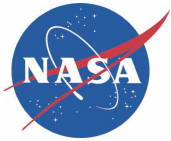


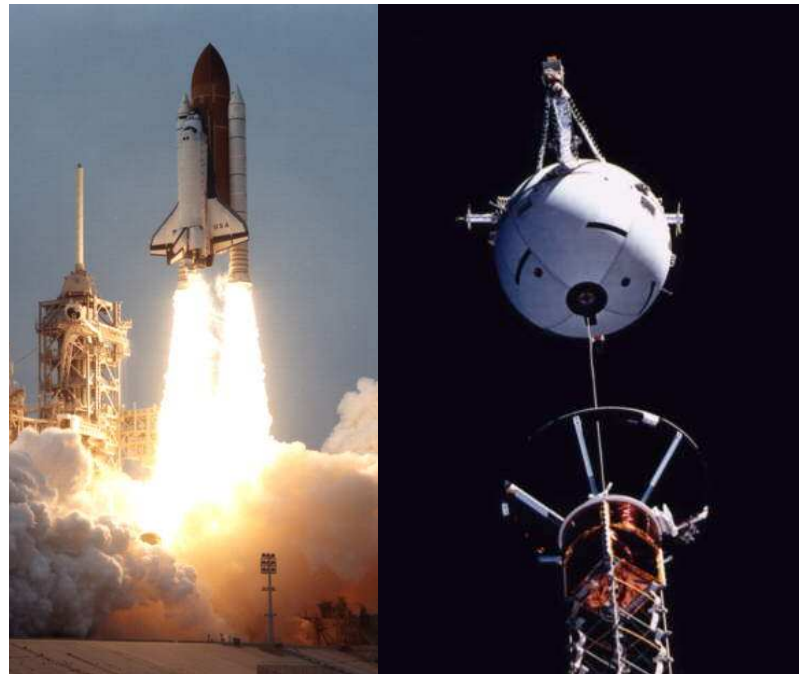
Tether Technologies for Enhancement of the International Space Station



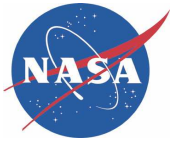
Tether Technology

Tethers are a remarkably promising space technology. They have flown in space on numerous occasions and each time we have learned a great deal more about their potential.

- ◆ TSS-1
- ◆ TSS-1R
- ◆ SEDS-1
- ◆ PMG
- ◆ SEDS-2

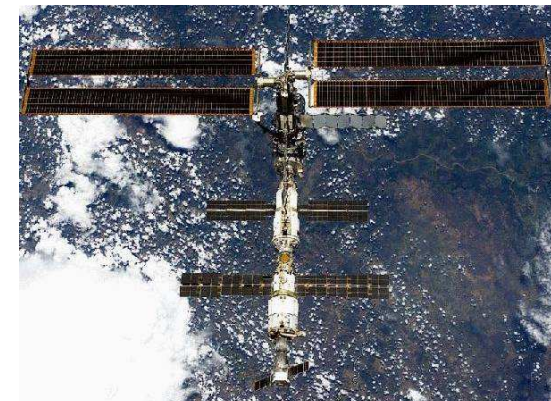
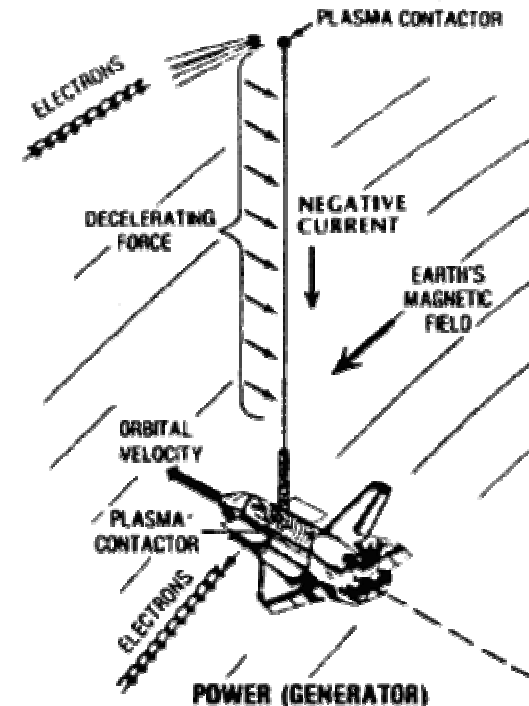


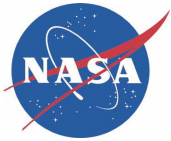
- ◆ ISS Reboost
- ◆ Ionospheric Science
- ◆ Satellite Deorbit
- ◆ Momentum-exchange around the Earth and Moon
- ◆ Jovian electrocapture



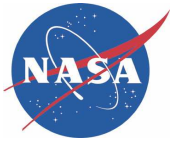
Tethers Offer Many Benefits to the ISS

- ◆ **Tethers can stabilize the attitude of the space station without propellant and with very little power**
 - ISS configuration is inherently unstable—short (~1-2 km), simple tether with guided boom provides gravity-gradient stabilization
 - Relieves CMGs and propellant req'ts for CMG desaturation
- ◆ **A tether can provide standoff for an electric propulsion (EP) system to reboost the station**
 - EP studies in the past have been stymied by plume impingement, thruster installation, plumbing, power consumption
 - An EP spacecraft on a short tether (~500 m) with its own power supply can provide reboost without these issues
- ◆ **A small electrodynamic (ED) tether system can reboost the station without propellant**
 - Ionospheric current driven by solar power through conductive tether (~5 km) provides reboost force through magnetic interaction.
 - No resupply propellant requirements
- ◆ **A large electrodynamic tether system can reduce the inclination of the station**
 - Electrodynamic forces can be used to provide out-of-plane forces needed to reduce station inclination.
- ◆ **ISS can demonstrate tether technologies needed for robust exploration activities**
 - ED tethers systems map into future momentum-exchange tethers for reusable, propellantless propulsion to GEO and the Moon.



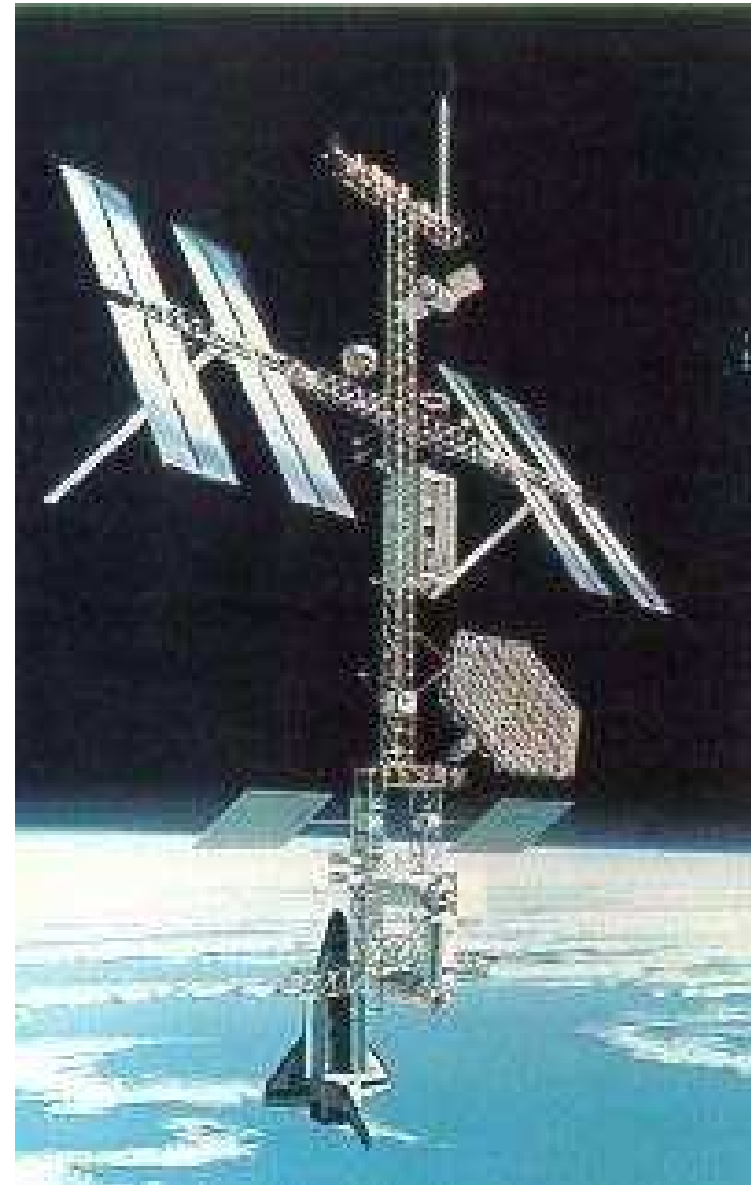


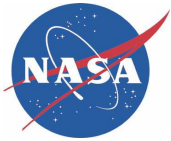
Gravity-Gradient Tether Stabilization of the International Space Station



Early Station Concepts Were GG-Stabilized

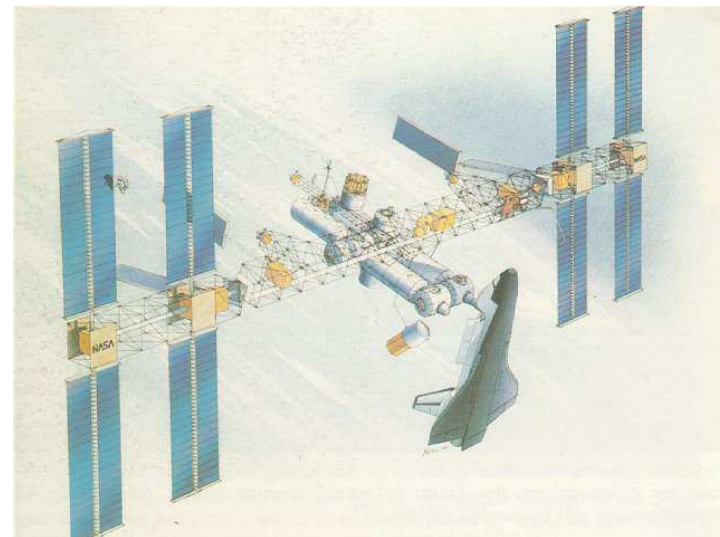
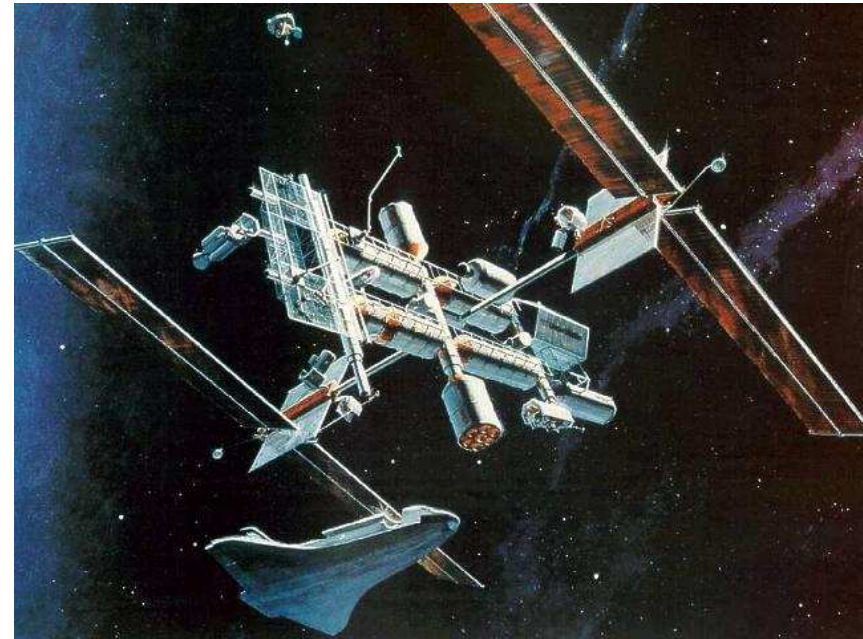
- ◆ Gravity-gradient stabilization was a simple, attractive way to stabilize any satellite in a local vertical, local horizontal (LVLH) configuration.
- ◆ Early station concepts such as the “Power Tower” or “Big-T” (circa 1985) relied on gravity-gradient stabilization

