Alenia

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Jicable'91

SPACE TETHERS
New Cable Technology for Space Applications

Versailles 24 June 1991

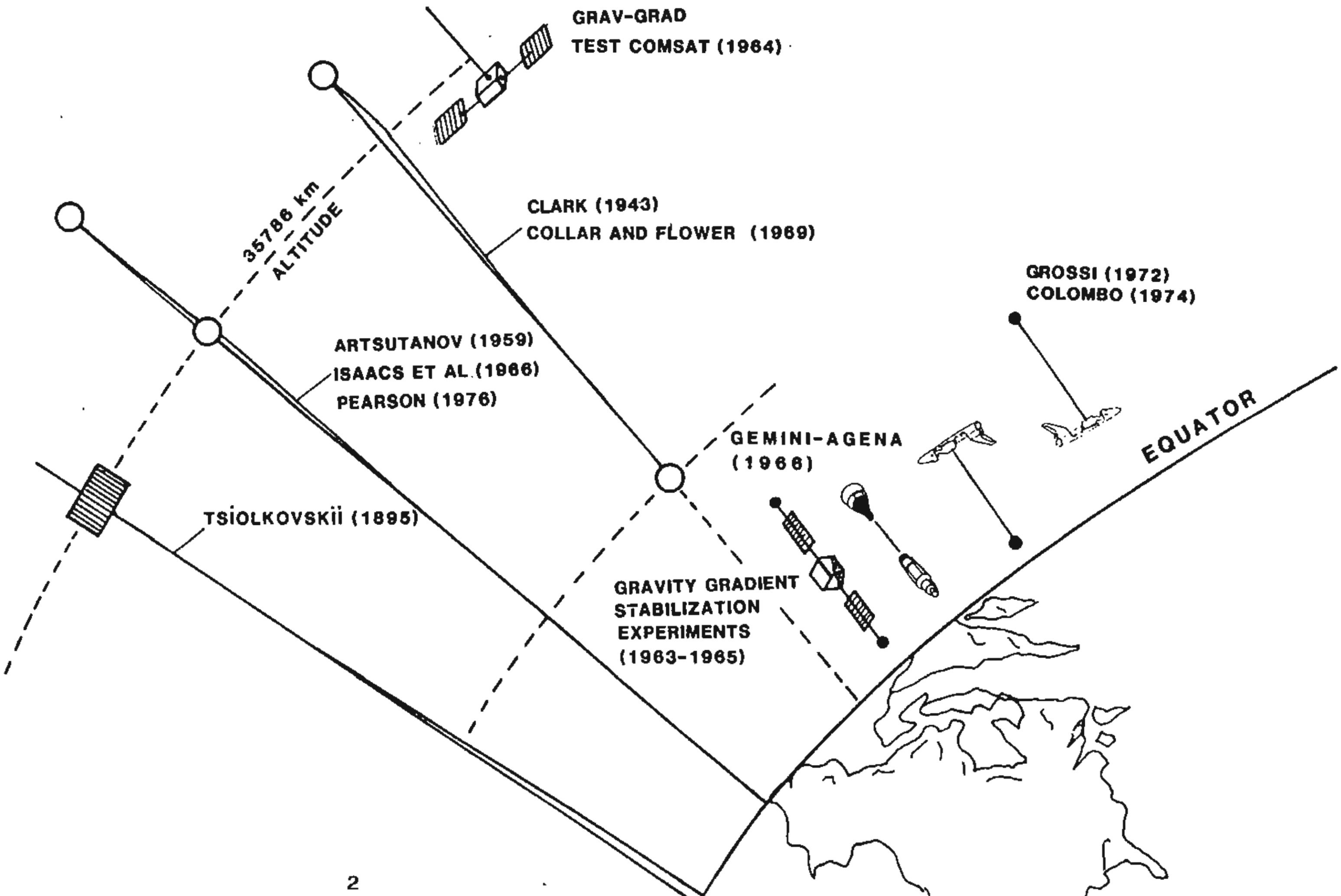
Third international conference on polymer insulated cables

Presented by:
Franco Bevilacqua

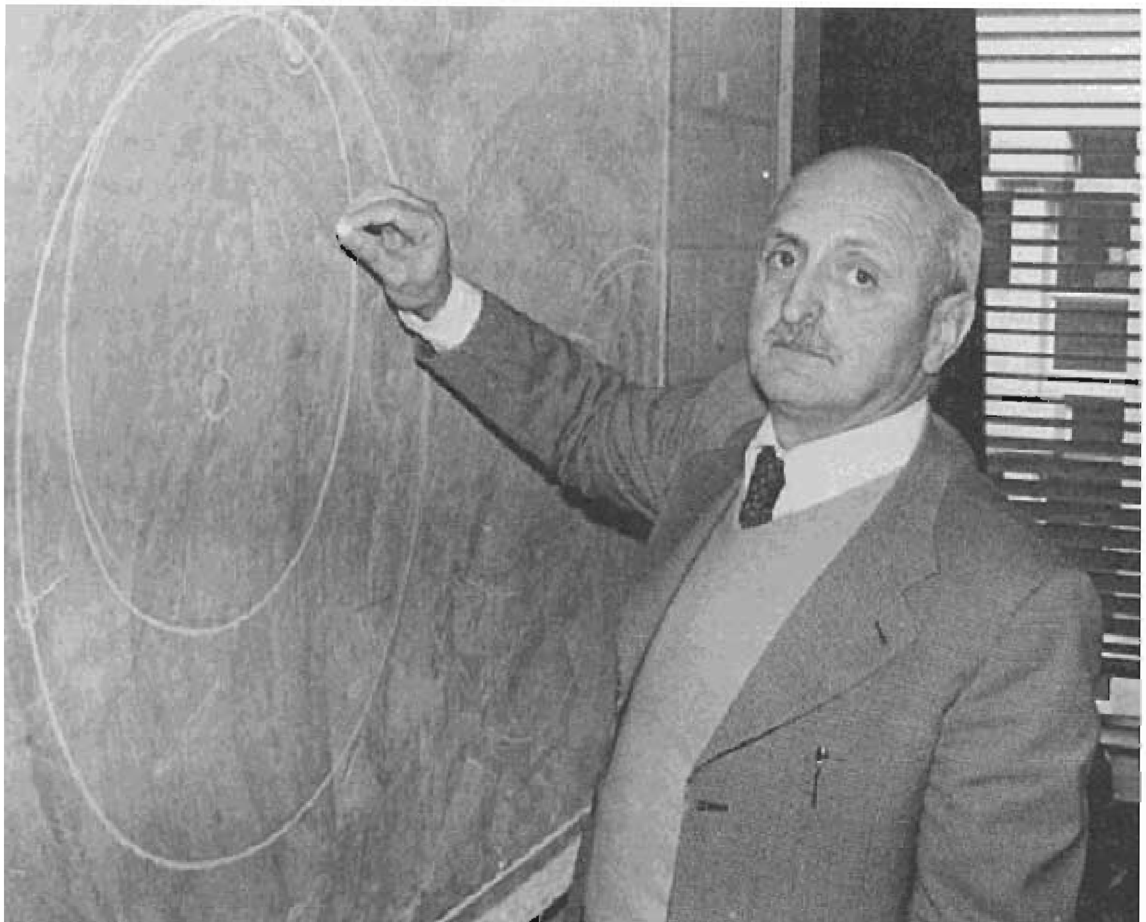
THE TETHER CONCEPT - GENESIS

IN THE BEGINNING WAS THE CENTER OF MASS
AND ALL THE EQUIPMENT WAS WITH THE CENTER OF MASS
AND WITHOUT THE CENTER OF MASS NOTHING WAS MADE
AND MAN SAID, "LET THERE BE THE TETHER"
AND THERE WAS THE TETHER
AND MAN SAW THAT THE TETHER WAS GOOD
AND MAN SEPARATED THE EQUIPMENT
FROM THE CENTER OF MASS.

DEVELOPMENT OF SPACE GRAVITY-GRADIENT CONCEPTS



THE ORIGINATOR



Giuseppe Colombo
1920-1984

Pioneer in modern problems of celestial mechanics; his understanding of the dynamics of natural and artificial bodies in space paved the way for his many contributions to space research.

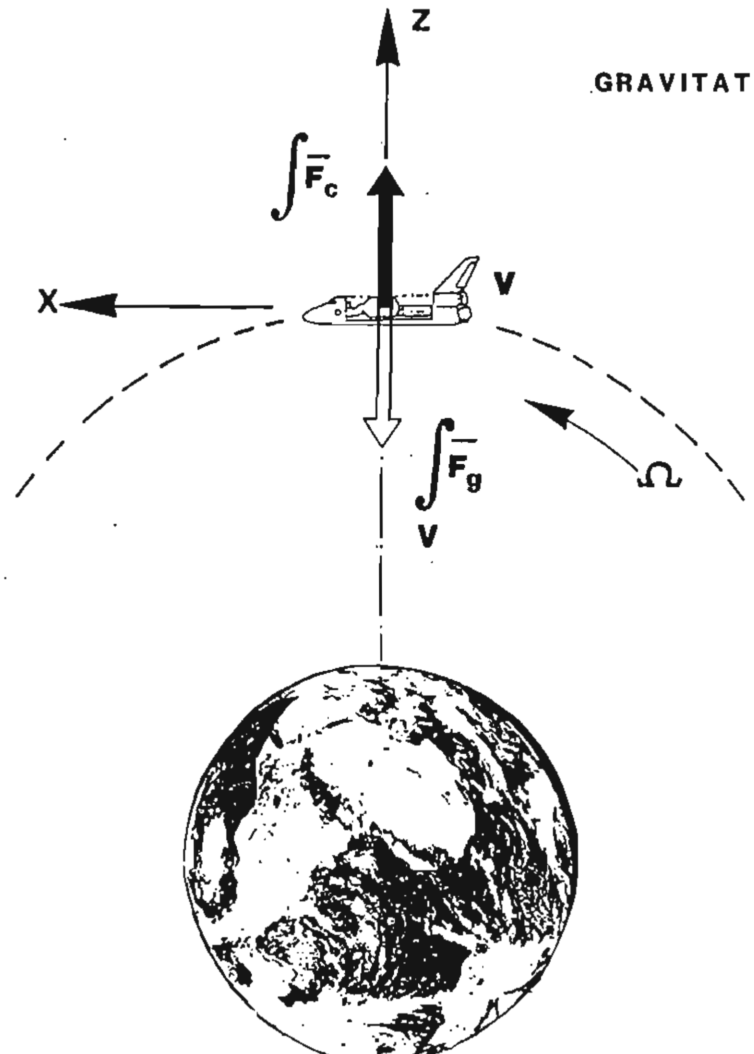
Early proponent of a permanently manned space station for scientific research; for development of new materials under microgravity conditions; to serve as base for solar system exploration missions, etc.

