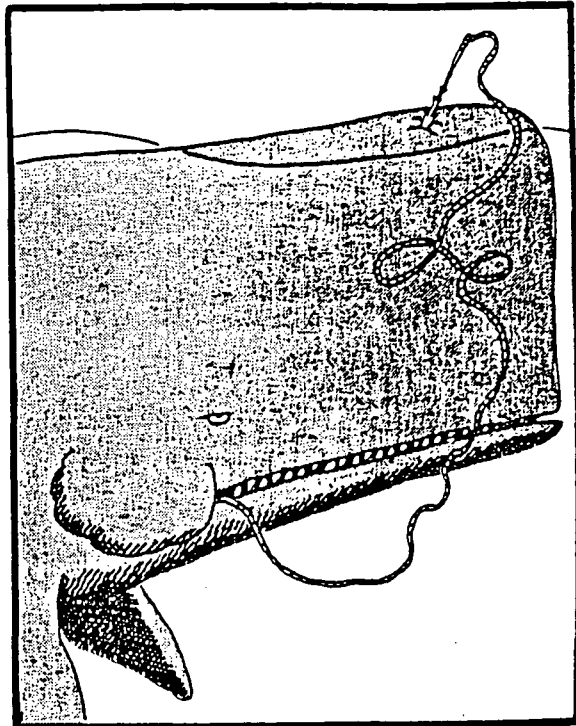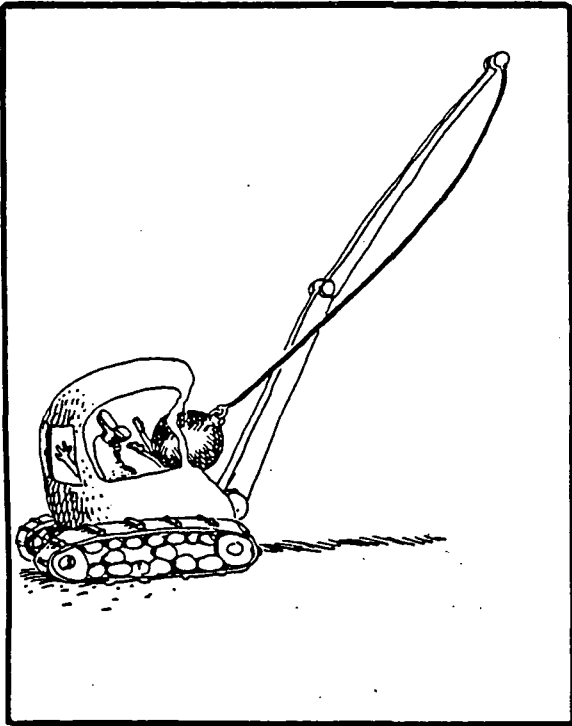TENSION CONTROL FOR LIBRATION DAMPING... AND DEPLOYMENT/RETRIEVAL

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These are real issues.

The point is for us to show with high assurance that these cartoons do not represent plausible tether operational failure modes--before someone else suggests that they might. If we do our homework ahead of time, these remain only cartoons. OK?

And here we have a cartoon which highlights another tether operational issue. If we happened to live in a solar system where micrometeoroids were rare, we wouldn't have to worry about this sort of thing. But in many tether applications, it turns out that the longevity of the tether & the feasibility of the given operation entirely depend on micrometeoroid sensitivity. There are some early tether applications I am studying in which the tether mass required to keep this risk below .1% is about 20 times the tether mass needed simply to support the payload.

There is a very ambitious concept proposed by Jerome Pearson, which seems feasible from a dynamics and strength-of-materials point of view . It involves a beanstalk which rises from the moon's surface and supports itself by hanging past the L-1 point into the earth's gravity field. It requires a tapered tether of something at least as strong as Kevlar, but it can be done with current materials. The main problem is that you can invest 3,000 tonnes of tether in making this system and then start deploying it, and it will probably be broken before it is half-way deployed, because it's an immensely long tether with a lot of area and a lot of exposure. Now one can cure this problem by making the tether in the form of a net or a "tensile Eiffel tower," and having automated "linemen" repairing it all the time. But the point here is that the practicality or the design can be driven by the fact that we live in a solar system where, one might say, "the gods throw rocks" (and gravel, and sand, and dust).