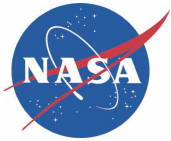




Gravity-Gradient Stabilization Contrary to μG

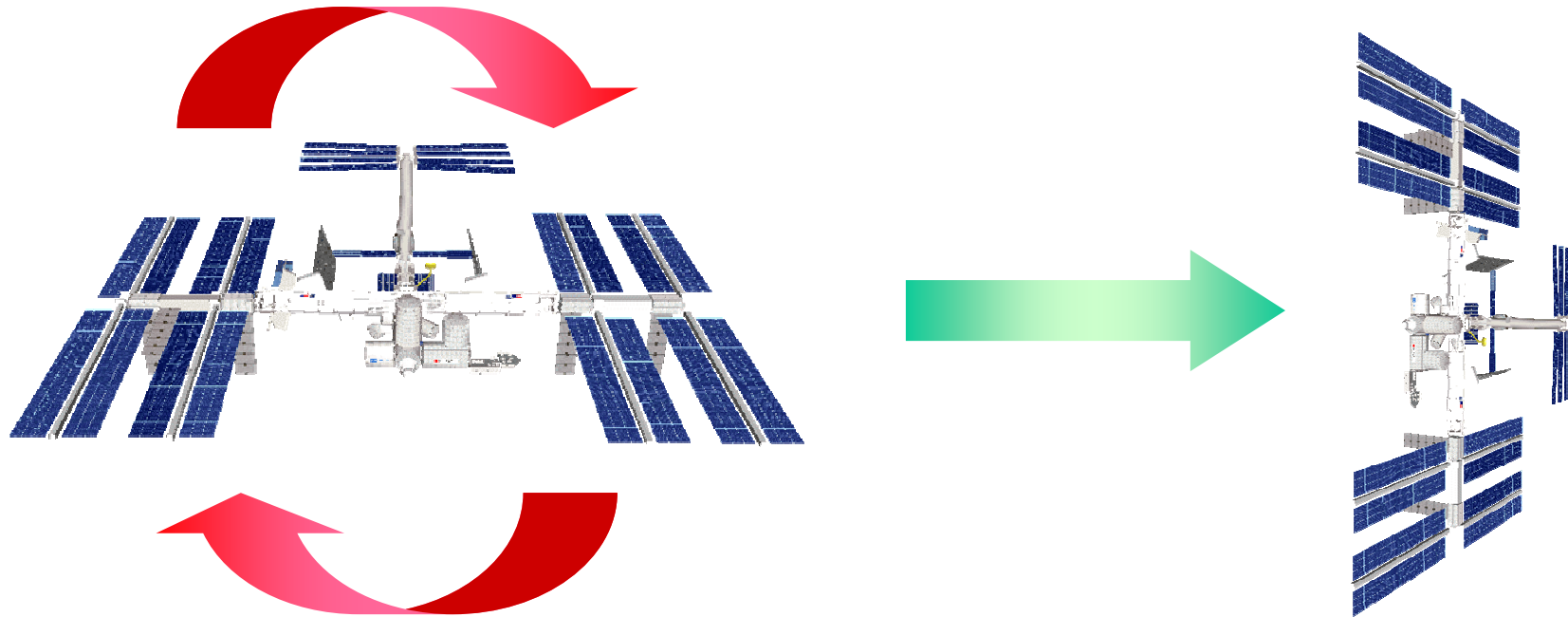
- ◆ Gravity-gradient stabilized concepts were very unpopular with scientists wishing to conduct microgravity experiments since pressurized modules were often far from station center-of-mass (CM).
- ◆ Later station configurations located pressurized modules at CM to avoid this problem.
- ◆ But instead of exploiting GG-stabilization, many “balanced” configurations have to fight gravity-gradient de-stabilization.



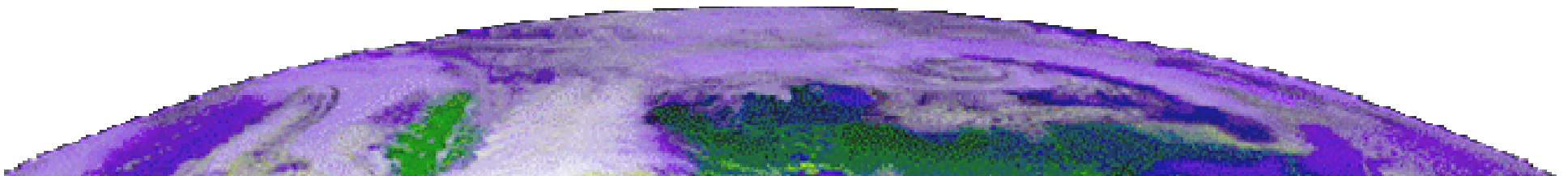


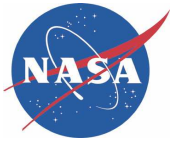
ISS—An Unstable Configuration

Gravity-gradient forces are a constant torque on the ISS. Without active attitude control, the ISS will assume a vertical orientation.



The control moment gyros (CMG) are used to maintain this attitude. When the CMGs become saturated, thrusters on the Service Modules fire while the gyros desaturate.

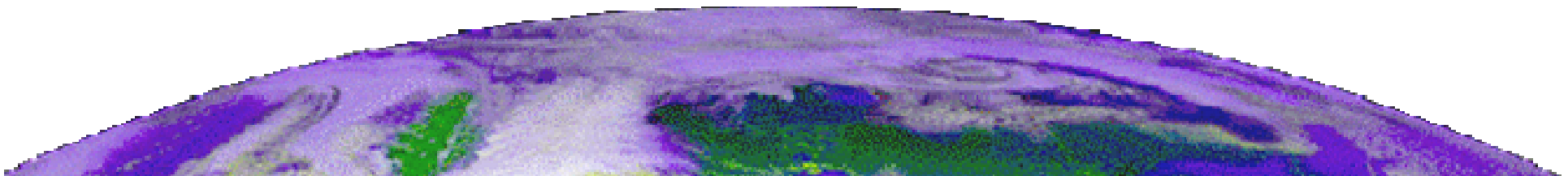
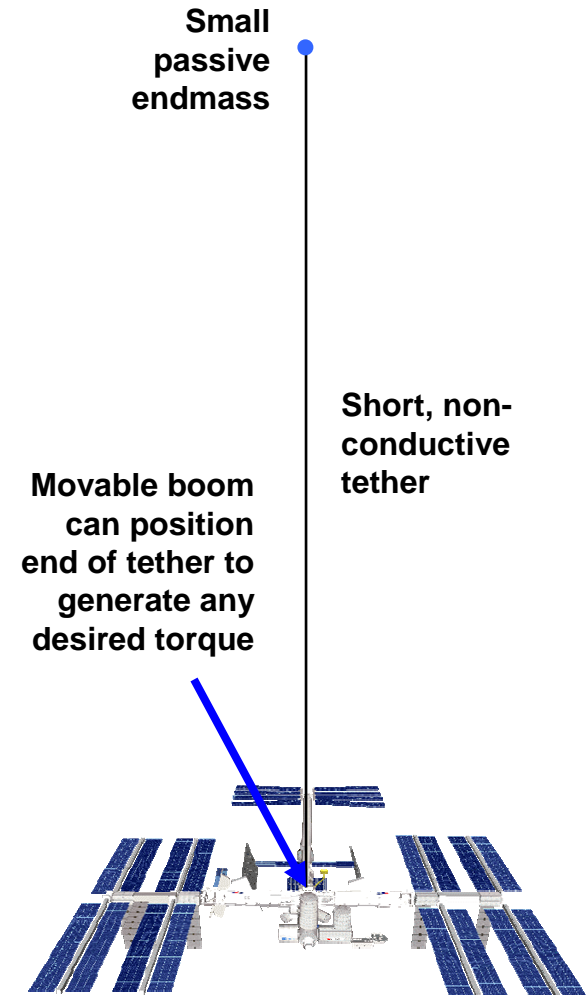


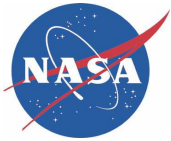


A tether can be used to naturally stabilize ISS

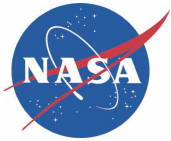
The solution to the gravity-gradient problem is to reconfigure the moment-of-inertia (MOI) of the space station in a gravity gradient configuration.

- ◆ Moment-of-inertia is $\text{mass} \times (\text{distance})^2$.
- ◆ Tethers can put a small mass (~100 kg) at large distances (100s of meters) and provide a large alternation in MOI for very little mass.
- ◆ By attaching the tether to a moveable boom on the ISS (preferably on the Z1 truss) torques can be generated to compensate for disturbing torques such as
 - Gravity-gradient torques
 - CMG desaturation
- ◆ Thus, the station can actually “torque” against the tether and desaturate CMGs—saving the propellant currently being used on the Zvezda (service) module for CMG desaturation.
- ◆ This configuration also provides a reliable, passive stabilization system in the event of total CMG failure.





Tethered Electric Propulsion Reboost of the International Space Station



Past ISS Reboost Alternatives

◆ ISS Electric Propulsion Study (Sackheim – March 2002)

- Initially included six electric propulsion systems
- Down-selected to three most promising EP systems
 - Arcjets
 - Hall thrusters
 - Ion thrusters

◆ Key assumptions included:

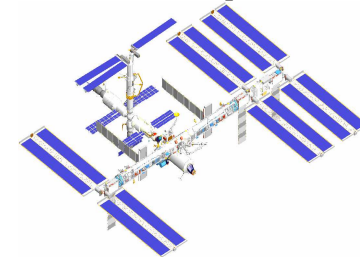
- Accommodation of shadowing effects
- For dedicated solar power systems of some options, the necessary cross-sectional area for solar arrays is roughly 1.5 times the space station average cross-sectional area
- ISS orbit is assumed to be circular in calculations
- Use of a linear fit of the JSC atmospheric density data at intermediate altitudes
- Implementation objective to keep ISS altitude as near the microgravity environment altitude

◆ Excerpt from Final Report Recommendation

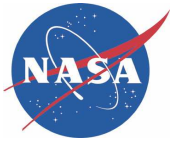
“...Russian performance, along with early success of the Shuttle to provide ISS reboost, now makes the case far more difficult to justify an electric propulsion system development—one whose cost is in the same magnitude as the previous studies [\$160-600M].”