A prime mover for international cooperation in scientific research. Guided Italy into joint projects with the United States, and stimulated the country's industrial development in the space sector.

Influenced both the National Aeronautics and Space Administration and the European Space Agency in developing missions for exploration of the solar system.

Conceived, developed and promoted the first practical use of tethers in space, a concept on the way to becoming reality through the Tethered Satellite System, a joint effort by the United States and Italy.

ORBITING SYSTEM



GRAVITATIONAL FORCES + CENTRIFUGAL FORCES = 0

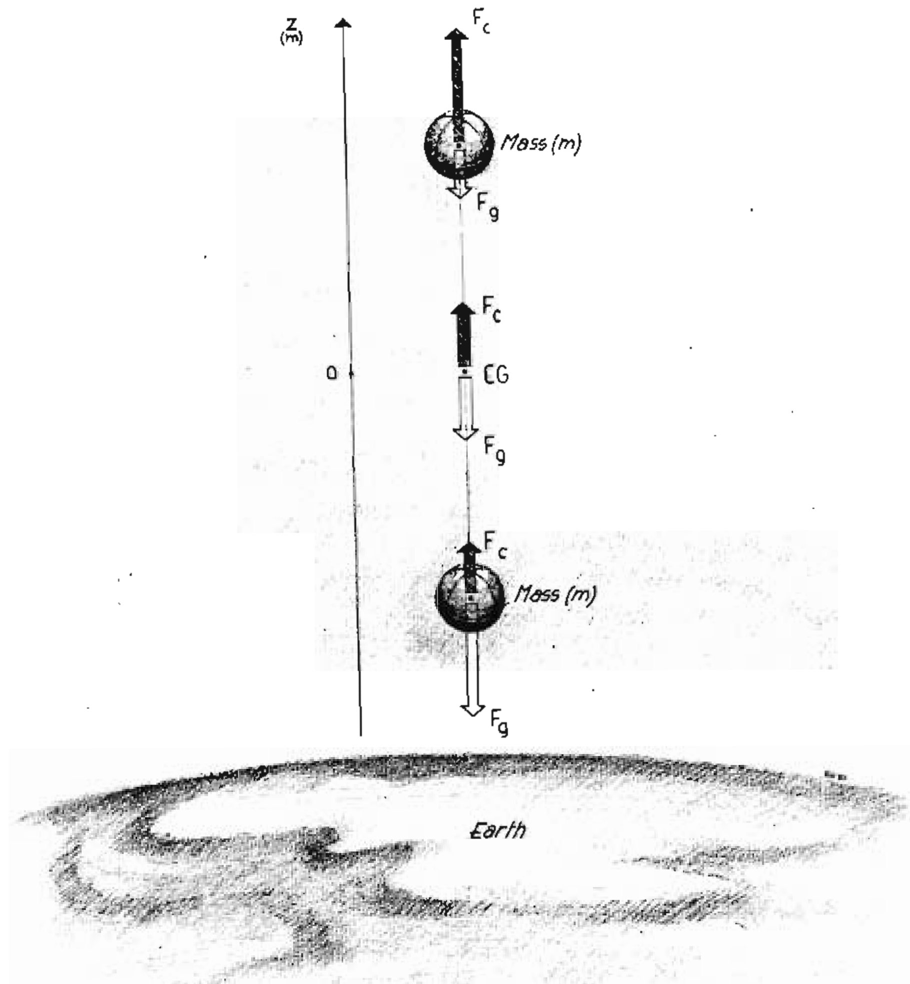
$$-\int_V \frac{GM}{r^3}\,\bar{r}\,dm + \int_V \Omega^2\,\bar{r}\,dm = 0$$

$$I_0 \subset V \mapsto \bar{F}_g = -\bar{F}_c \mapsto \frac{GM}{r_0^2} = \Omega^2\, r_0 \mapsto$$

$$r_0 = \left(\frac{GM}{\Omega^2}\right)^{1/3}$$

$$I_0 = V \cap S_{r_0} \cap \text{ORBITAL PLANE} \;(\text{DIM } I_0 = \infty^1)$$

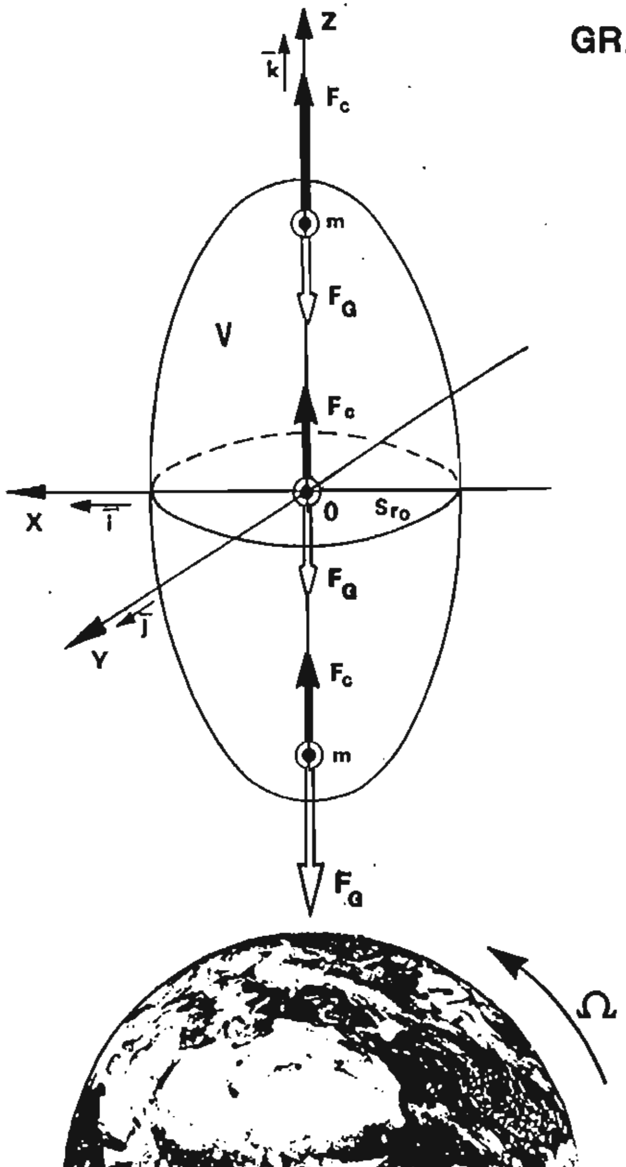
SPACE TETHER CONCEPT



$$\bar{F}_g + \bar{F}_c \simeq \frac{\partial \bar{F}_g}{\partial z} + \frac{\partial \bar{F}_c}{\partial z} \quad z = 3m\Omega^2 z$$

Gravity Gradient $= \dfrac{\partial \bar{F}_g}{\partial z} = 2m\Omega^2$

Centrifuge Gradient $= \dfrac{\partial \bar{F}_c}{\partial z} = m\Omega^2$



GRAVITY GRADIENT ALONG THE LOCAL VERTICAL

$$V_1 = V - S_{r_o} \Longmapsto |\bar{F}_g| \neq |\bar{F}_c|$$

$$\bar{F}_z = \bar{F}_g + \bar{F}_c \neq 0$$

$$\bar{F}_z \simeq \left(\frac{\partial \bar{F}g}{\partial r} + \frac{\partial \bar{F}c}{\partial}\right) z = 3\, m\, \Omega^2 z\, \bar{K}$$

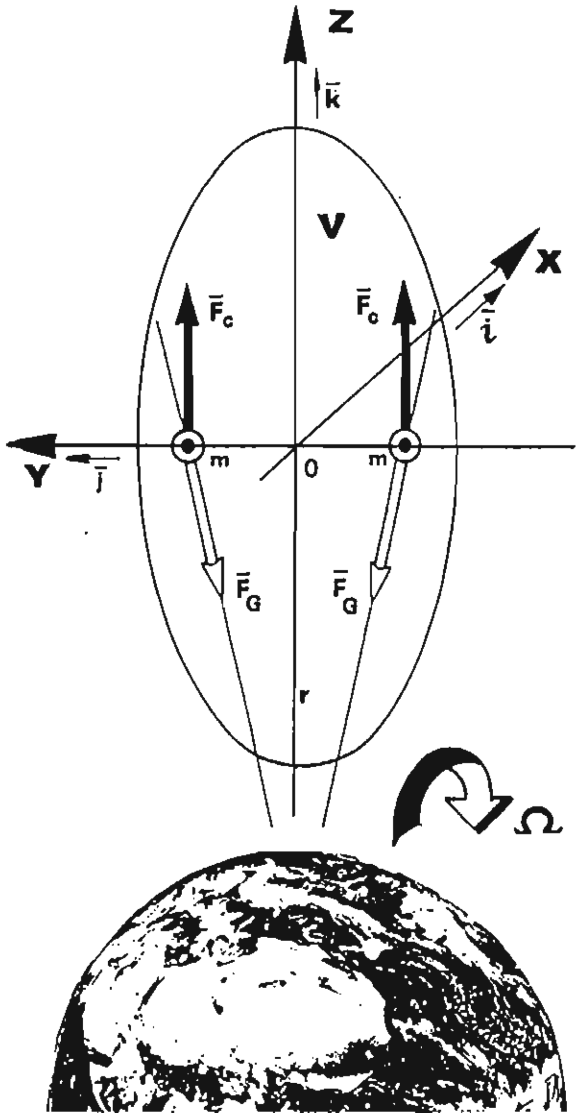
GRAVITATIONAL GRADIENT $= \dfrac{\partial \bar{F}g}{\partial r} = 2\, m\, \Omega^2\, \bar{K}$