"You're kidding! . . . I was struck twice by lightning too!"

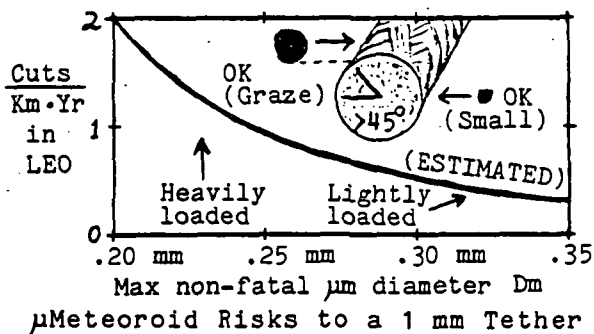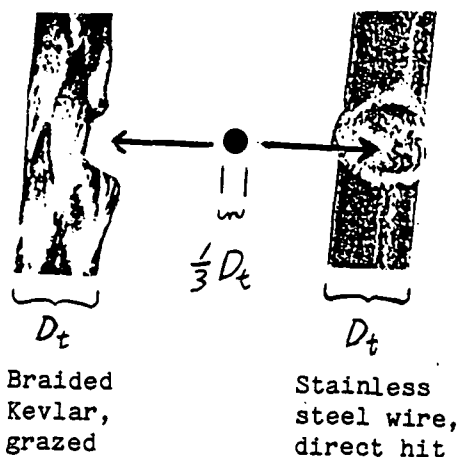Very large meteoroids are rare; small ones are not!

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Now to look at impact hazards more carefully, it turns out that because of hypervelocity effects, even a fairly small particle--1/3 the diameter of the tether--can cause fairly significant damage. And the problem is not just that gods throw rocks--in addition to that, we leave debris in space. When you start looking at the debris problem, you realize that the effective area of a tether for collision with objects much wider than the tether is really the length of the tether, times the width of the DEBRIS. The major debris risk to tethers seems to be associated mainly with the few hundred largest objects, whose combined width is several kilometers. When you take that width, times the length of a tether, times the average relative velocity of objects passing each other in low orbit, which is about ten kilometers per second, then you find that tethers can be effectively sweeping out very large volumes of space.

Now luckily, the worst risk is above the proposed space station altitude-- the densest region is 600 to 1100 kilometers. But if you want to have a long tether deployed permanently above the space station, figure on it getting cut about every 1,000 kilometer-years. If it's a 100-km tether, it will be cut once every 10 years, on the average. If it's a 500 km tether, then every two years, on the average. And this risk is independent of the thickness of the tether. It can be many cm in diameter--thick enough that the probability of failure due to meteoroids is low--but still, impact with debris will cut it.

In the lower right corner of the viewgraph, we see the space elevator concept. The main debris hazard is in the lowest 4000 km, and again, it is primarily between 600 and 1100 km. And it turns out that a space elevator like this will be cut a little more than once a year on the average, because the total width of the stuff that can cut it is on the order of 5 km--and that's only the current debris population.
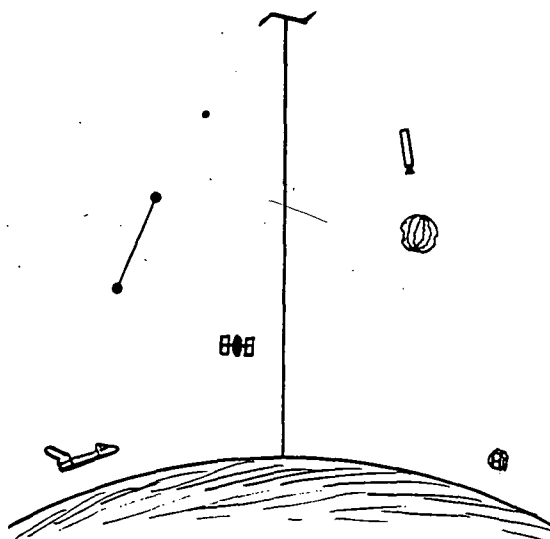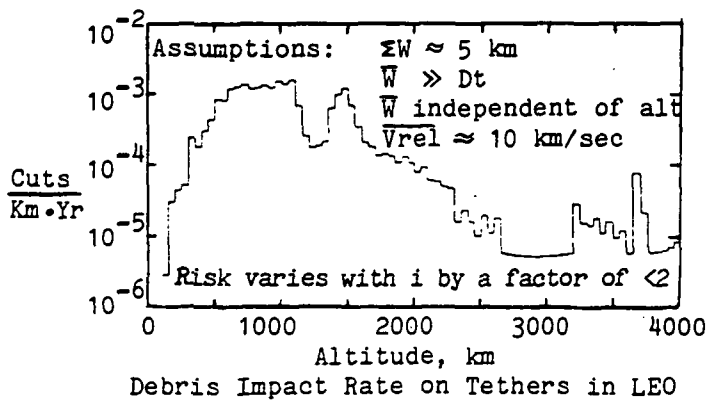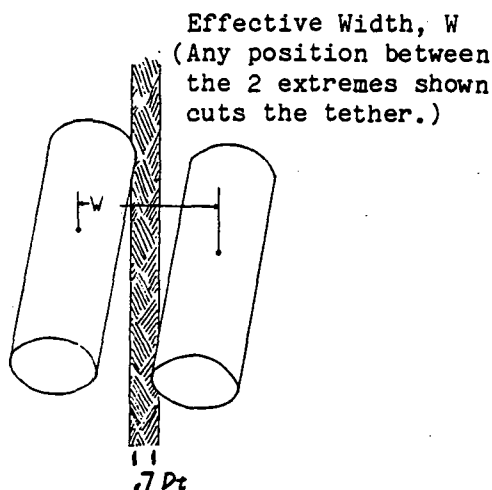
So micrometeoroids and debris are important issues.