Electric Propulsion for *ISS* Reboost

Final Report

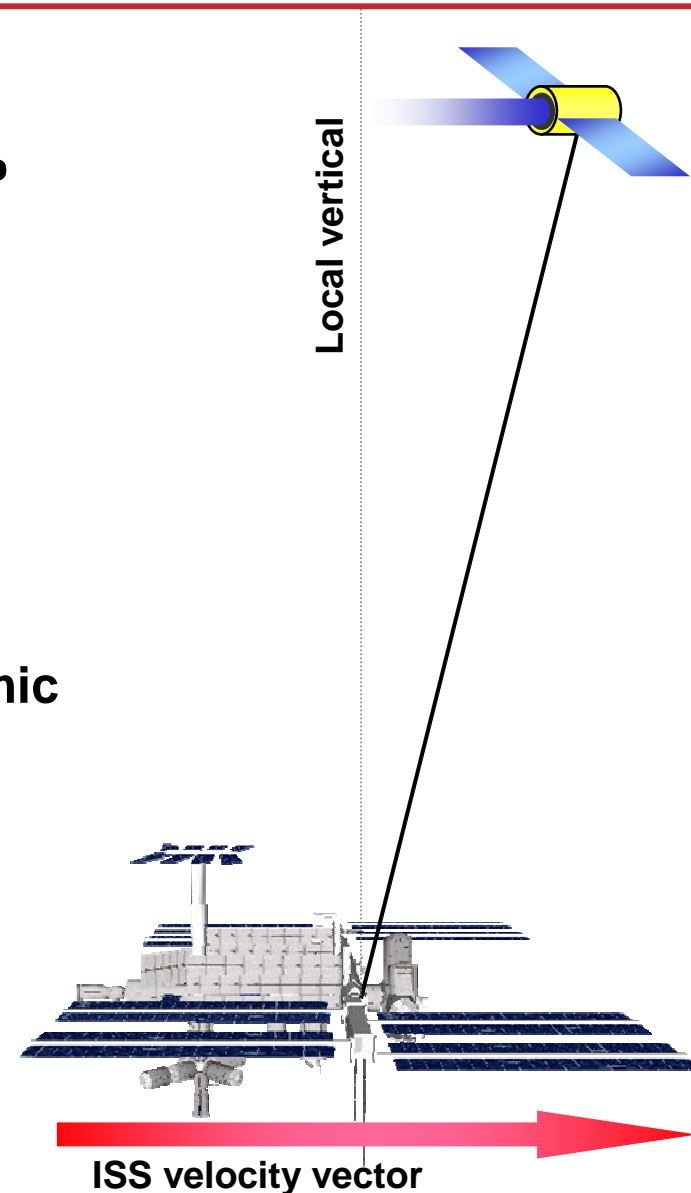


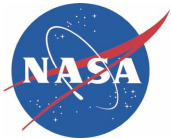
March 2002



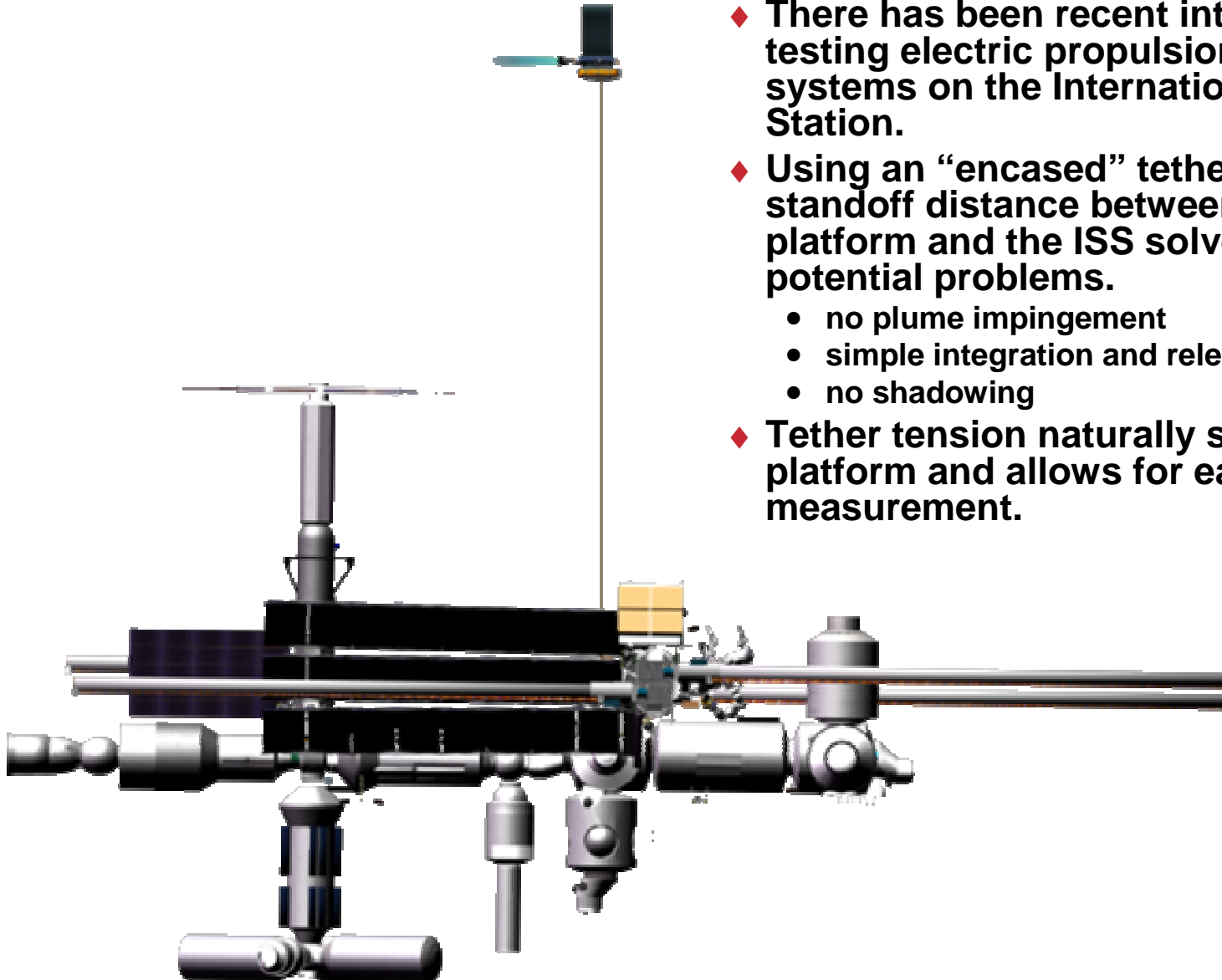
ISS Tethered EP Reboost

- ◆ **Tethered electric propulsion system avoids many drawbacks of station EP**
 - dedicated power
 - no plume impingement
 - simple integration and release
 - no shadowing
 - continuous thrust possible without inclination change
- ◆ **Drawbacks are propellant and power consumption relative to electrodynamic tether system**
- ◆ **Tether tension naturally stabilizes system and transmits force to ISS**

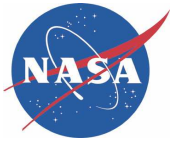




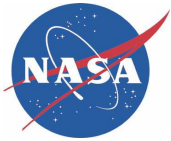
ISS Tethered EP Test Platform



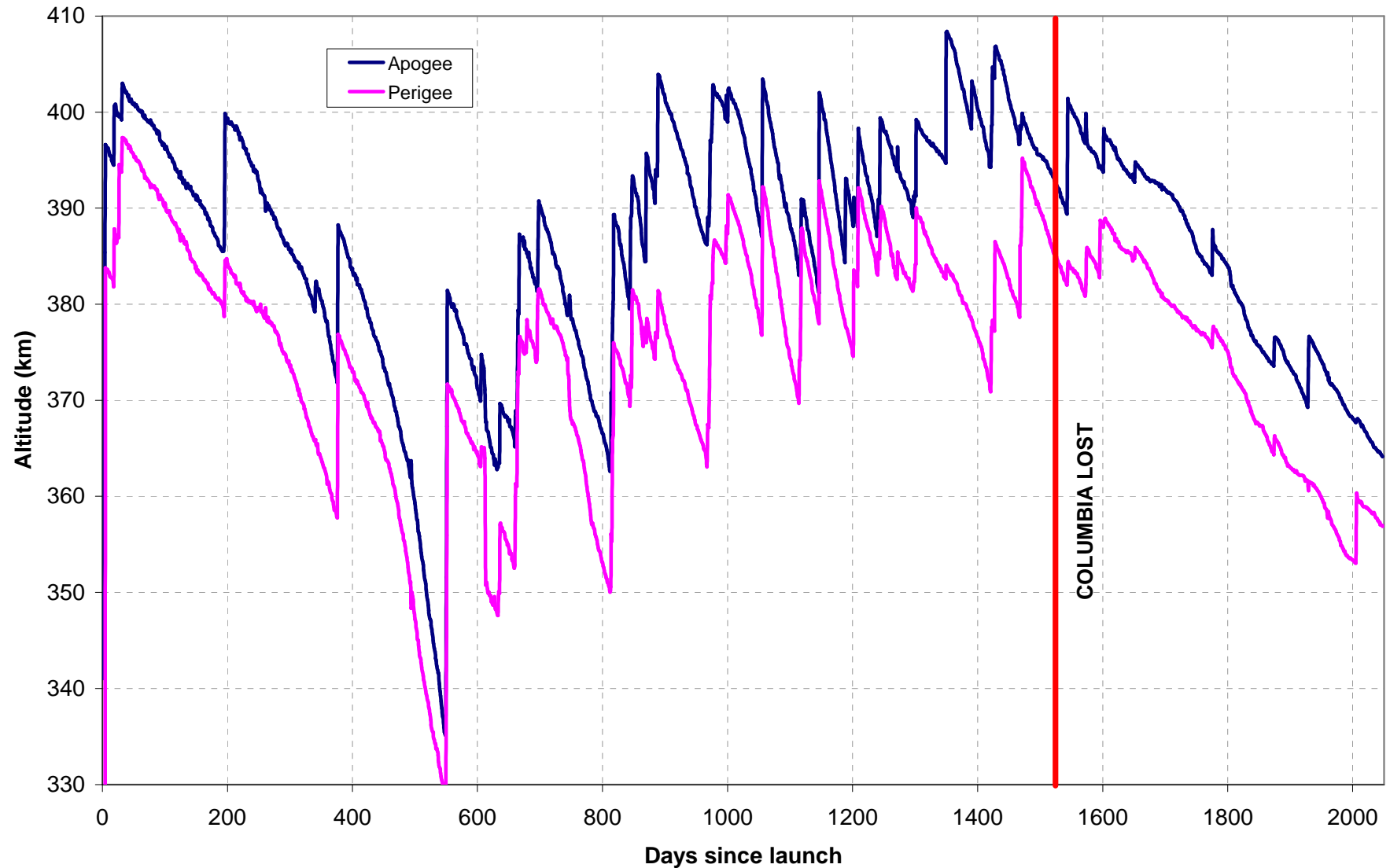
- ◆ There has been recent interest in testing electric propulsion (EP) systems on the International Space Station.
- ◆ Using an “encased” tether to provide standoff distance between the test platform and the ISS solves many potential problems.
 - no plume impingement
 - simple integration and release
 - no shadowing
- ◆ Tether tension naturally stabilizes the platform and allows for easier thrust measurement.