CENTRIFUGAL GRADIENT $= \dfrac{\partial \bar{F}c}{\partial r} = m\, \Omega^2\, \bar{K}$

$$r > r_o \Longmapsto |\bar{F}_c| > |\bar{F}_g|$$

$$r < r_o \Longmapsto |\bar{F}_c| < |\bar{F}_g|$$

GRAVITY GRADIENT IN THE HORIZONTAL PLANE



IN-ORBITAL PLANE:

$$F_x = 0$$

OUT- OFF-ORBITAL PLANE :

$$V_y = V - P_{x-z} \Longrightarrow \bar{F}_g \neq -\bar{F}_c$$

$$\bar{F}_y = \bar{F}_g + \bar{F}_c = \bar{F}_g \frac{y}{r} \bar{j} = -F_c \frac{y}{r} \bar{j} = -m r \Omega^2 \frac{y}{r} \bar{j}$$

$$F_y = -m\Omega^2 y \bar{j}$$

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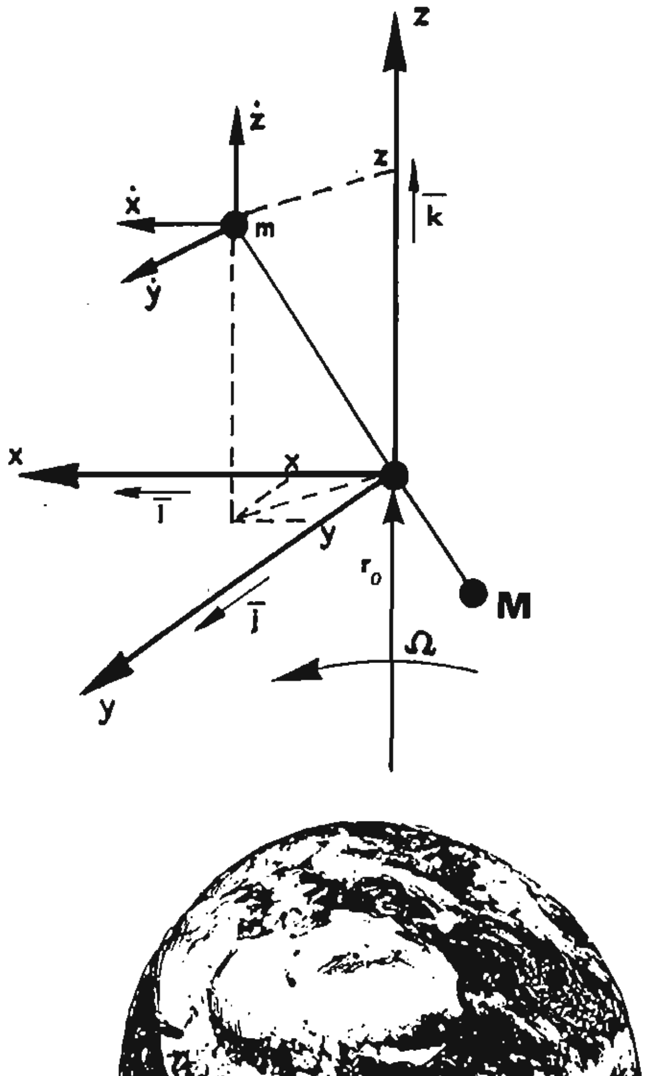
VELOCITY DEPENDANT FORCES



$$\dot{x} \Rightarrow \Delta\Omega \simeq \frac{\dot{x}}{r} \Rightarrow \Delta\bar{F}_c \simeq 2mr\,\Omega \cdot \Delta\Omega\,\bar{K}$$

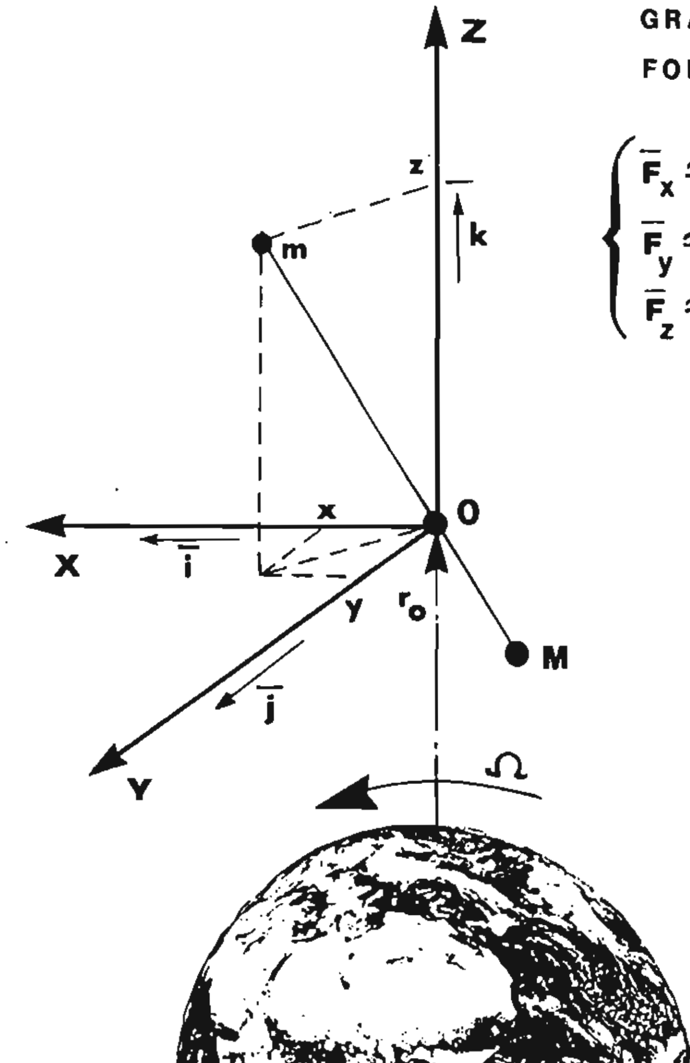
$$\bar{F}_{\dot{x}} \simeq 2m\Omega\dot{x}\,\bar{K}$$

$$\dot{y} \Rightarrow \bar{F}_{\dot{y}} \simeq 0$$

$$\dot{z} \Rightarrow \bar{F}_{COR} = -2m\Omega\dot{z}\,\bar{i} \simeq \bar{F}_{\dot{z}}$$

$$\begin{cases} \bar{F}_{\dot{x}} \simeq 2m\Omega\dot{x}\,\bar{K} \\ \bar{F}_{\dot{y}} \simeq 0 \\ \bar{F}_{\dot{z}} \simeq -2m\Omega\dot{z}\,\bar{i} \end{cases}$$

TETHERED SYSTEMS EQUATIONS OF MOTION



GRAVITY GRADIENT FORCES

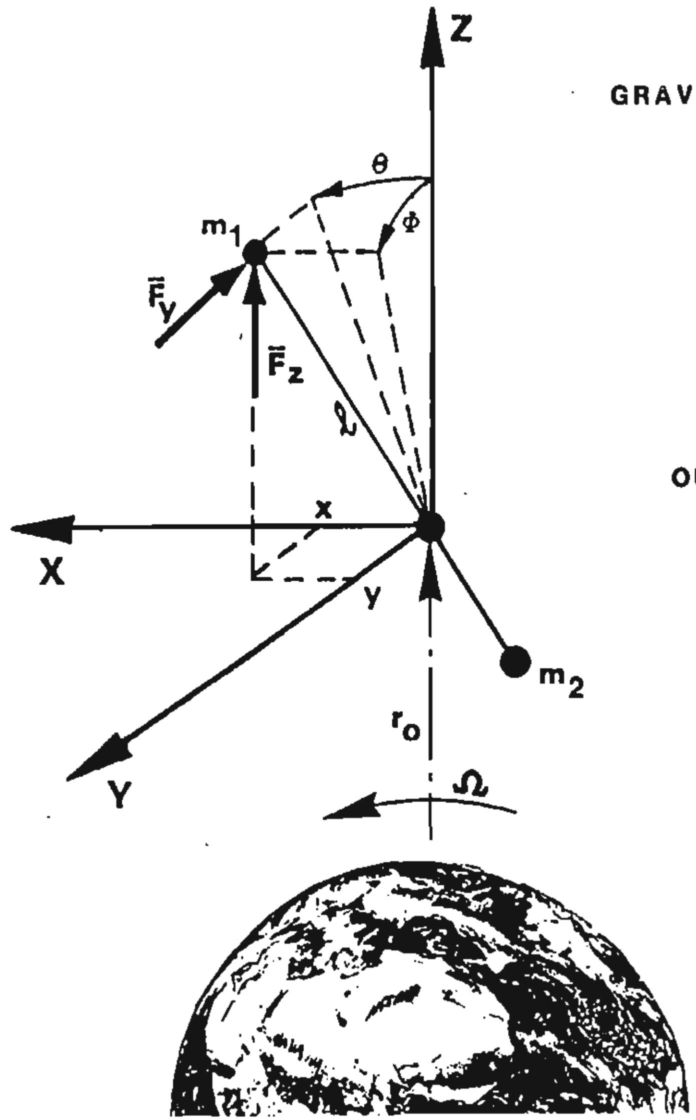
$$\begin{cases} \bar{F}_x \simeq 0 \\ \bar{F}_y \simeq -m\Omega^2 y\,\bar{j} \\ \bar{F}_z \simeq 3m\Omega^2 z\,\bar{k} \end{cases}$$