C-2

Impact Hazards for Tethers

D_t

$\frac{1}{3} D_t$

Braided Kevlar, grazed

Stainless steel wire, direct hit

$\frac{\text{Cuts}}{\text{Km} \cdot \text{Yr}}$ in LEO

2

1

0

OK (Graze)

$> 45°$

OK (Small)

(ESTIMATED)

Heavily loaded

Lightly loaded

.20 mm   .25 mm   .30 mm   .35

Max non-fatal μm diameter Dm

μMeteoroid Risks to a 1 mm Tether

For tethers with Dt > 1 (mm),
& Max non-fatal Dm = .25 Dt,

$$\frac{\text{μm cuts}}{\text{Km} \cdot \text{Yr}} \approx Dt^{-2.6}$$

Effective Width, W
(Any position between
the 2 extremes shown
cuts the tether.)

W

.7 Dt

$\frac{\text{Cuts}}{\text{Km} \cdot \text{Yr}}$

10^{-2}

10^{-3}

10^{-4}

10^{-5}

10^{-6}

Assumptions: $\Sigma W \approx 5$ km
                $\overline{W} \gg Dt$
                $\overline{W}$ independent of alt
                $\overline{Vrel} \approx 10$ km/sec

Risk varies with i by a factor of <2

0   1000   2000   3000   4000

Altitude, km

Debris Impact Rate on Tethers in LEO

Debris Risk to the Lowest 4000 km
of an Earth-based Space Elevator:

$$\text{Risk} = \frac{\Sigma \text{Width} * \overline{V} * \text{RelDensity at } \lambda = 0}{\text{Earth "Surface Area" at Alt}}$$
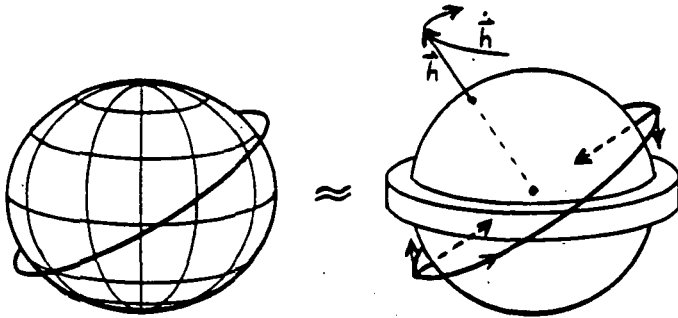
$$= \frac{\sim 5 \text{ km} * \sim 7.3 \text{ km/sec} * \sim .72}{4 * pi * \text{Sqr}(\sim 7378 \text{ km})}$$