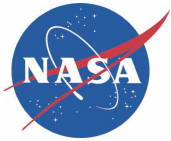


Electrodynamic Tether Reboost of the International Space Station



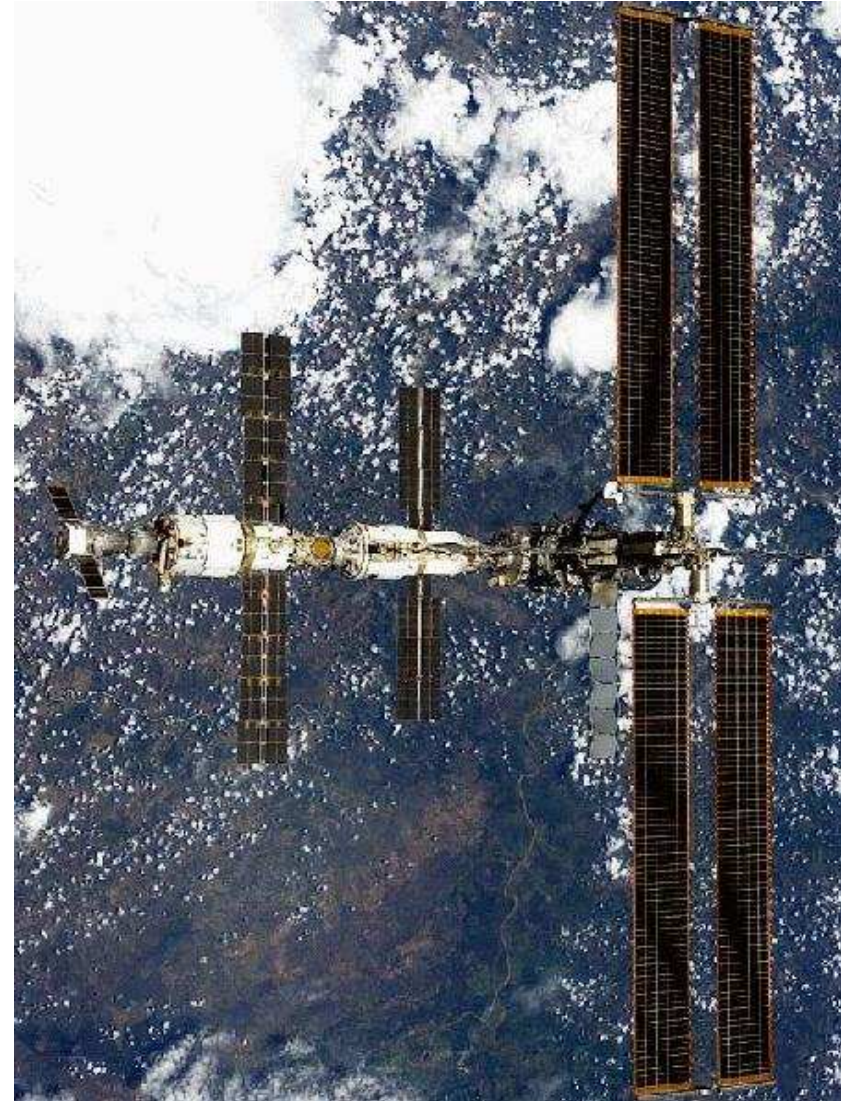
ISS Altitude History 1998-2004

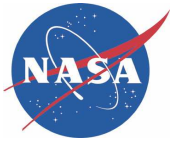




The Problem of Propulsive Reboost

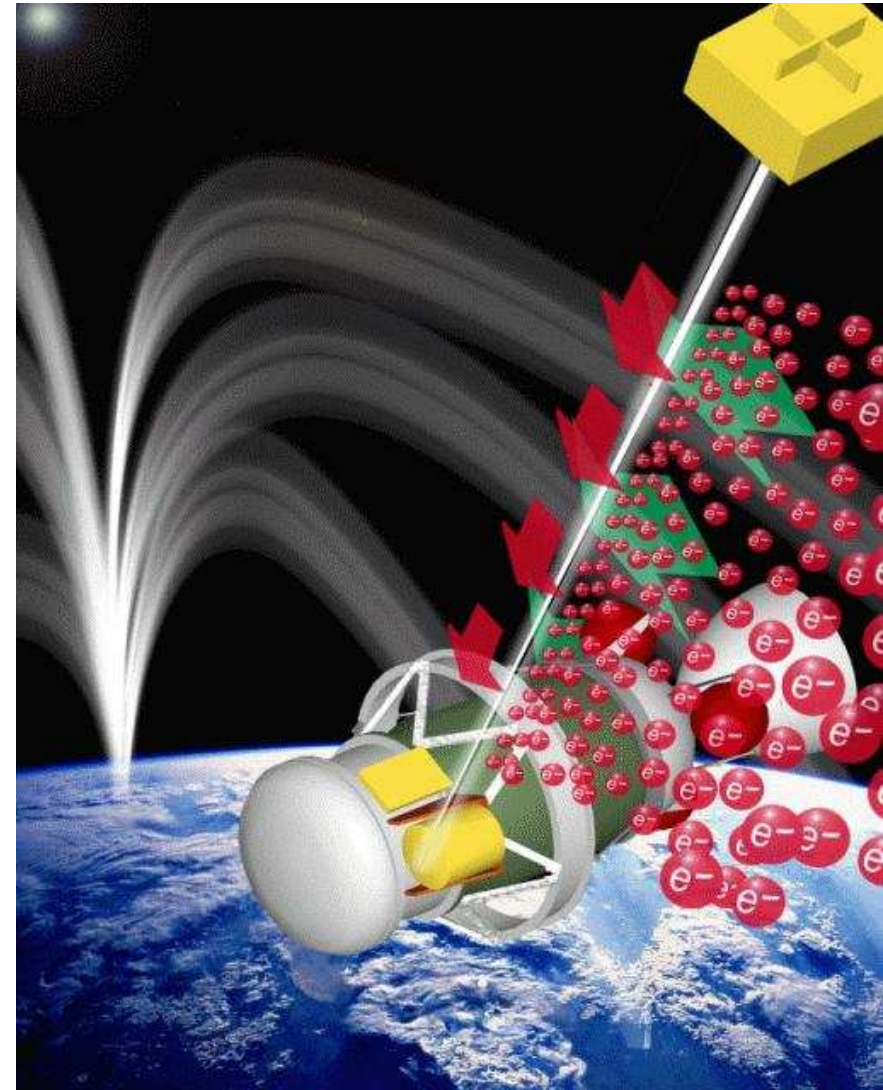
- ◆ **ISS LEO operation requires reboost**
 - Large drag area (solar arrays)
 - Drag will increase significantly as more solar arrays are added
- ◆ **Propulsive reboost involves momentum exchange with propellant**
- ◆ **Low I_{sp} reboost consumes large amounts of propellant and little electrical power**
 - Jet power comes from chemical energy
 - Consumes significant amounts of propellant but little power
- ◆ **High I_{sp} reboost consumes large amounts of electrical power and little propellant**
 - Jet power comes from electrical energy
 - kW-level power supplied by ISS
- ◆ **Electrodynamic tether reboost consumes modest amounts of power and no propellant!**





Electrodynamic Tether Propulsion

- ◆ **Electrodynamic tether propulsion is fundamentally momentum exchange**
 - Tether system “pushes” against the terrestrial magnetic field.
 - Force is imparted to the tether via the Lorentz force ($F = IL \times B$).
 - Electrical current is driven through tether by a solar power supply.
 - Electron collection and emission to and from the ionosphere “closes the circuit”.
- ◆ **ED tether propulsion does not consume propellant**
 - Some cathode concepts have a small amount of consumables—others are propellantless.
- ◆ **ED tether propulsion is significantly better than most EP technologies for producing thrust from electric power**
 - similar to hydrazine arcjet (but needs no fuel)
 - 3x better than ion engines





ED Tether Reboost was proposed to ISS in the late 1990's

National Aeronautics and
Space Administration
Lyndon B. Johnson Space Center
2101 NASA Road 1
Houston, Texas 77058-3696



APR 01 1996

EA12-96-011

TO: OA/Manager, Space Station Program
YA/Manager, Phase 1 Program

FROM: EA12/Chief Engineer for International Space Station

SUBJECT: Technology Development of Tether Applications to
International Space Station (ISS) and Mir

I have reviewed potential application of tethers for the ISS presented by a team from MSFC's Program Development organization. These applications include:

1. Reboost of ISS by momentum exchange, electrodynamic thrust, or towing.
2. Deboost and return/reentry of payloads and trash.
3. Electrical power generation.
4. Microgravity environment enhancement.

Electrical power generation has been demonstrated by the Shuttle/Tethered Satellite System (TSS) in 1992 and 1996 and by the Plasma Motor Generator in 1993. Deboost of small payloads was demonstrated by the Small Expendable Deployer System (SEDS) experiments in 1993 and 1994. Momentum exchange was demonstrated on the SEDS and on the second TSS mission.

A significant reduction in ISS reboost and payload/spent stage deorbit propellant is possible using tethers. Some of the concepts could provide routine and/or backup reboost capability for ISS even with loss of vehicle access. In addition, an effective way to utilize Orbiter residual OMS propellant for reboost can be realized by one of the tether concepts.

I recommend we support continued technology development of tether applications to ISS and Mir through cooperative funding from the ISS Advanced Engineering and Technology Development, Phase 1 Mir Risk Mitigation Experiment program and other programs in Codes X and M. I have asked the MSFC Program Development people to propose appropriate flight experiments that will demonstrate capability to reboost the ISS using tethers. Such

◆ Concept was included in Preplanned Program Improvement planning until termination

- Frank Buzzard, ISS Chief Engineer, endorsed the approach (letter included).

◆ ED reboost was not pursued at that time.

- Stated reason was, “come back after assembly is complete – we have too much to worry about right now with the baseline design...”

EA12-96-011

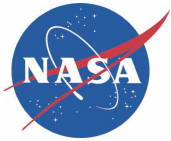
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experiments may include the use of several principles mentioned above, and may include flights on Mir as early precursor demonstrations.

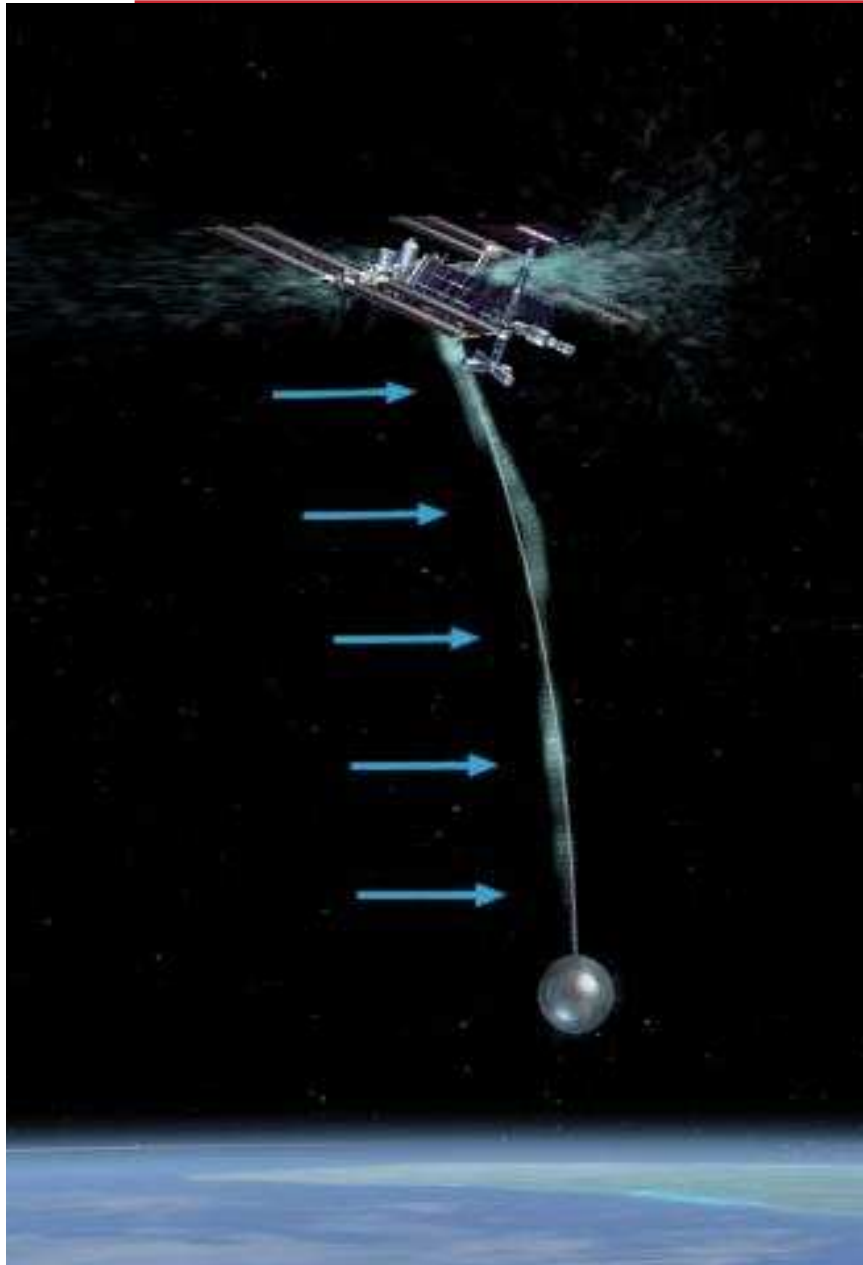
Flight demonstrations should also be pursued in the areas of electrical power generation, deboost and return/reentry of payloads and trash, and microgravity enhancement for potential use on the ISS.

Your support is appreciated. Please contact Mr. John Butler, Code PS02, at the Marshall Space Flight Center, telephone 205-544-4833, for further information.