VELOCITY DEPENDANT FORCES

$$\begin{cases} \bar{F}_{\dot{x}} \simeq 2m\Omega\dot{x}\bar{K} \\ \bar{F}_{\dot{y}} \simeq 0 \\ \bar{F}_{\dot{z}} \simeq -2m\Omega\dot{z}\,\bar{i} \end{cases}$$

$$\bar{F}_e = m\Big[(\ddot{x} + 2\Omega\dot{z})\,\bar{i} + (\ddot{y} + \Omega^2 y)\,\bar{j} + (\ddot{z} - 2\Omega\dot{x} - 3\Omega^2 z)\,\bar{K}\Big]$$

$\bar{F}_e$: EXTERNAL FORCES



TETHERED SYSTEMS BASIC DYNAMICS
LIBRATIONS

GRAVITY GRADIENT COMPONENTS ACTING ON m_1:

$$\begin{cases} F_x = 0 \\ F_y = - m_1 \Omega^2 y \\ F_z = 3 m_1 \Omega^2 z \approx 3 m_1 \Omega^2 \ell \end{cases}$$

IN PLANE ANGLE : $x - z : \theta = \dfrac{x}{\ell}$

OUT-OF-PLANE ANGLE : $y - z : \Phi = \dfrac{y}{\ell}$

BASIC EQUATIONS:

$$m_1 \ell^2 \ddot{\theta} = - F_z \ell \theta = - 3 m_1 \Omega^2 \ell^2 \theta$$

$$m_1 \ell^2 \ddot{\Phi} = - F_z \ell \Phi - F_y \ell = - 4 m_1 \Omega^2 \ell^2 \Phi$$

$$\ddot{\theta} = - 3 \Omega^2 \theta$$
$$\ddot{\Phi} = - 4 \Omega^2 \Phi$$

Comparison between :

(A) : TERRESTRIAL PENDULUM and **(B)** : ORBITING PENDULUM

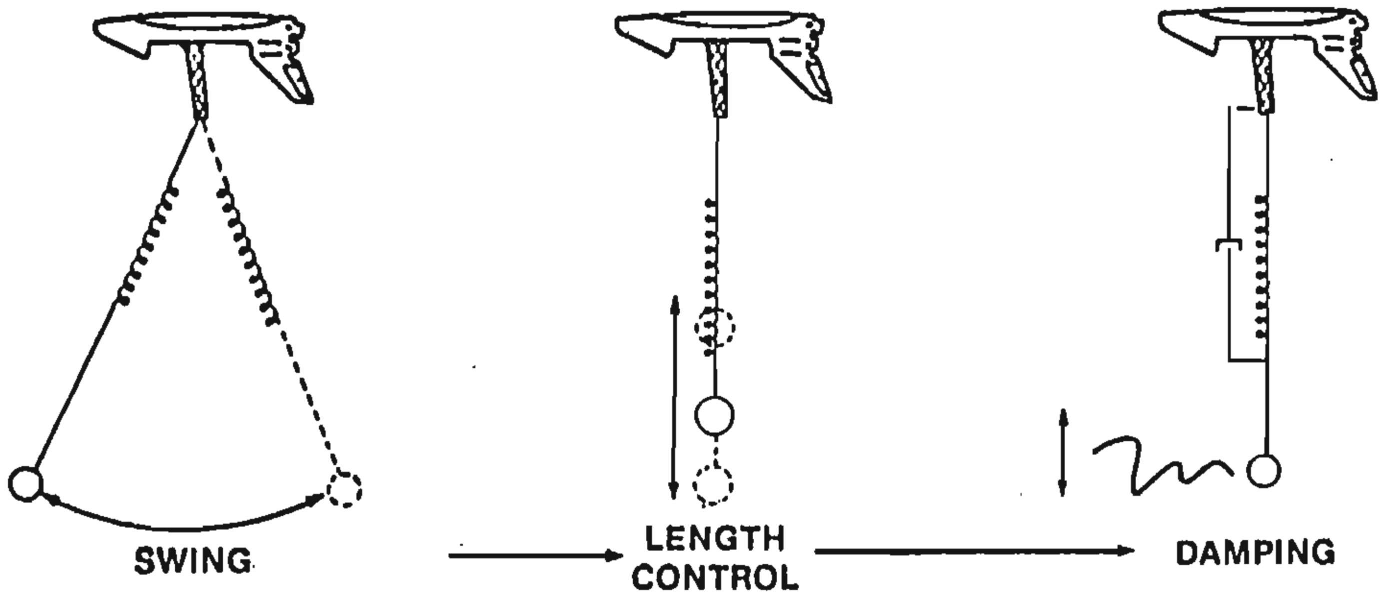
(A)

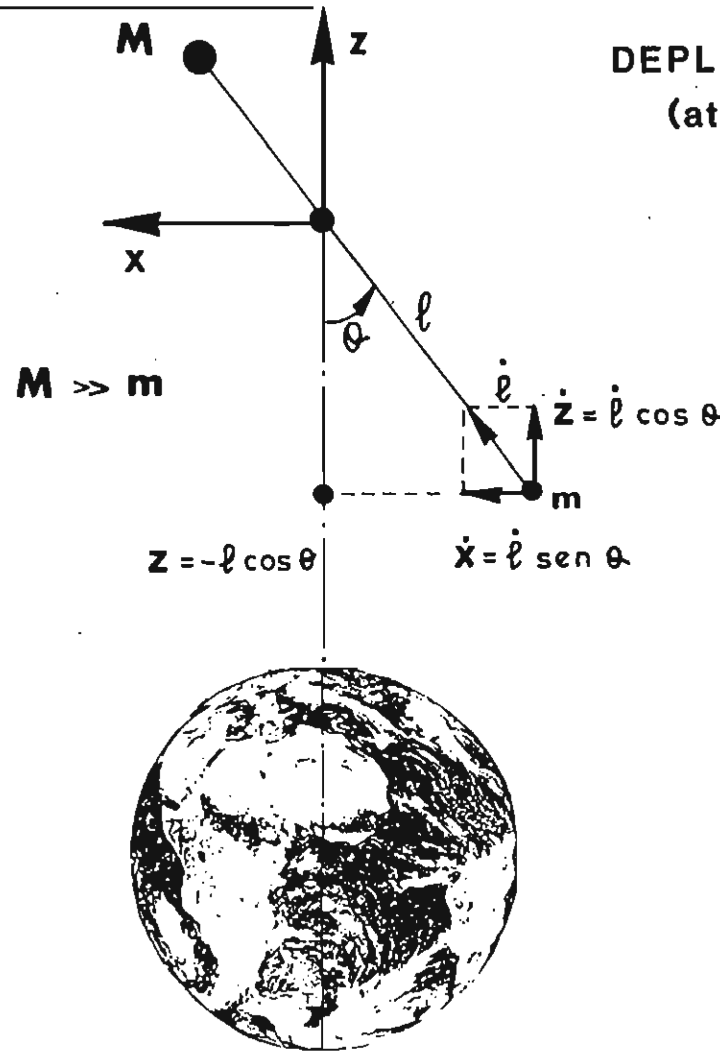
PULSATION : $\sqrt{\frac{g}{\ell}} = \sqrt{\frac{G \cdot M}{r_E^2 \cdot \ell}}$

(B)

$\sqrt{3}\,\Omega = \sqrt{3} \cdot \sqrt{\frac{G\,M}{r_o^3}}$ in-plane

$2\,\Omega = 2 \cdot \sqrt{\frac{G\,M}{r_0^{\,3}}}$ out-of-plane


SWING
LENGTH CONTROL
DAMPING



DEPLOYMENT AND RETRIEVAL
(at a constant angle : θ)

$$\begin{cases} \bar{F}_x = 0 \\ \bar{F}_y = -m\,\Omega^2 y\,\bar{j} \\ \bar{F}_z = 3m\,\Omega^2 z\,\bar{K} \end{cases} \qquad \begin{cases} \bar{F}_{\dot{x}} \simeq 2m\,\Omega\,\dot{x}\,\bar{K} \\ \bar{F}_{\dot{y}} \simeq 0 \\ \bar{F}_{\dot{z}} \simeq -2m\,\Omega\,\dot{z}\,\bar{i} \end{cases}$$