$$\approx 3.9E-8/\text{sec} \approx \boxed{1.2 \quad \text{cuts/year}}$$

Another entirely different sort of issue which, again, has nothing to do with tether dynamics per se, but affects the feasibility of tether applications, is differential nodal regression in LEO. If you have two facilities in orbits with the same inclination but different altitudes, they periodically are in the same orbital plane. But at other times, they are not. And so, if you have a multi-stage tether transportation scheme which might be described as a "staircase to the stars," or a "fire brigade", where you get thrown from one stage to the next, and are then caught and thrown from that to another one, you may end up--to change the analogy again--spending a long time waiting for the bus in between steps. This is because you have to wait until you and the next stage have regressed into the same plane. Thus you may spend years getting from LEO to GEO. And those years happen to be in the Van Allen belts, which are not a nice place to be.

So one has to look at these constraints.

Orbital Perturbations

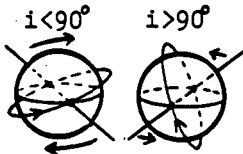OBLATENESS CAUSES LARGE SECULAR CHANGES IN Ω & ω:

$\dot{\Omega}$: up to 1 rad/week in LEO

$\dot{\omega}$: up to 2 rad/week in LEO
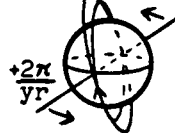
Nodal Regression in LEO:

$i<90°$ $i>90°$

$$\dot{\Omega} \approx \frac{-63.6 \cos i \text{ rad/yr}}{(a/re)^{3.5} (1-e^2)^2}$$
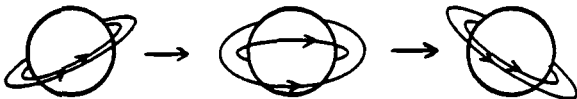
$(r_e = 6378 \text{ km})$

For sun-synchronous orbits: $(i=100° \pm 4°)$

$$\cos i \approx -.0988 (a/r_e)^{3.5} (1-e^2)^2$$

$+\frac{2\pi}{yr}$

For coplanar low-ΔV rendezvous between 2 objects $(e_1 = e_2 \approx 0, \ i_1 = i_2)$, nodal coincidence intervals are:

$$\Delta t_{nc} \approx \frac{180 \ (\bar{a}/re)^{4.5}}{\Delta a \ |\cos i|} \text{ km·yrs}$$

Apsidal recession in LEO:
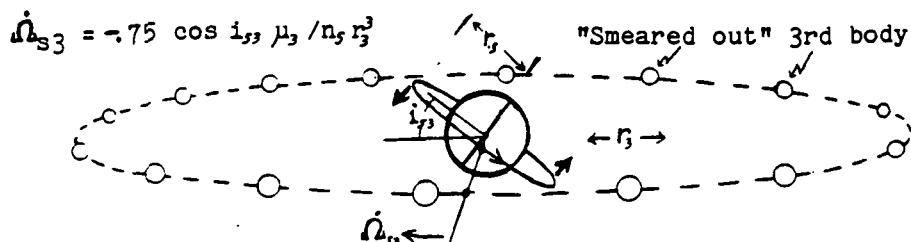
$$\dot{\omega} \approx \frac{63.6(2 - 2.5 \sin^2 i)}{(a/r_e)^{3.5} (1-e^2)^2} \text{ rad/yr}$$

$i<63.4°$ $i=63.4°$ $i>63.4°$

Motion of the longitude of perigee with respect to the sun's direction ("noon") is:

$$\bar{\omega}_s = \dot{\omega} + \dot{\Omega} - 2\pi/yr$$

$$\dot{\Omega}_{s3} = -.75 \cos i_{s3} \ \mu_3 / n_s r_3^3$$
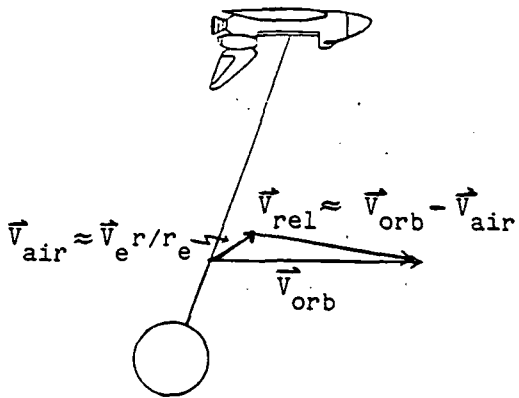
"Smeared out" 3rd body

Third-Body Perturbations (non-resonant orbits)

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Another issue is aerodynamic drag, and the resultant heating. It turns out that on the tethered satellite, for example, the drag on the tether (mainly on the bottom 10 km of tether) will be about twenty times the drag on the satellite itself. Now this is entirely acceptable for a one-day mission, but for space-station-based applications, hanging a satellite down this far would have a very large effect on the space station over long periods.