Frank T. Buzzard



Downward-deployed ED Tether



♦ Advantages

- Simplest and most straightforward application
- Only mechanical connection to ISS
- Independent of ISS power and ISS plasma contactors
- Quick disconnect
- Stabilizes ISS attitude in a gravity-gradient configuration; gyros can desaturate against tether without propellant consumption
- High “power alpha” and power storage allows flexibility for reboost timing
- Total system mass of ~1000 kg
- Attractive as an experiment or backup to existing reboost strategy

♦ Current investments can be leveraged to support concept

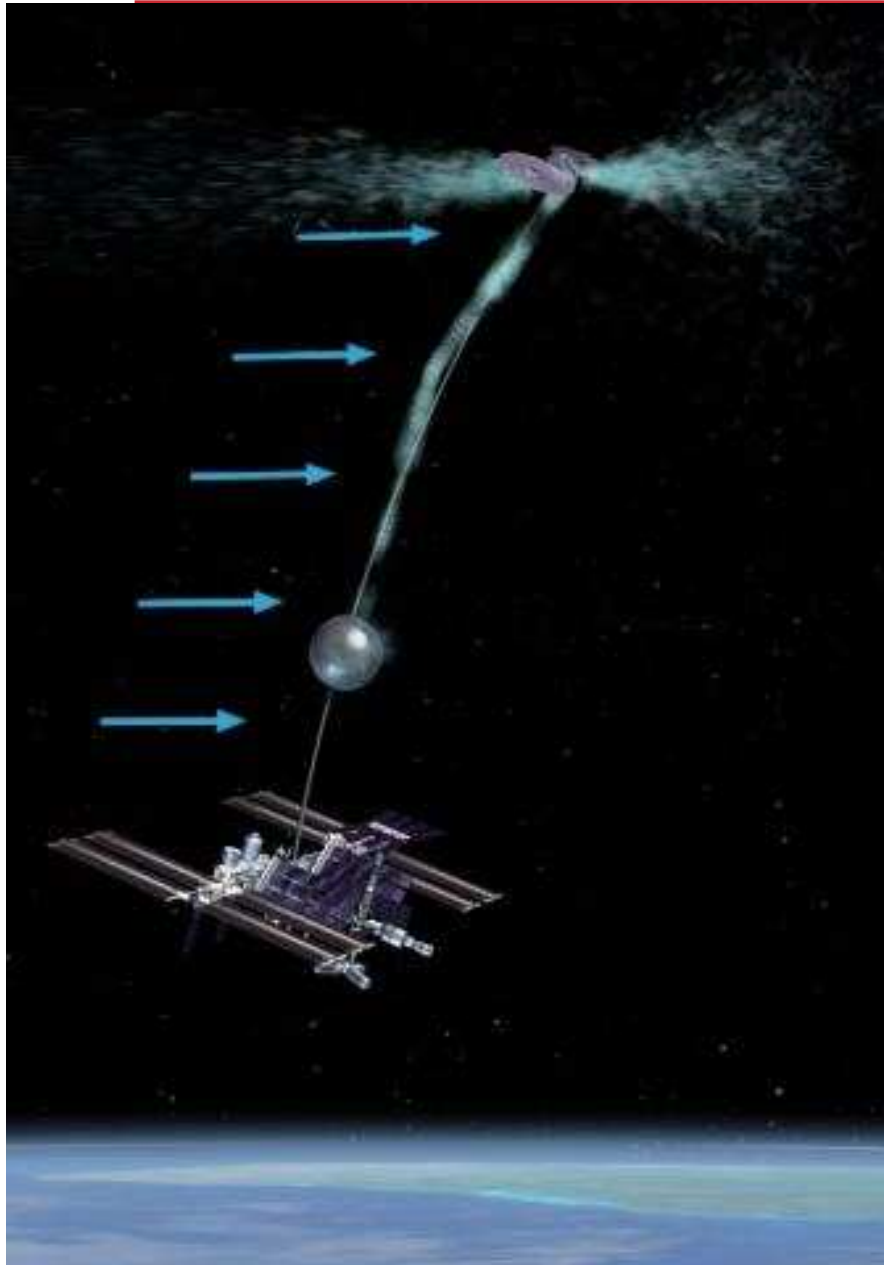
- Power node
- Survivable, insulated multi-strand tether
- Grid-sphere anode for free electron collection

♦ Disadvantages

- Was thought to interfere with X-38 escape along R-bar vector
- Some center-of-mass shift
- Some orbital inclination change (can be minimized, but not eliminated)



Upward-deployed ED Tether



◆ Advantages

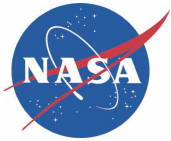
- Only mechanical connection to ISS
- Independent of ISS power and ISS plasma contactors
- Quick disconnect
- Stabilizes ISS attitude in a gravity-gradient configuration; gyros can desaturate against tether without propellant consumption
- High “power alpha” and power storage allows flexibility for reboost timing
- Total system mass of ~1000 kg
- Attractive as an experiment or backup to existing reboost strategy

◆ Current investments can be leveraged to support concept

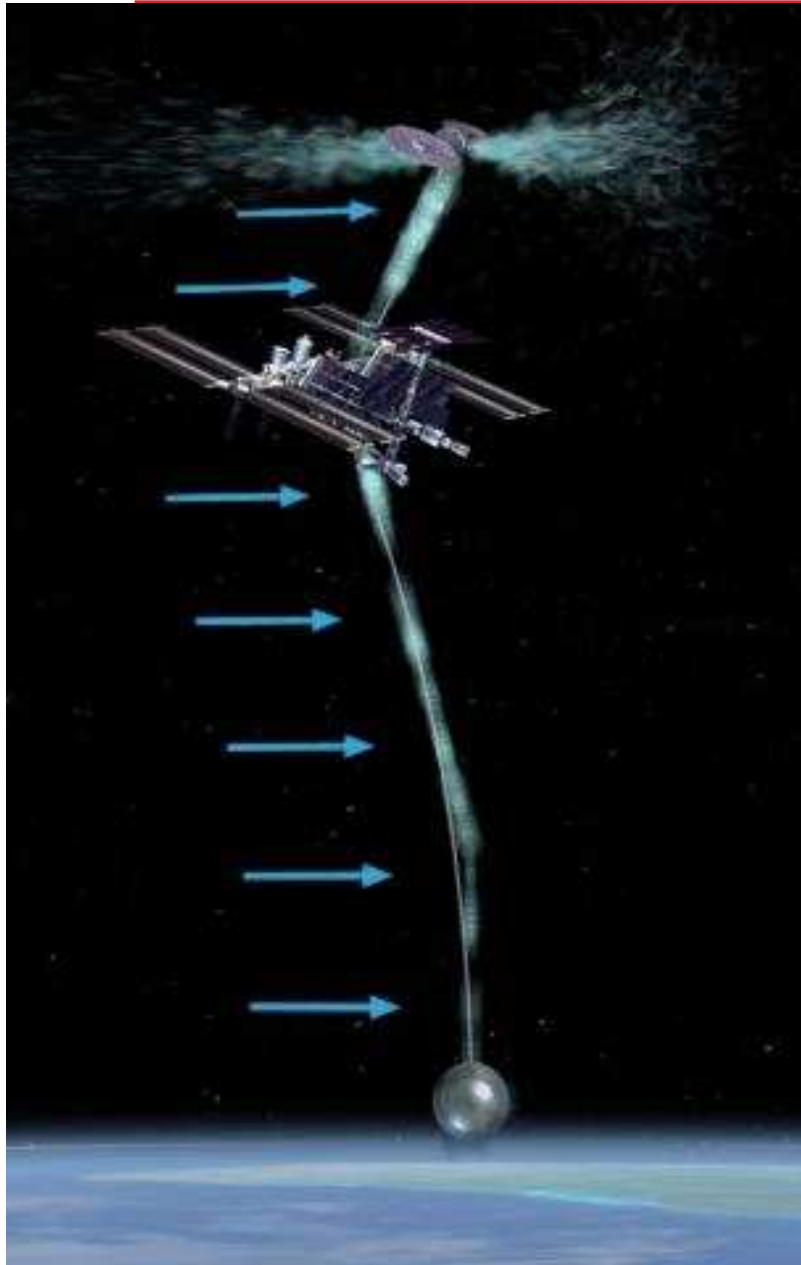
- Power node
- Survivable, insulated multi-strand tether
- Grid-sphere anode for free electron collection

◆ Disadvantages

- Significant center-of-mass shift
- Some orbital inclination change (can be minimized, but not eliminated)



Pass-through ED Tether Design with “Tunable CM”



♦ Advantages

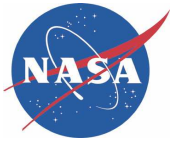
- No center-of-mass shift
- Modest connection to ISS (motor and reel)
- Independent of ISS power and ISS plasma contactors
- Quick disconnect thru guillotine
- Stabilizes ISS attitude in a gravity-gradient configuration; gyros can desaturate against tether without propellant consumption
- High “power alpha” and power storage allows flexibility for reboost timing
- Total system mass of ~1000 kg
- Attractive as an experiment or backup to existing reboost strategy

♦ Current investments can be leveraged to support concept

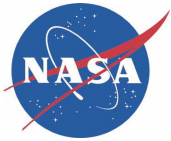
- Power node
- Survivable, insulated multi-strand tether
- Grid-sphere anode for free electron collection

♦ Disadvantages

- Might interfere with radial approaches (but radial approaches are not planned)
- Some orbital inclination change (can be minimized, but not eliminated)

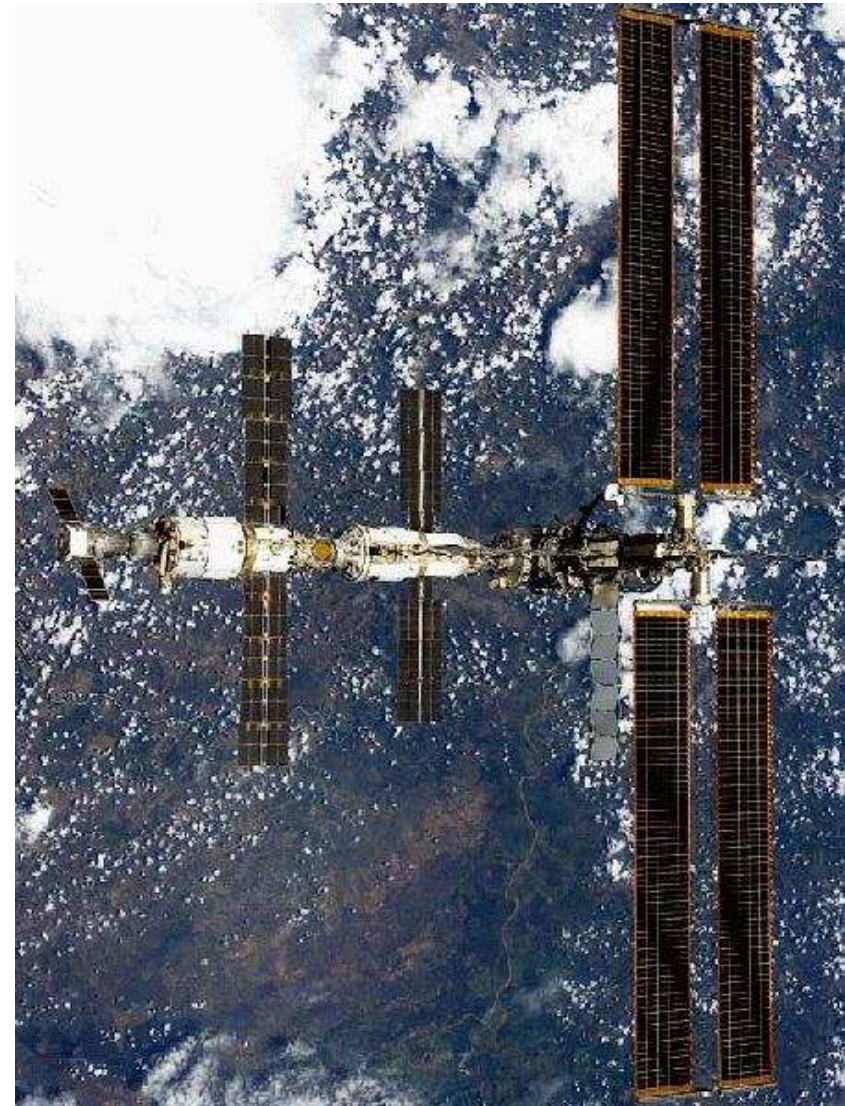


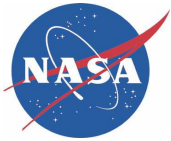
Reducing the Orbital Inclination of the International Space Station



Why Consider ISS Inclination Reduction?