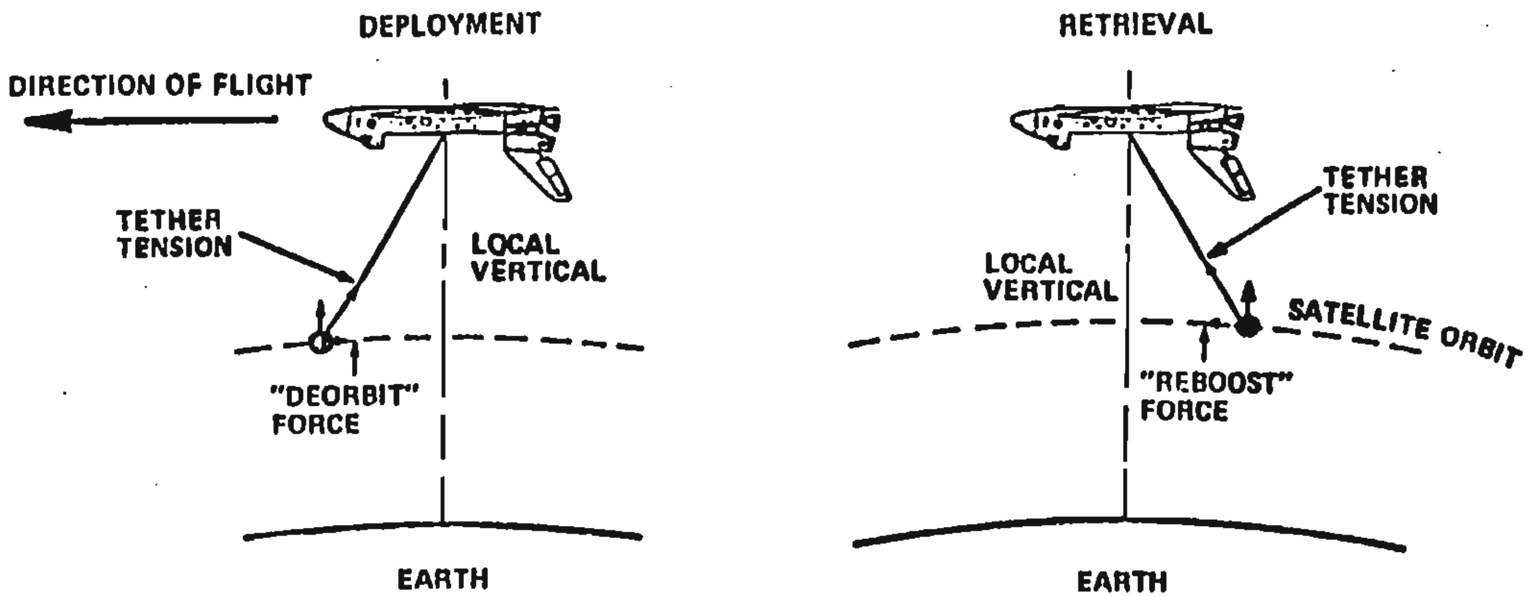
$$\bar{F}_z = -3m\,\Omega^2\,\ell\,\cos\theta\,\bar{K}$$
$$\bar{F}_{\dot{x}} = -2m\,\Omega\,\dot{\ell}\,\text{sen}\,\theta\,\bar{K}$$
$$\bar{F}_{\dot{z}} = -2m\,\Omega\,\dot{\ell}\,\cos\theta\,\bar{i}$$

$$\left(\bar{F}_z + \bar{F}_{\dot{x}}\right)\cdot \text{sen}\,\theta + \bar{F}_{\dot{z}}\cdot\cos\theta = 0$$

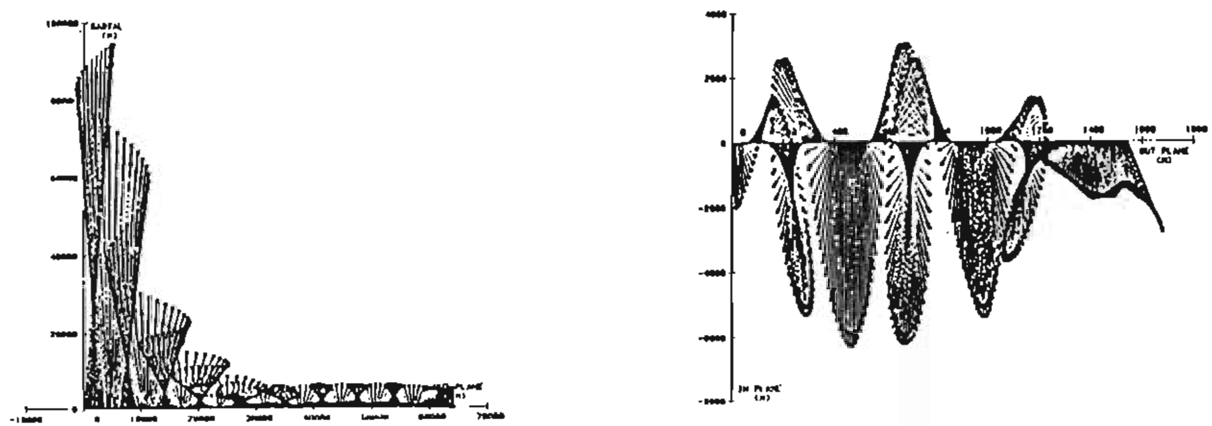
$$2m\,\Omega\,\dot{\ell} + 3m\,\Omega^2\,\ell\,\text{sen}\,\theta\,\cos\theta = 0$$

$$\frac{\dot{\ell}}{\ell} = -\alpha = -\frac{3}{2}\,\Omega\,\cos\theta\,\text{sen}\,\theta$$

$$\boxed{\ell = \ell_0\, e^{-\alpha t}}$$

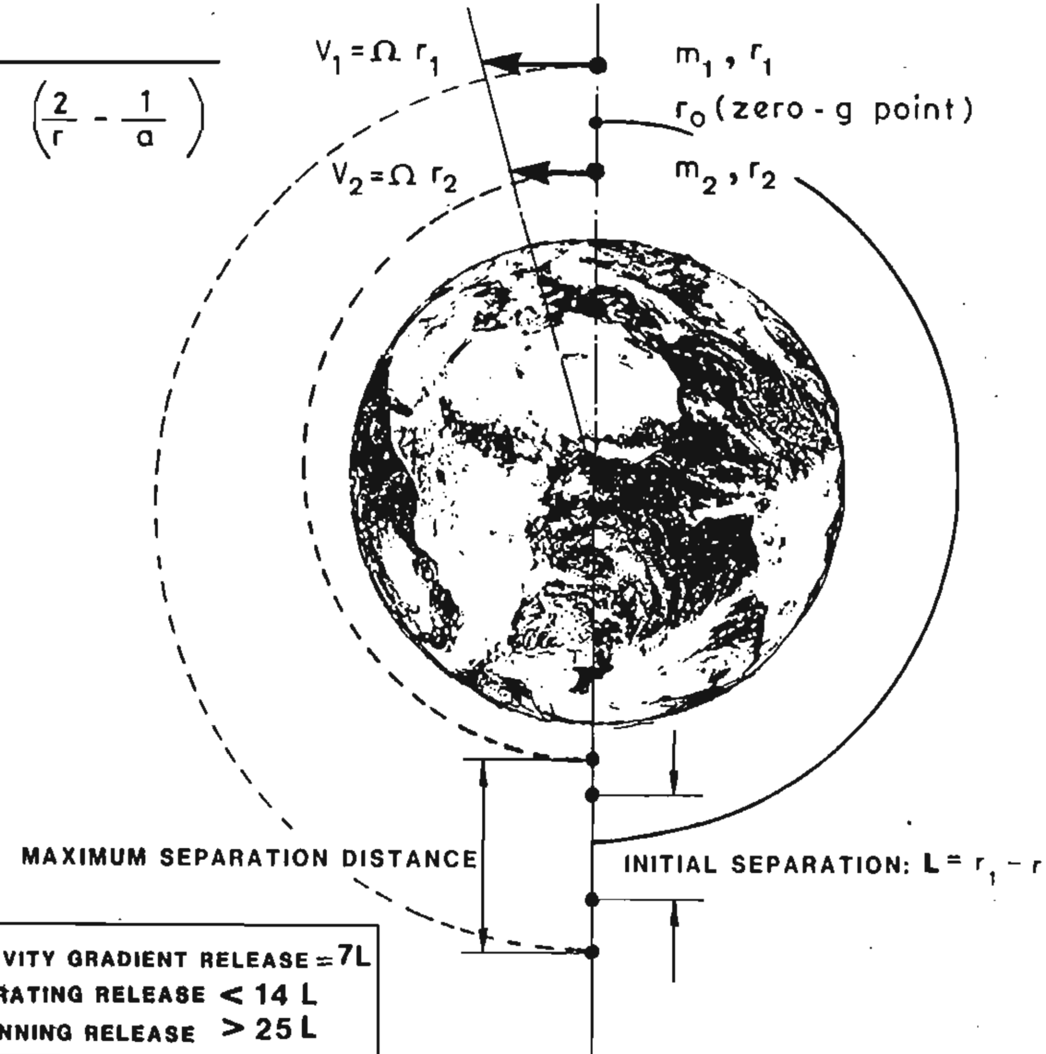

DEPLOYMENT
DIRECTION OF FLIGHT
TETHER TENSION
LOCAL VERTICAL
"DEORBIT" FORCE
EARTH
RETRIEVAL
TETHER TENSION
LOCAL VERTICAL
SATELLITE ORBIT
"REBOOST" FORCE
EARTH

RETRIEVAL MANEUVER DYNAMICS SIMULATION

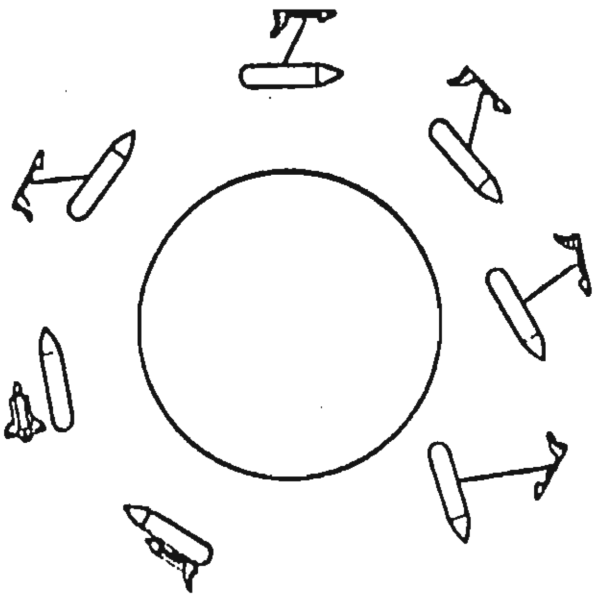


MOMENTUM EXCHANGE USING TETHERS

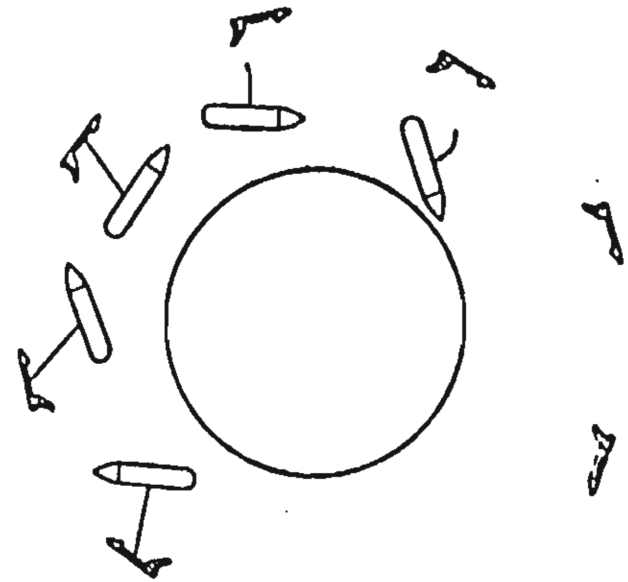
$$V = \sqrt{GM\left(\frac{2}{r} - \frac{1}{a}\right)}$$