The resulting drag can cause out-of-plane libration dynamics, due to the equatorial bulge in the atmosphere and the out-of-plane drag component due to the atmosphere's rotation with the earth. And low altitudes also increase the tether's exposure to atomic oxygen, which degrades most tether materials.
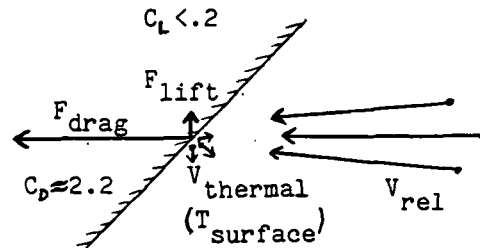
Aerodynamic drag is also important in an entirely different way. An understanding of aerodynamic drag and its effect on orbital life is important because the main reason for boosting objects into higher orbits in LEO is to reduce the amount of aerodynamic drag. Since tethers tend to boost objects into eccentric orbis, the question arises: How do I compare the tether boost effect with a two-impulse rocket boost into a circular orbit? Well, probably the fairest way to do so is to find what circular orbit gives the same orbital life as a given eccentric orbit. And so that requires an understanding of aerodynamic drag and orbital decay.
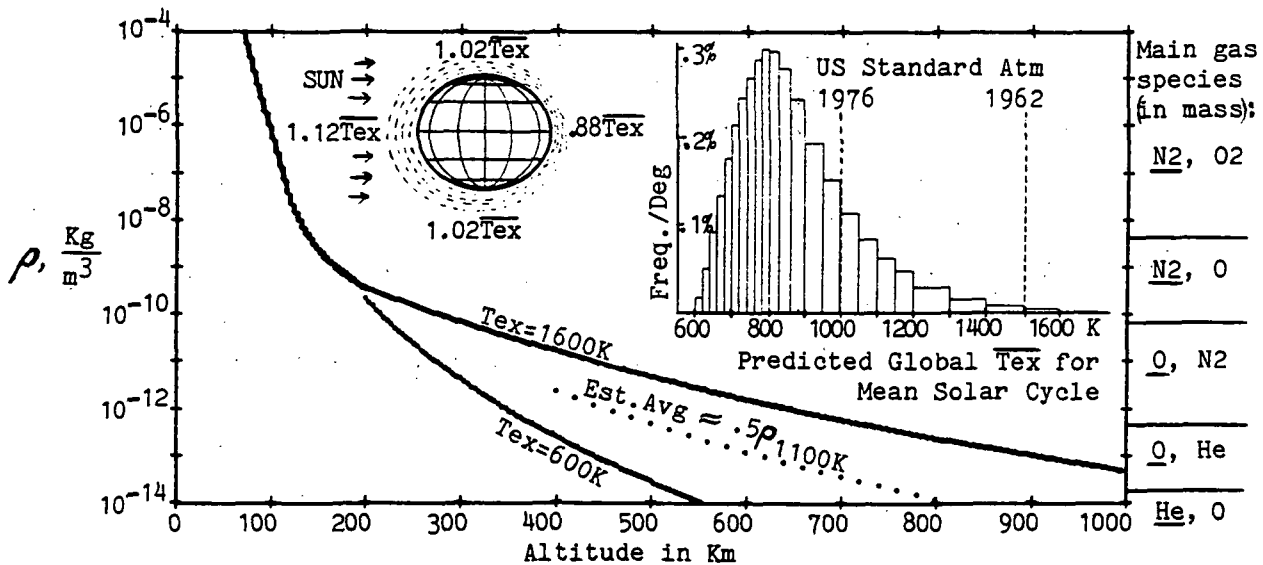
Aerodynamic Drag