- ◆ **28.5° was original station inclination.**
 - Latitude of KSC (28.5° north) and minimum inclination accessible from KSC—due-east launch azimuth.
 - Maximum payload capacity for Shuttle
- ◆ **Soviet space stations (Salyut, Mir) were at 51.6° inclination.**
 - Baikonur Cosmodrome is at 45.6° north latitude, but 51.6° is the minimum inclination that can be reached on an acceptable launch azimuth.
 - Inclination is based on where rocket boosters drop downrange—in USSR instead of in Mongolia.
- ◆ **When Russia joined the ISS, the inclination had to be increased to allow access from Baikonur.**
 - Significant performance reduction for KSC launches.
 - Less applicability to future “beyond-LEO” scenarios
- ◆ **In light of CAIB mission recommendations and NASA’s new direction, the high-inclination orbit of the ISS is an increasing liability.**
 - Launch performance reduction.
 - ISS cannot serve as “safe-haven” for lunar vehicles assembled in 28.5° orbits.
- ◆ **Recently, a Soyuz launch site has been constructed in French Guiana for satellite launches.**
 - Manned Soyuz/Progress missions from French Guiana would obviate Russian need for high-inclination ISS.
 - No more Proton launches for station assembly planned from Baikonur.



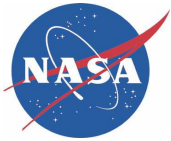


Manned Soyuz/Progress from French Guiana

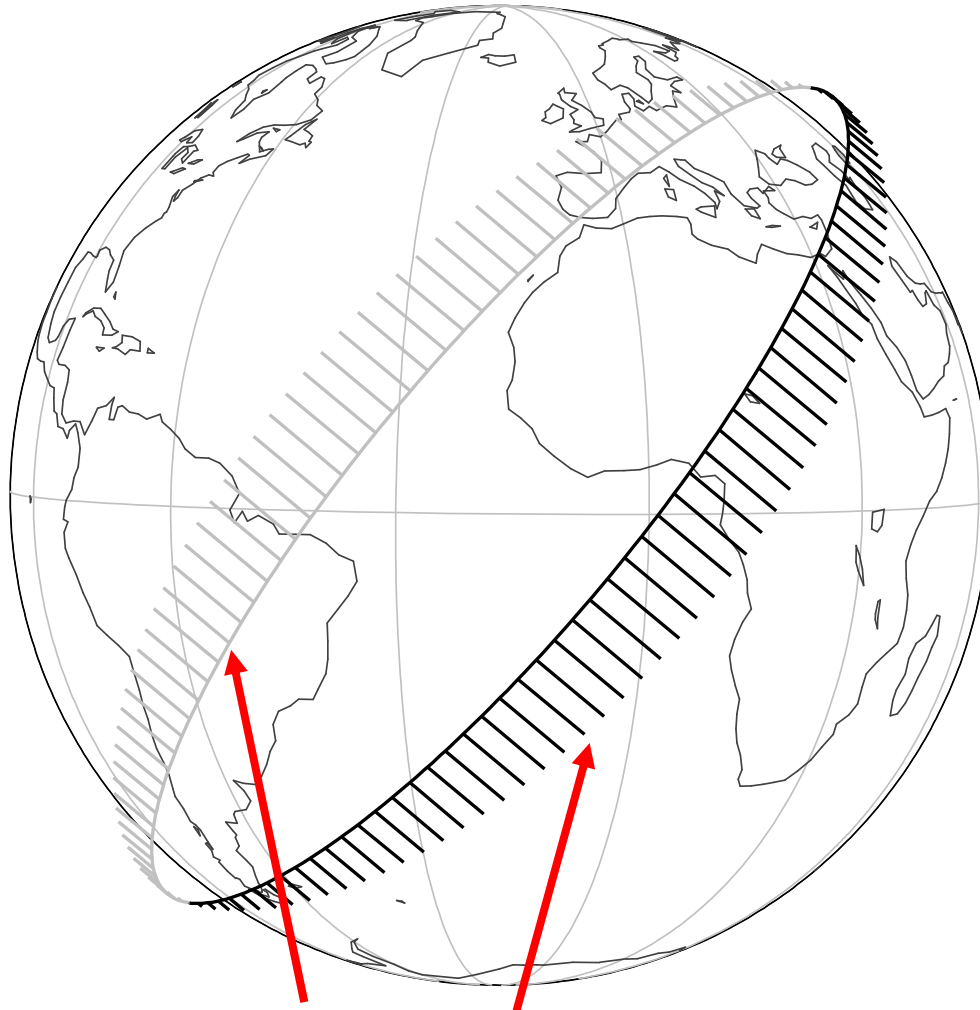
- ◆ There are "no showstoppers" in using the Soyuz launch pad planned for the European Space Center at Kourou, French Guiana, to send astronauts and cosmonauts to the International Space Station.
- ◆ Arianespace CEO Jean Yves Le Gall says a "small working group" formed to consider the issue has found the only additional facility needed to support human spaceflight from Kourou is a "specific building for the preparation of the astronauts."
- ◆ The pad to be built there will be identical to the famous "Start 1" pad at the Baikonur Cosmodrome where ISS flights originate today, and the over-ocean flight path to ISS will not be restricted by the need to avoid populated areas as at land-locked Baikonur, he adds.
- ◆ Although Le Gall stresses that nothing is in the works, Soyuz launches by Arianespace could give NASA and the European Space Agency a way around the Iran Non-Proliferation Act, which is complicating funding arrangements among ISS partners by prohibiting U.S. government payments to Russia for ISS support (AW&ST Aug. 9, p. 23).
- ◆ Reference: Aviation Week and Space Technology, August 16, 2004, pg 19



The new Soyuz launch site in Kourou, French Guiana should be operational by 2006.



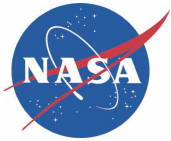
Changing Orbital Inclination



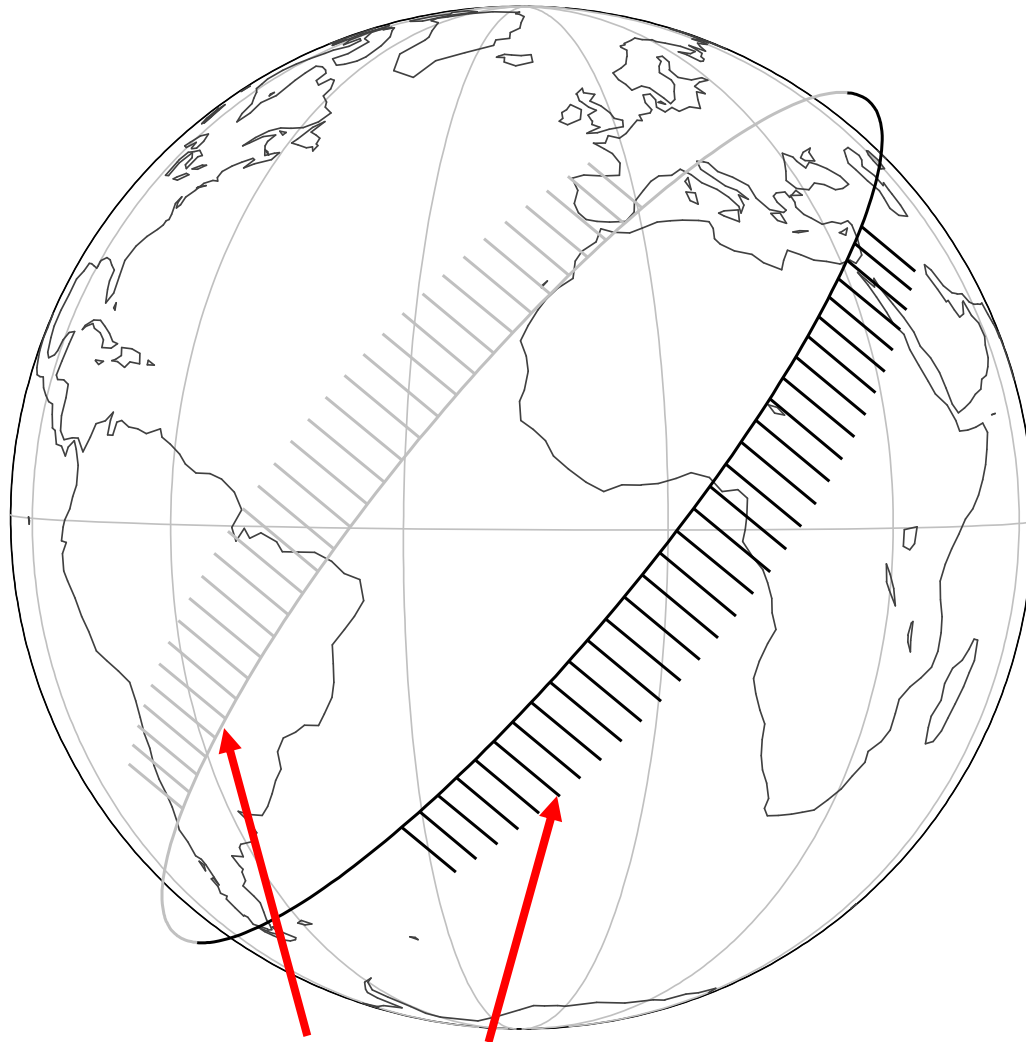
The lines represent a constant, negative, out-of-plane force vector multiplied by the cosine of argument of latitude at each location along the orbit—this indicates the “effectiveness” of the out-of-plane force in changing orbital inclination and how it changes with location.

$$\frac{di}{dt} = \frac{F_w}{mv} \cos u$$

- ◆ This equation describes the time-rate-of-change of orbital inclination of a circular orbit:
 - F_w = out-of-plane force
 - m = mass of object
 - v = circular orbital velocity
 - u = argument of latitude (angle from the ascending node measured in the orbital plane)
- ◆ Orbital inclination can only be changed by the application of out-of-plane force.
- ◆ In order to be effective, out-of-plane force must be applied at the ascending and descending nodes of the orbit, and in opposite directions at each.

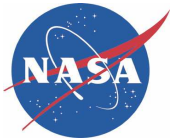


Practical Aspects of Inclination Change



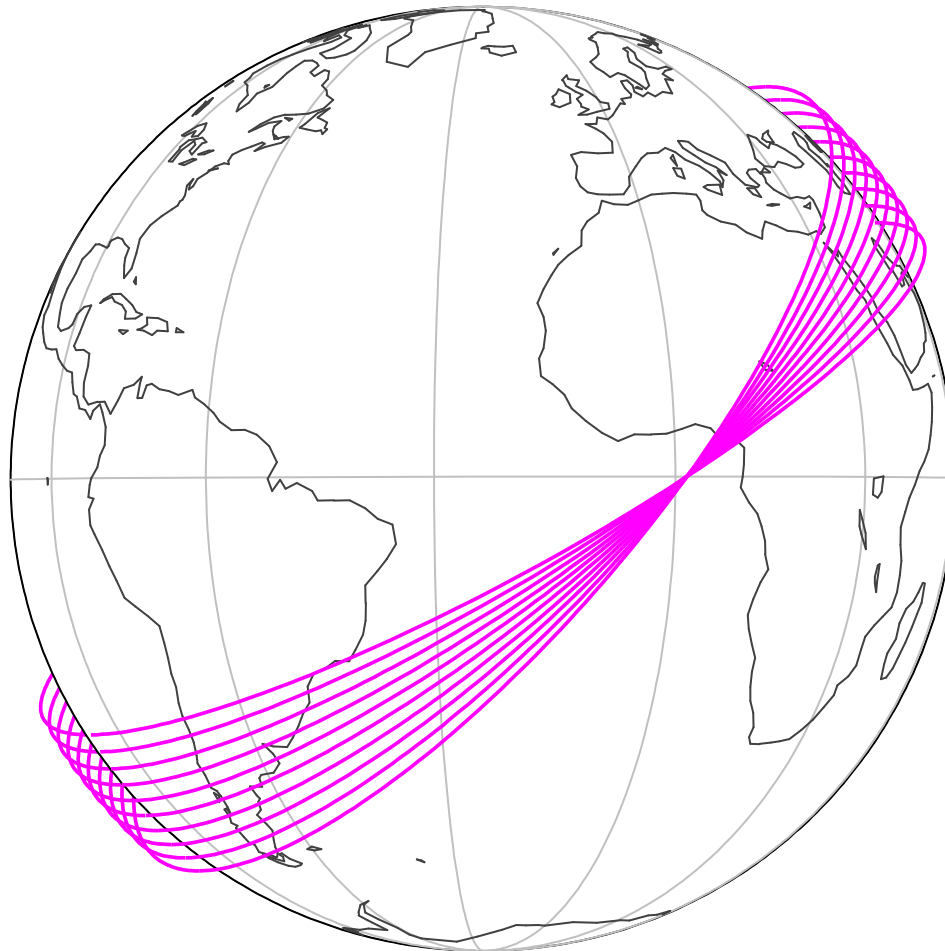
- ◆ Because of the cosine dependence on out-of-plane force, any non-impulsive propulsion system used for plane change will be able to change inclination only about 50% of the orbital period.
- ◆ To maximize efficiency, out-of-plane propulsion should be applied along two thrust arcs, centered on the nodes.
- ◆ If the arcs were 90° in angular extent, the thrusting profile would be ~70% efficient vs. an instantaneous impulse applied only at the nodes.
- ◆ Wider arcs are less efficient, shorter arcs are more efficient.