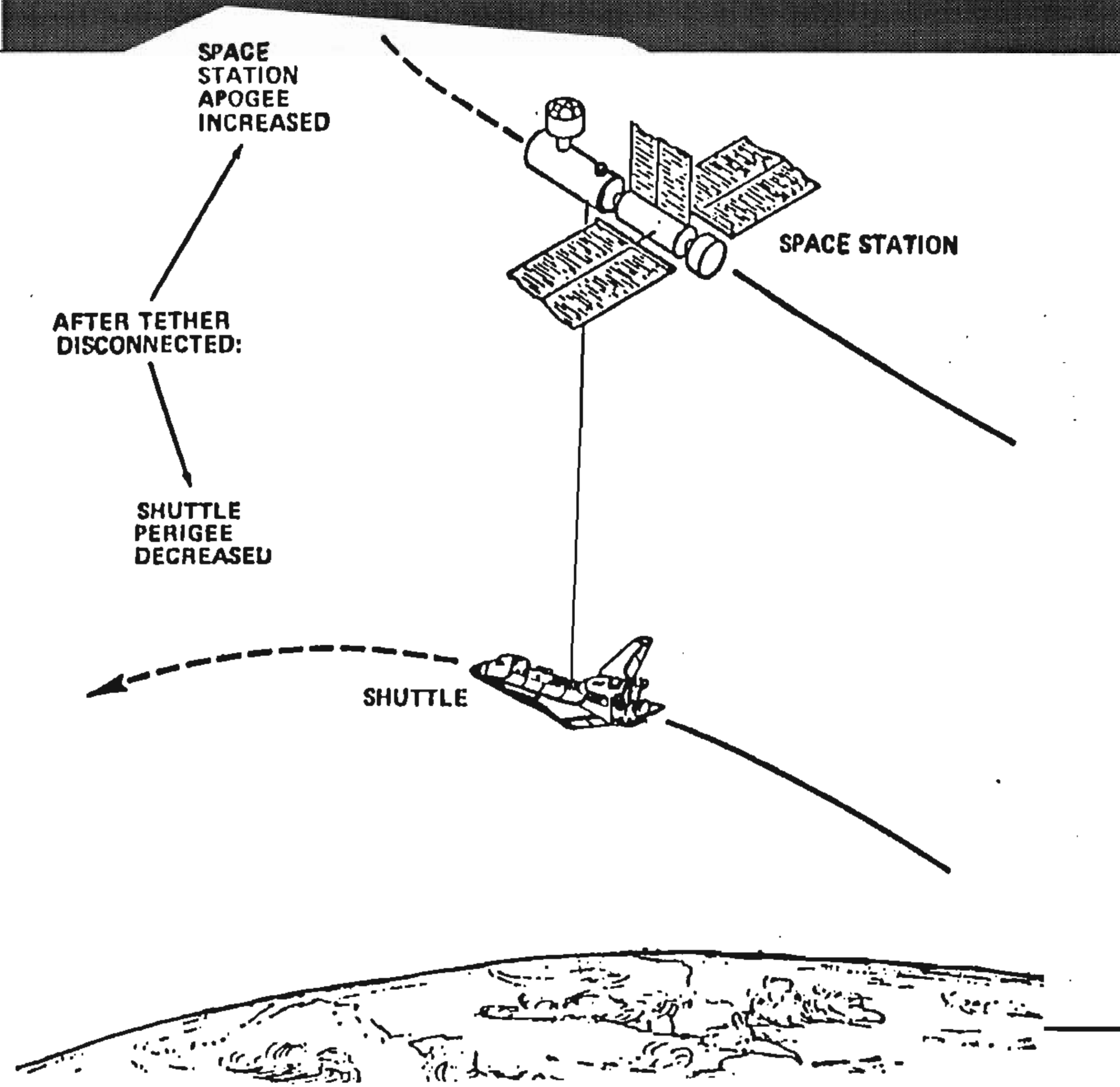
GRAVITY GRADIENT RELEASE $\simeq$ 7L
LIBRATING RELEASE < 14 L
SPINNING RELEASE > 25 L