$$\vec{V}_{air} \approx \vec{V}_e r/r_e$$

$$\vec{V}_{rel} \approx \vec{V}_{orb} - \vec{V}_{air}$$

$$\vec{V}_{orb}$$

$$F_{drag} = .5 \int \rho \, C_D \, V_{rel}^2 \; \text{Width} \; \delta r$$

$$V_e = .465 \; \text{Cos(Lat)} \; \text{km/sec}$$

$$C_L < .2$$

$$F_{lift}$$

$$F_{drag}$$

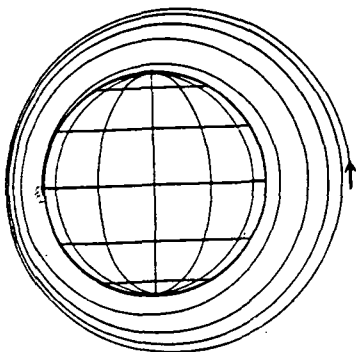$$C_D \approx 2.2 \qquad V_{thermal} \qquad V_{rel}$$

$$(T_{surface})$$

Lift & Drag in Free-Molecular Flow

$$(\bar{\lambda} \gg D_{tether}; \; \bar{\lambda} \approx \frac{10^{-7} \, kg/m^2}{\rho})$$

Air Density as Function of Altitude & Exosphere Temperature

US Standard Atm 1976 1962

Predicted Global $\overline{Tex}$ for Mean Solar Cycle

SUN
1.02 Tex
1.12 Tex
.88 Tex
1.02 Tex

$Tex = 1600K$

Est. Avg $\approx .5\rho_{1100K}$

$Tex = 600K$

$\rho, \frac{Kg}{m^3}$

Altitude in Km

Main gas species (in mass):

N2, O2

N2, O

O, N2

O, He

He, O

$70 < \text{Alt} < 118: \rho \approx 11\exp(-\text{Alt}/6)$	$-\rho/\dot{\rho} = H = 6 \; (km)$
$118 < \text{Alt} < 200: \rho \approx (\text{Alt}-95)^{-3}/2600$	$H = (\text{Alt}-95)/3$
$200 < \text{Alt} \; \& : \quad \rho \approx \dfrac{1.47E-16 \; Tex(3000-Tex)}{(1+2.9(\text{Alt}-200)/Tex)^{10}}$ $\rho > 1E-14$	$H = .1(\text{Alt}-200)+Tex/29$

Circular
Orbit Life $\approx \dfrac{.15 \; m^2 yr}{kg} \dfrac{M}{C_D A} \dfrac{(1 + 2.9(r-6578)/Tex)^{11}}{3000 - Tex}$

$(-14 < \text{Log}\rho < -10)$

Equal-Life
Circ. Alt. $\approx$ Perigee $+ \dfrac{Apo - Per}{2 + .154(Apo-Per)/H_{Per}}$

Now, to put this all together, the major constraints in momentum-transfer applications, which is what I'm mainly interested in and will be working with the most in the transportation session, are shown in the top row of the top table. For all momentum transfer applications you face constraints with apside location, forces on the end masses, micrometeoroid sensitivity, and tether recoil. And in the different subsets shown, you have issues that can crop up and be quite important in specific cases.

When you look at permanently dployed tethers—constellations, platforms, and things like that—you have to worry more about things like aerodynamic drag, libration, tether degradation, meteoroids, debris, and recoil & orbit changes after a tether break. Looking at tether operational issues, which are really important due to the constraints they impose that you simply have to learn to live with, I think the best thing for the space station is to assume that tether breakage is possible, no matter how many backups you have—such as five separate tethers or something. If you assume that failure is possible, then you have to have a recovery from a tether failure that is do-able, that is imaginable, that can be costed into the normal operating procedures. So don't regard tether failure as a low-probability system failure mode, because someone in an operations group will determine whether your system will fly, based on whether your proposed backup modes after tether failure are things that are feasible and cost-effective.

Generic Issues in Various Tether Applications

MAJOR CONSTRAINTS IN MOMENTUM-TRANSFER APPLICATIONS

CONSTRAINT: APPLICATION	ORBIT BASICS	TETHER DYNAMICS	TETHER PROPERTIES	TETHER OPERATIONS
All types	Apside location	Forces on end masses	μmeteoroid sensitivity	Tether recoil at release
Librating		Tether can go slack		Facility attitude & "g"s variable
Spinning		High loads on payload		Retrieval can be difficult
Winching		High loads on payload		Extremely high power needed
Rendezvous	Orbit planes must match			Short launch & capture windows
Multi-stage	Dif. nodal regression			Waiting time between stages
High deltaV	Gravity losses	Control of dynamics	Tether mass & lifetime	Retrieval energy; Facility △ alt.