Since inclination change is most effectively done at the nodal crossings, these lines represent a constant, out-of-plane force vector multiplied by the cosine of argument of latitude at each location along two 90° arcs centered on the nodes.

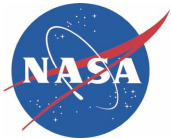


Orbital Inclination Change of the ISS

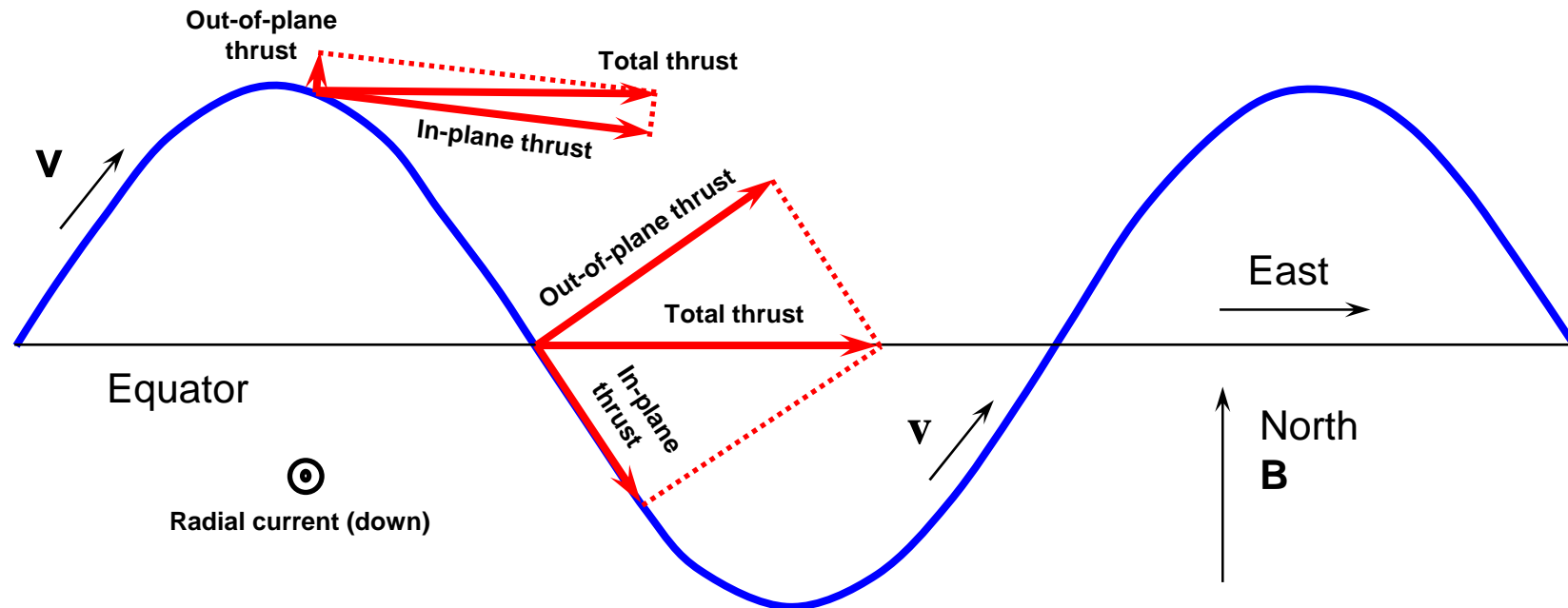
- ◆ The orbital inclination of the ISS could be reduced from 51.6° to 28.5° (or less) by using rocket propulsion or an electrodynamic tether to generate the necessary out-of-plane forces.
- ◆ For this magnitude of inclination change, the ideal ΔV required would be ~3100 m/s, which is approximately the same amount of ΔV required to place the entire ISS on a trans-lunar trajectory.



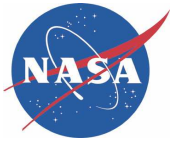
- ◆ This ΔV will require a large amount of propellant (and power) for rocket-based options, and the propellant required will be a significant fraction of the ISS mass:
 - 70% for LH2/LOX @ 450s
 - 53% for hydrazine arcjet @ 600s
 - 16% for xenon Hall @ 2000s
- ◆ For a 250 MT ISS, this equates to an ideal propellant requirement of:
 - 175 MT of LH2/LOX
 - 133 MT of hydrazine
 - 40 MT of xenon
- ◆ Electric rockets will also require significant power for this maneuver—for a 4-year plane change the orbit-averaged power would be (for a 250 MT ISS):
 - 33 kWe for hydrazine arcjet @ 55% eff
 - 110 kWe for xenon Hall @ 55% eff



ED Tethers Can Generate Out-of-Plane Forces

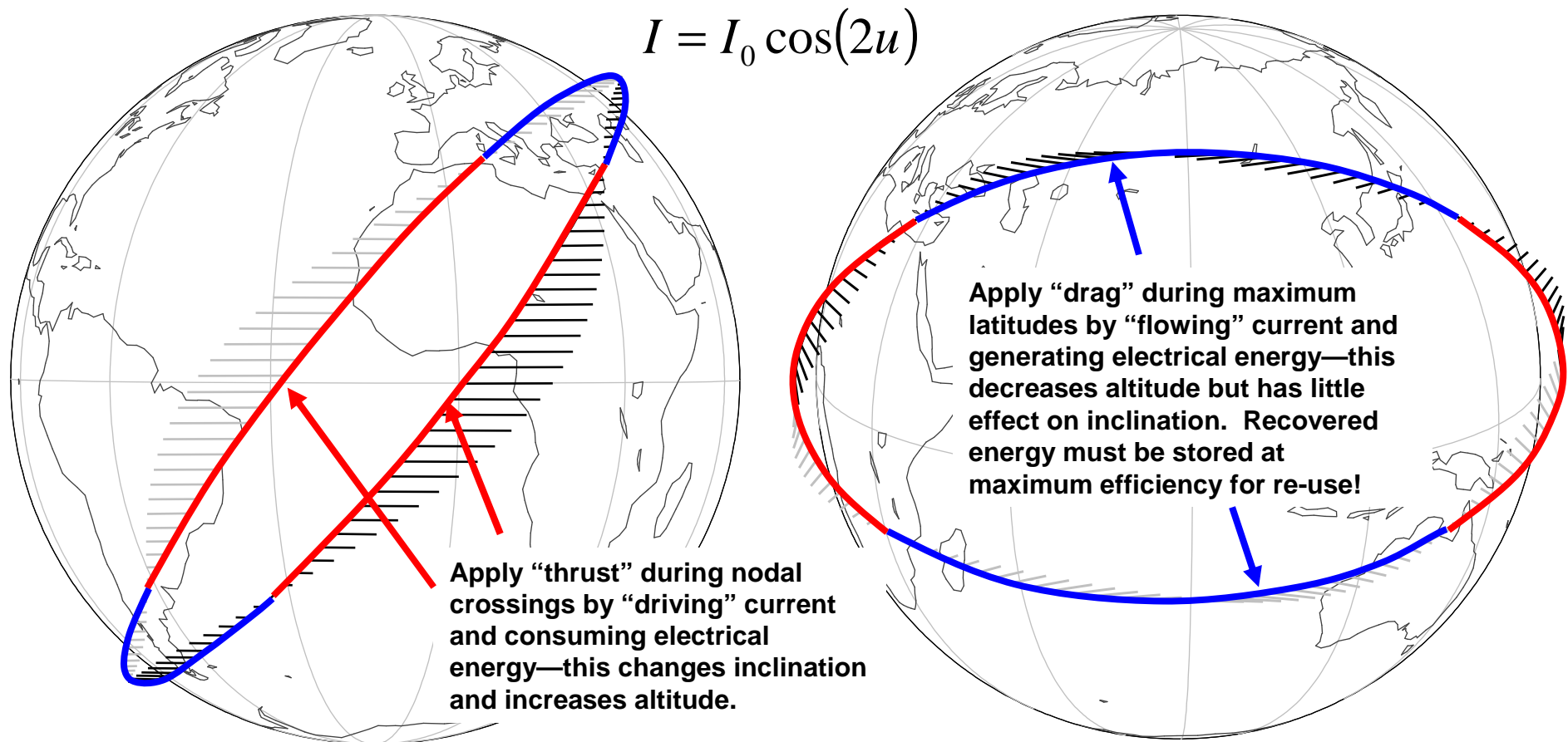


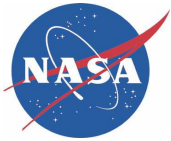
- ◆ Depending on the location in the orbit, the east-west forces that are generated by an ED tether can have a significant out-of-plane component.
 - ED tether forces have a maximum out-of-plane component at the nodal crossings.
 - ED tether forces have a maximum in-plane component at the maximum latitudes.
- ◆ But the voltage consumed/generated by the tether is **ONLY** proportional to the velocity across magnetic field lines (eastward velocity)—therefore, the power consumed/generated by the tether is proportional to the in-plane thrust generated!
 - This is logical since only in-plane forces increases/decrease orbital energy and angular momentum.
 - Inclination change does not change orbital energy or the magnitude of angular momentum.
 - Mother Nature keeps the books balanced...no free lunch but you don't have to pay for what you don't eat!
- ◆ We can exploit this effect to create tether forces that alter orbital inclination for minimal power consumption and no propellant consumption!