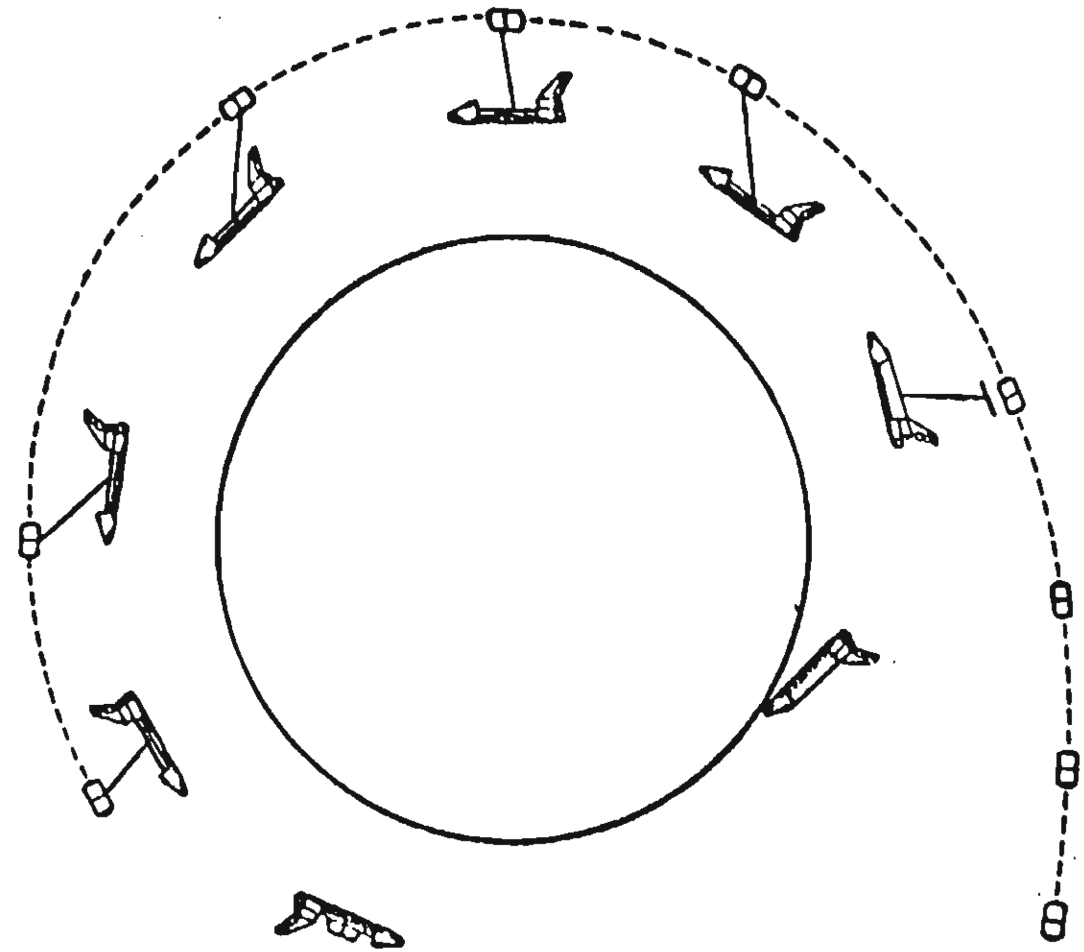


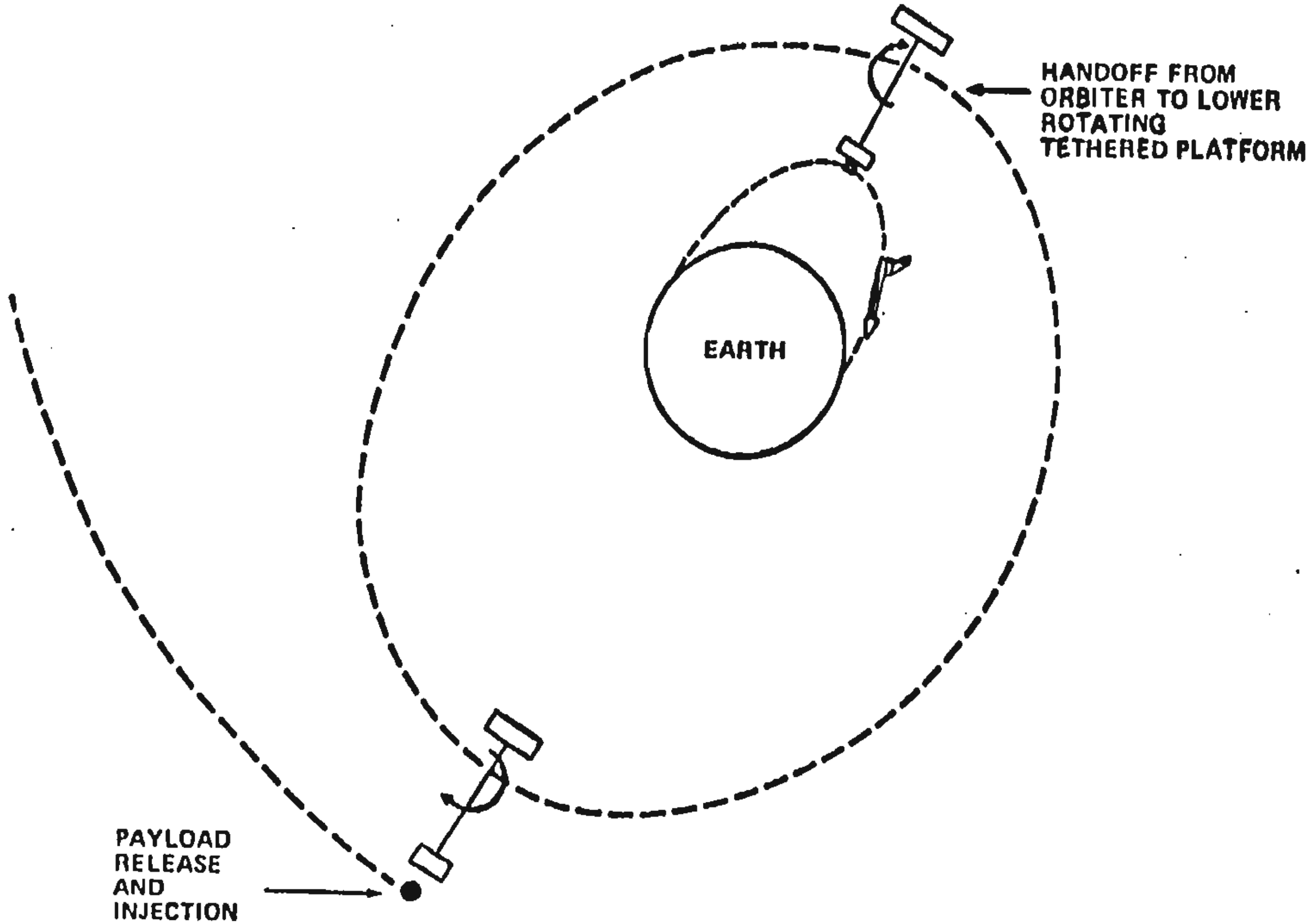
PENDULUM SETUP

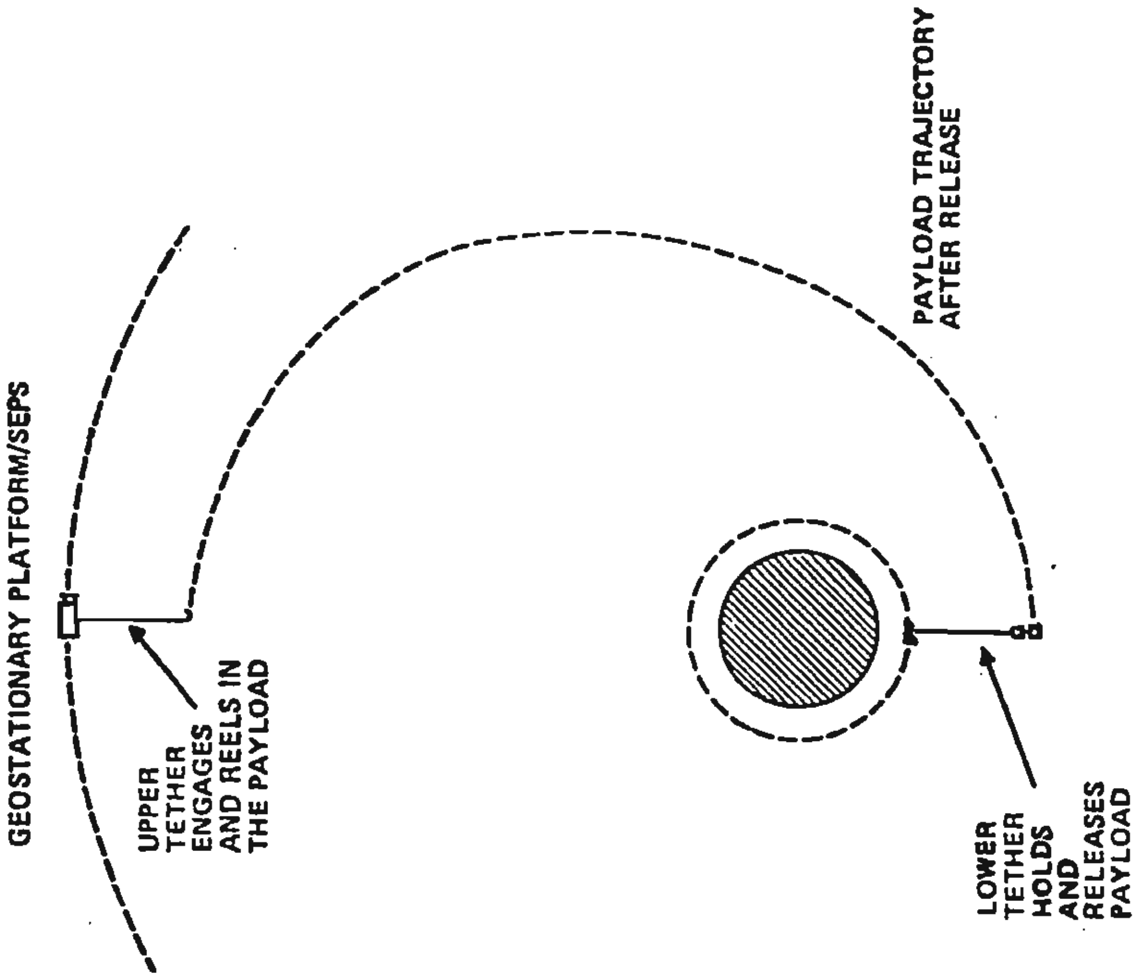


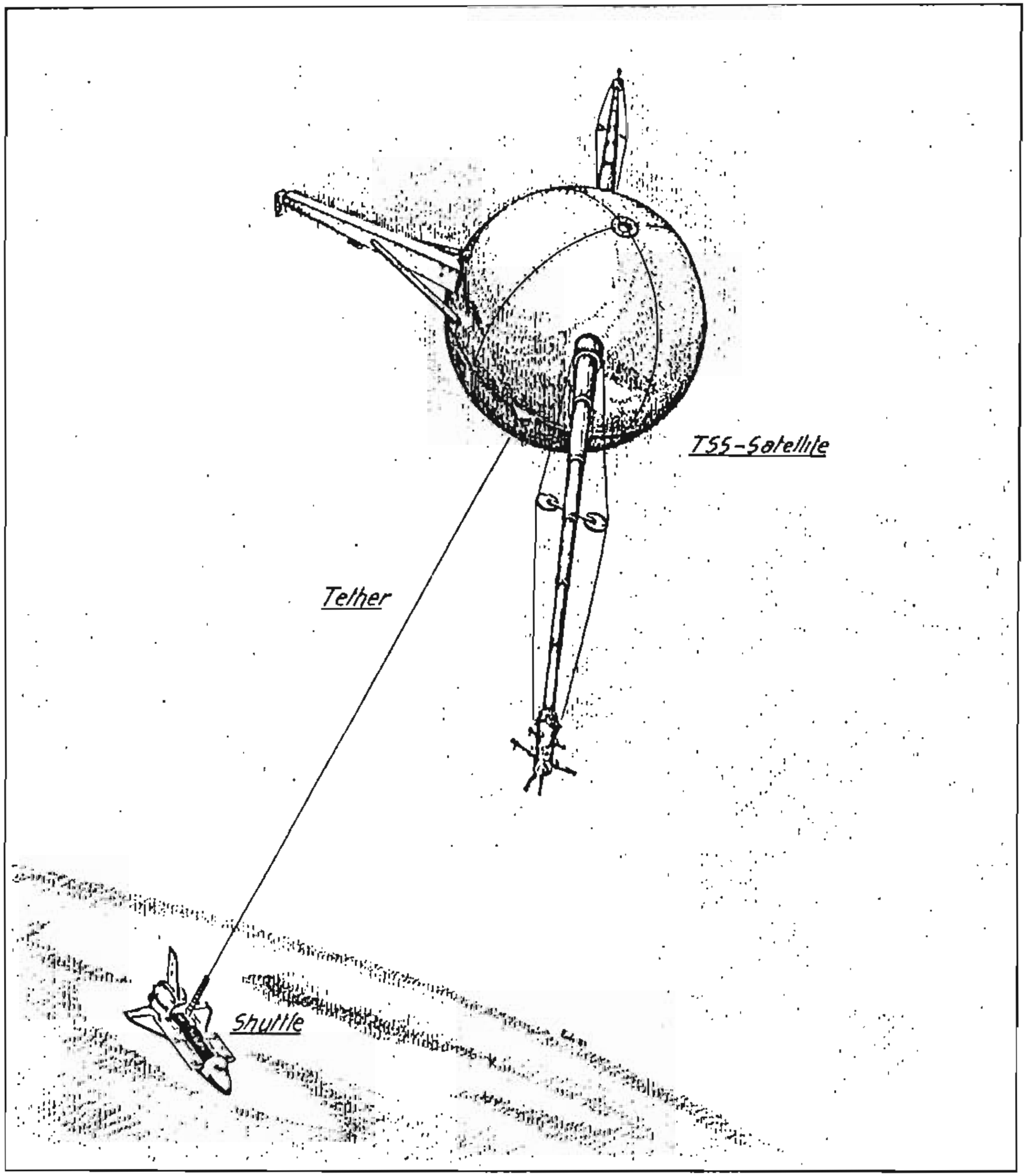
PENDULUM SWING & RELEASE


SPACE
STATION
APOGEE
INCREASED
SPACE STATION
AFTER TETHER
DISCONNECTED:
SHUTTLE
PERIGEE
DECREASED
SHUTTLE




HANDOFF FROM ORBITER TO LOWER ROTATING TETHERED PLATFORM
EARTH
PAYLOAD RELEASE AND INJECTION


PAYLOAD TRAJECTORY AFTER RELEASE
GEOSTATIONARY PLATFORM/SEPS
UPPER TETHER ENGAGES AND REELS IN THE PAYLOAD
LOWER TETHER HOLDS AND RELEASES PAYLOAD