MAJOR CONSTRAINTS WITH PERMANENTLY-DEPLOYED TETHERS

CONSTRAINTS: APPLICATION	ORBIT BASICS	TETHER DYNAMICS	TETHER PROPERTIES	TETHER OPERATIONS
All types	Aero. drag	Libration	Degradation, μmeteoroids & debris impact.	Recoil & orbit changes after tether break
Electrodynamic	Misc changes in orbit	Plasma disturbances	High-voltage insulation	
Aerodynamic	Tether drag & heating			
Beanstalk (Earth)			Tether mass; debris impact	Consequences of failure
Gravity Use: Hanging Spinning		Libr-sensitive		<.1 gee only. Docking awkward

Now, I'd like to summarize and end with a couple of images, since the senator who just spoke referred to the importance of imagination. One is that Professor Colombo, at his banquet speech two years ago in Williamsburg, talked about a group which I would like to learn more about: the "imagineers"--the people who are engineers, but who have flights of fancy that they turn into practice. I think that we have to have analytical skills among us. And what we don't already have individually, we have to acquire by sitting with the right people at lunch and at dinner, so that we can do the ten-dimensional analysis of this one-dimensional physical structure.

But we also have to have imagination. And here's an example of the sort of menagerie, or zoo, of applications that one can imagine using animal analogues.

First, the TSS is like a spider: it goes down and can go back up on a string. Next, the space station might be configured like an animal that has its eyes on long stalks, because that has advantages in some cases. A space station may not be as clean as one would like, since it will be working with the shuttle and OMV and OTV. So putting the eyes of the space station--the astrophysical eyes--out on the ends of long tethers may be beneficial to both the eyes and the space station, by allowing them to play their individual roles with less interference. Another analogy is that the STS can act like a fish biting a baited hook. Or if the active object is an OMV at the end of the tether, the OMV can act like a chained dog and bite the ET on the nose to capture the shuttle.

A "monkey" can climb along tethers and other structures, and can free-fall from one structure to another merely by letting go at the right place. This is a way of getting around, not just in a forest on earth, but also in a forest or parade or large advanced infrastructure in LEO. The next image is of a water-skimming bird picking up small payloads: there is a possibility of doing some ram air-collection in the future--30 or 40 years from now perhaps. And then, for ambitious developments on the moon, you can be in lunar orbit and reach down and pick small objects off the surface, using a swinging or spinning tether much like an elephant uses its trunk. You can do prospecting over the whole moon with one facility in lunar polar orbit.

I think may be useful to send our imaginations back to the birth of sailing, and remember that the people who were developing sailing technology did not know the thousands of ways in which ropes would end up being useful. They worked on them a few at a time. And perhaps over the next 1,000 years, we will find as many uses for ropes in space as Venetians found for ropes on sailing ships.

I would like to end with a rather amusing image, that I think will bring home a point powerfully. And that is a cartoon which I saw recently. It shows a young lady, standing, and a young man, standing on her head. And he is saying to her, "Well, we've taken our clothes off, and I've gotten on top of you, but somehow I think we are doing something wrong. It doesn't feel very good." And she says, "I know what you mean. I'm getting cold, and I think I'm getting a headache."

The point--the relevant point here--is that, when you hear about something entirely new and different from anything you've ever done before, make sure you learn the relevant facts of life--because otherwise you will not only not do it right, but you may not ever even realize what a good thing it was that you were missing out on.

So what we need to do in the next three days--and over the next 10 years-- is to literally lose our technological and engineering innocence, so that we can go home with something a lot better than a cold and a headache.

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CARROLL: Now I would like to introduce Professor Silvio Bergamaschi, from the University of Padua. He is going to talk in far more detail about one of the subjects I have mentioned. Realistically, for a good introduction to tether fundamentals, we need to have ten such talks, one on each of the many topics that I have touched on. But we are still beginners, and Professor Bergamaschi will introduce us to one of the few fields in which we are now able to make this sort of introduction.