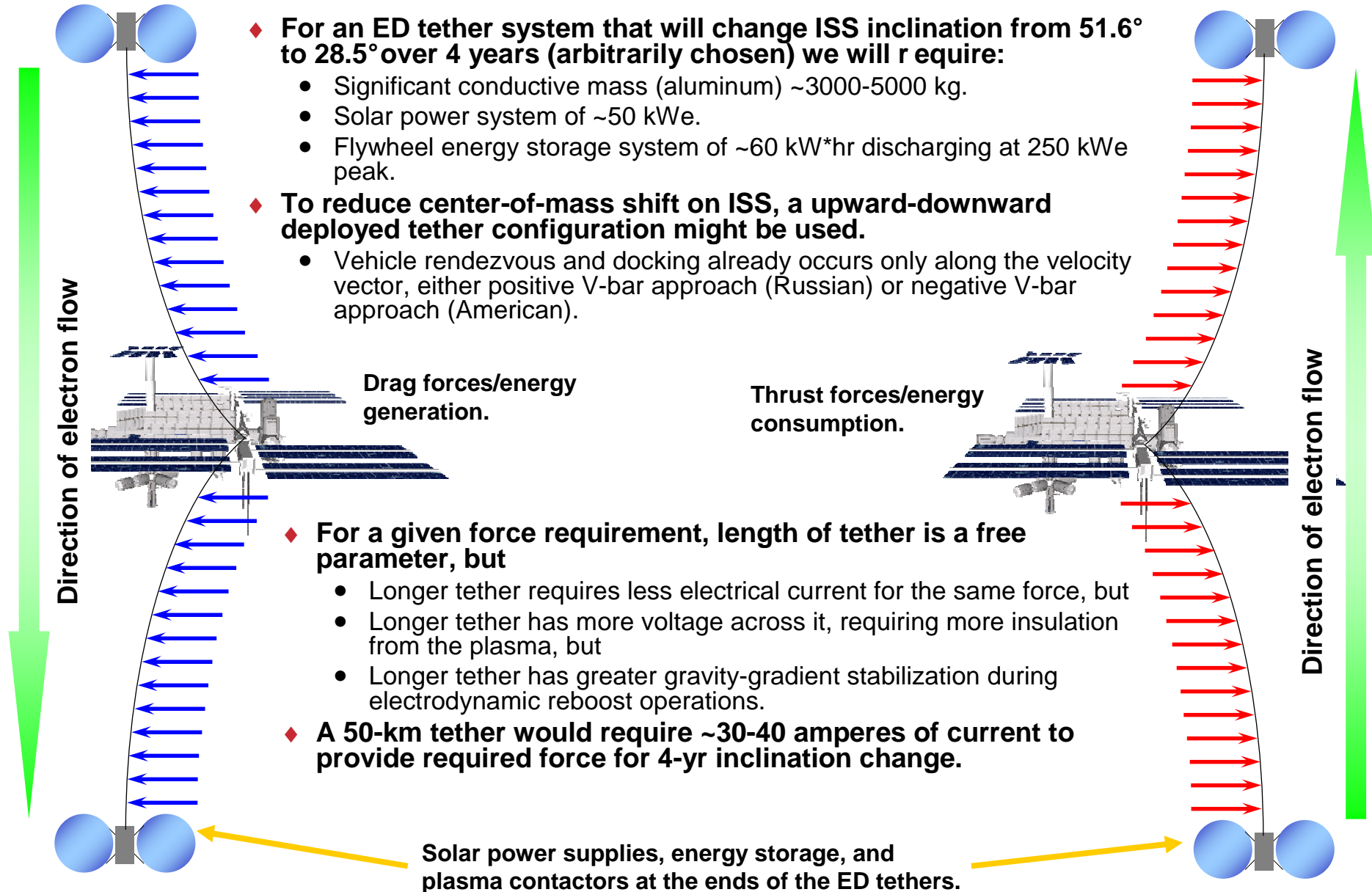
Inclination Reduction Using ED Tethers

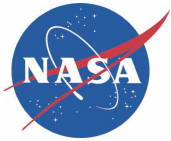
- ◆ Since ED tethers convert electrical energy to and from orbital energy, theoretically they can be used for plane change without NET consumption of energy!
- ◆ Electrical resistance in the conductive material, energy storage losses, and voltage drops across the plasma contactors cause deviation from this ideal.
- ◆ The electrical current control law changes directions twice during the orbit and varies with argument of latitude (u —the angle from the ascending node).





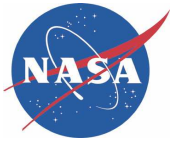
A Possible Configuration for ED Plane Change



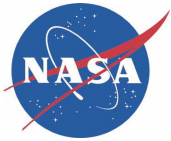


Conclusions/Recommendations

- ◆ Changing the ISS inclination from 51.6° to 28.5° could make the facility much more relevant to future exploration activities.
- ◆ A plane-change of this magnitude would be exceedingly difficult for rocket-based propulsion options due to the large ISS mass.
- ◆ The unique attributes of an electrodynamic tether make it very attractive for this difficult mission.
- ◆ An electrodynamic tether system for ISS plane change would be nearly identical in power, energy storage, length, current, and voltage levels to the electrodynamic reboost system of a MXER tether.
- ◆ Research in ISS plane change would then be applicable to MXER tether systems for human and cargo transport to GEO, L1, and the Moon.
- ◆ Recommend 12-month study (~4 FTE) at GRC and MSFC on tether design for ISS inclination change plus appropriate level of support from JSC (ISS system and impacts).



Cross-Cutting Tether Technology Needs



High Tensile-Strength Candidate Materials



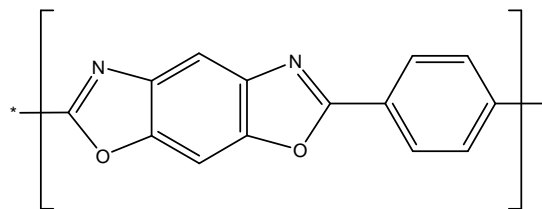
Spectra 2000

- ◆ Ultra-high molecular weight polyethylene (UHMWPE)
- ◆ 3.5 GPa tensile strength
- ◆ 970 kg/m³ density
- ◆ 1550 m/s characteristic velocity @ safety factor = 3



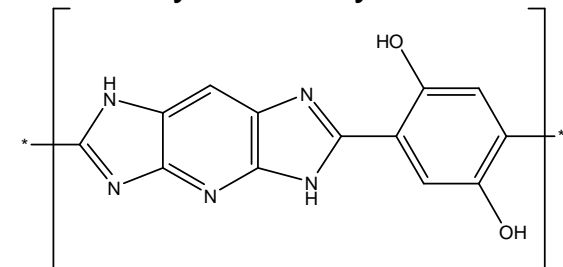
Zylon (PBO)

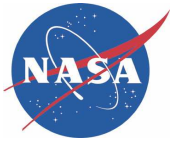
- ◆ Poly(p-phenylene benzobizoxazole)
- ◆ 5.8 GPa tensile strength
- ◆ 1540 kg/m³ density
- ◆ 1580 m/s characteristic velocity @ safety factor = 3



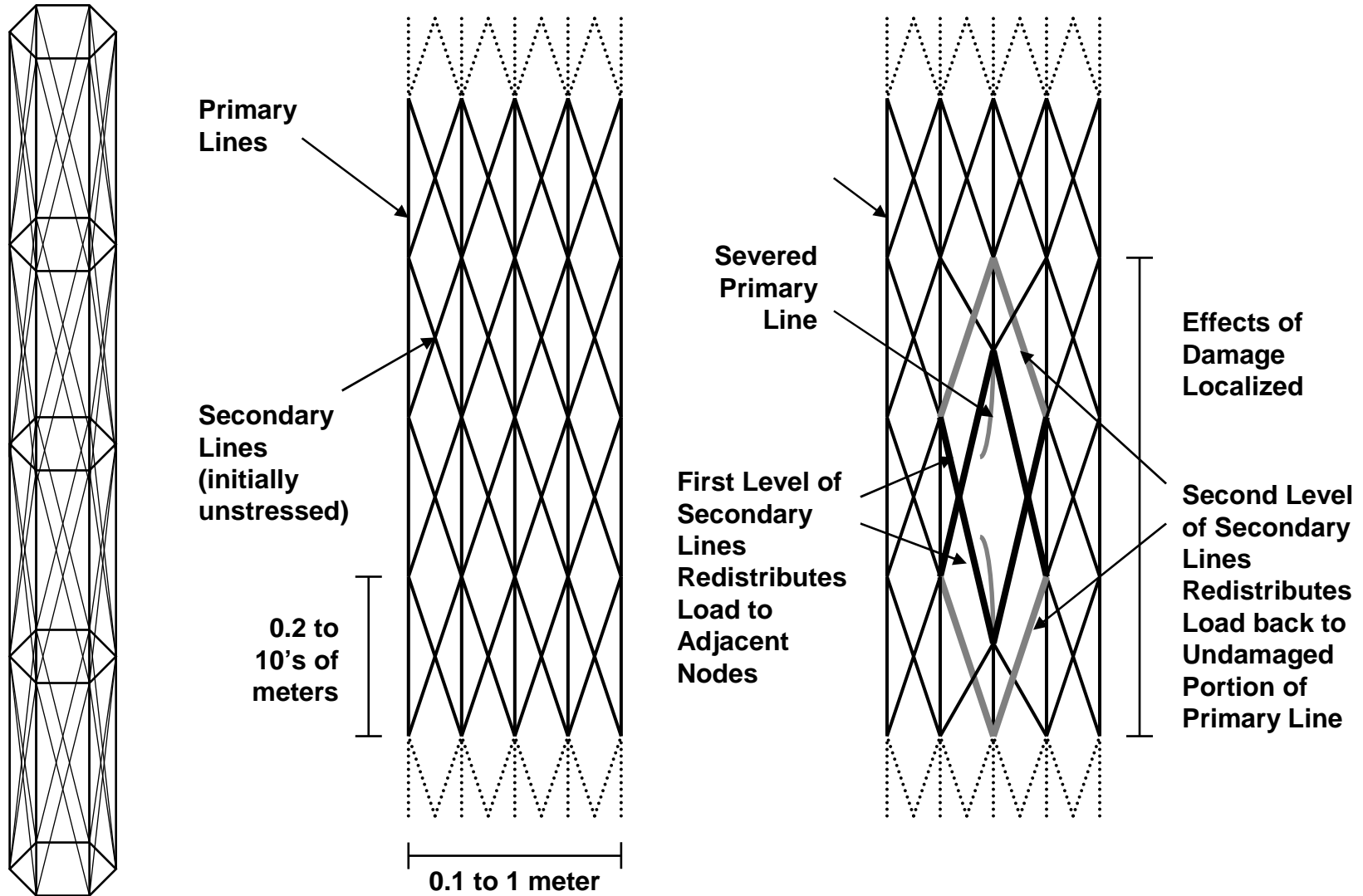
M5 (PIPD)

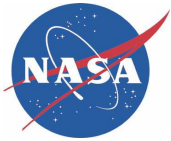
- ◆ Poly(p-phenylene diimidazopyridinylene)
- ◆ 5.3 GPa tensile strength
- ◆ 1700 kg/m³ density
- ◆ 1440 m/s characteristic velocity @ safety factor = 3





“Hoytether” Multistrand Survivable Tether Design





Surviving the Space Environment

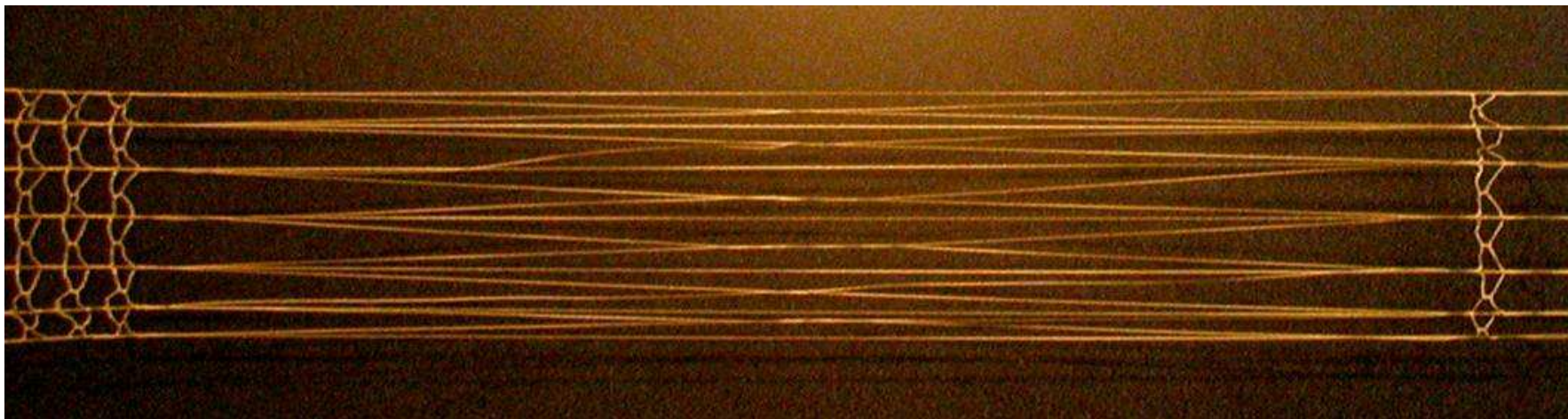
- ◆ External coating of tether materials by a lightweight oxide (silica, alumina, magnesia) should provide atomic oxygen protection to the underlying polymer.



PVD Al/ Al_2O_3 -coated PBO 6600 Braid



- ◆ Significant progress has also been made on the fabrication of multi-strand tether structures that can tolerate numerous debris impacts through redundant load-paths.





Field Emitter Array Cathode (FEAC)

◆ FEACs Have Many Advantages

- Low power, low mass, low volume
- Zero consumables
- Enables control of tether current
- Micro-tips emit electrons at low applied voltage (~75 V)

◆ Development Needs:

- Design to overcome space-charge limitations on current density
- Ruggedized to operate in LEO environment