TSS ELECTRODYNAMIC MISSION

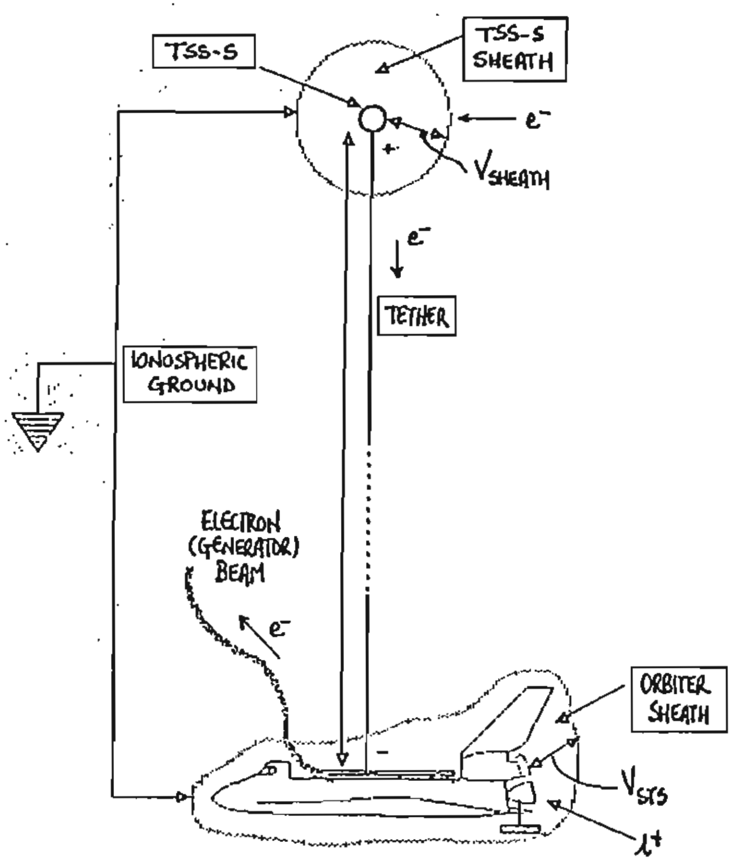
First TSS mission in late 1990 for electrodynamic studies of earth's ionosphere and magnetic field. In particular, feasibility test of power generation by tether interaction with magnetic field.

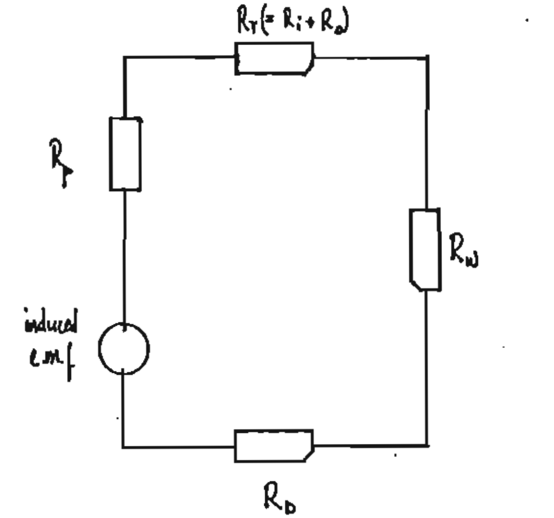
- *Spaceward satellite deployment*
- *20 Km long, electrically conductive tether*
- *36 hour mission duration*
- *Demonstrate closed-loop control of tethered satellite*
- *Demonstrate operation of satellite and orbiter-mounted electrodynamic instruments with conductive tether.*

THE TETHER CONCEPT - ELECTRODYNAMIC APPLICATIONS

- MOTION INDUCED E.M.V.: $\Phi = (\vec{v} \wedge \vec{B}) \cdot \vec{l}$ (CAN BE KV).
- CURRENT FLOWING THROUGH TETHER: $I_{MAX} = \Phi / R_{TETHER}$ (CAN BE AMPS).
- PLANETARY SCALE PERTURBATIONS CAN BE GENERATED.
- END POINT IMPEDANCE TO BE ADJUSTED DEPENDING ON APPLICATION
  - VERY LOW FOR POWER/THRUST GENERATION (HOLLOW CATHODES)
  - FUNCTION OF PERVEANCE FOR ELECTRO/ION BEAM GENERATORS
- HIGH VOLTAGE/LARGE CURRENT HANDLING TECHNOLOGY FOR SPACE USE IN EARLY DEVELOPMENT STAGE.
- MAJOR SHEATH MODELING EFFORT BEING STARTED/UNDER WAY IN PREPARATION TO TSS-1 MISSION.
- LOSSES IN THE IONOSPHERIC MEDIUM ARE BEING STUDIED.

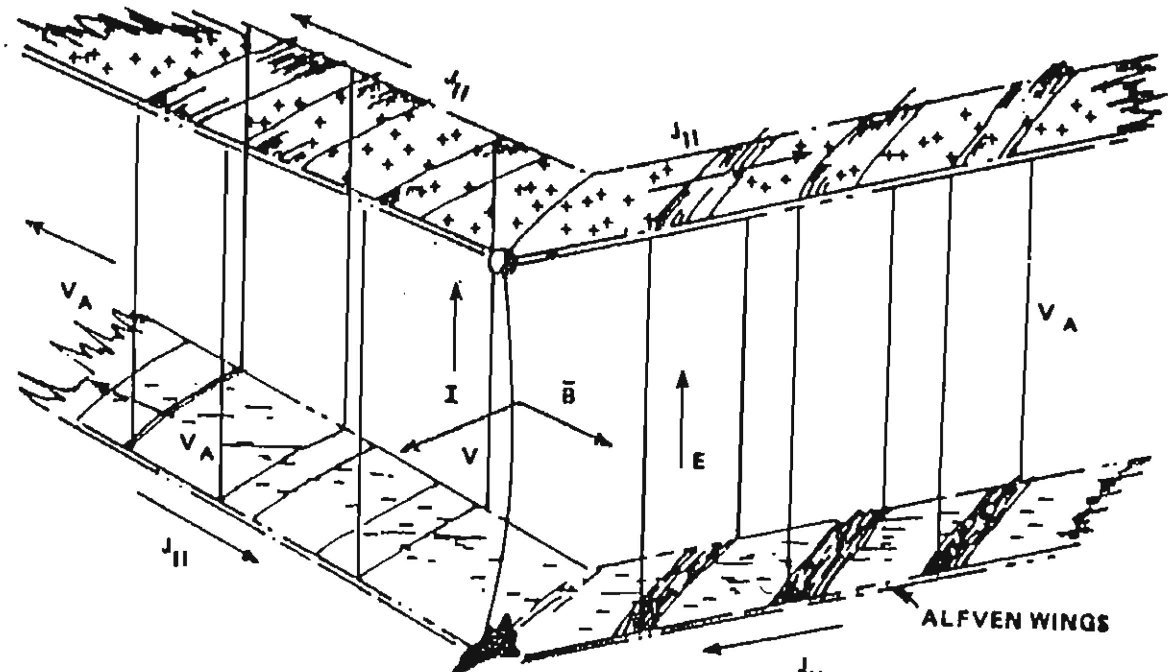
THE TETHER CONCEPT - ELECTRODYNAMIC APPLICATIONS





TSS schematics and electrical model (DC only)

Perturbation Induced By TSS In The Ionosphere



$$T \sim \frac{D}{V}$$

$$f \lesssim f^{*} \sim \frac{1}{T}$$

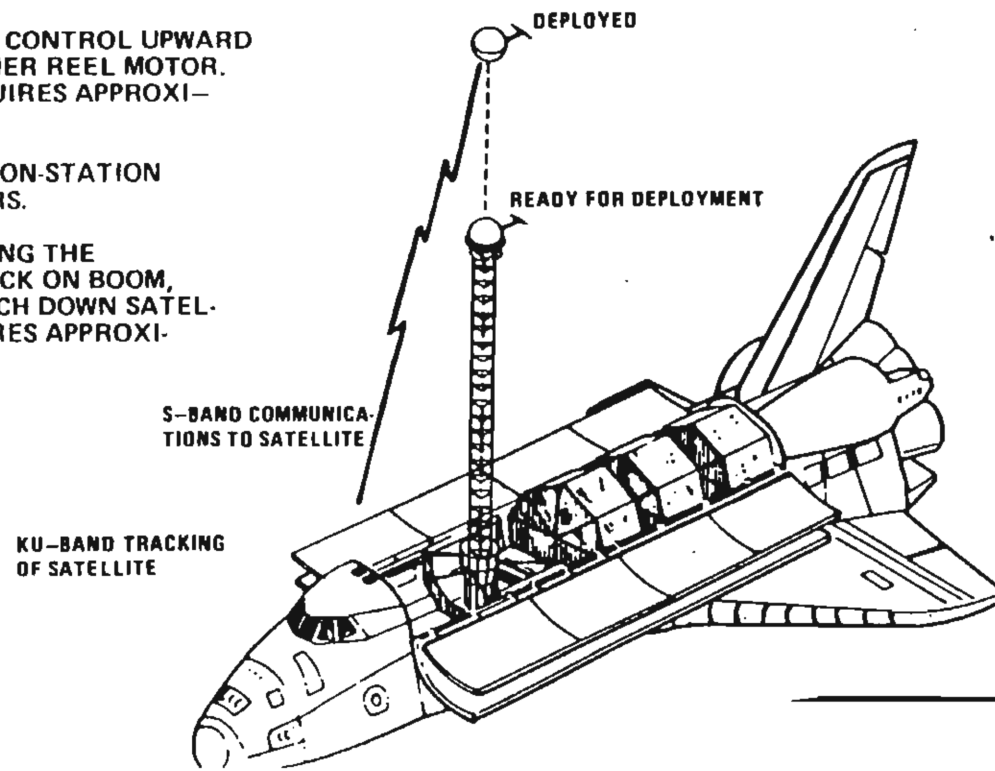
To have only AW radiated:

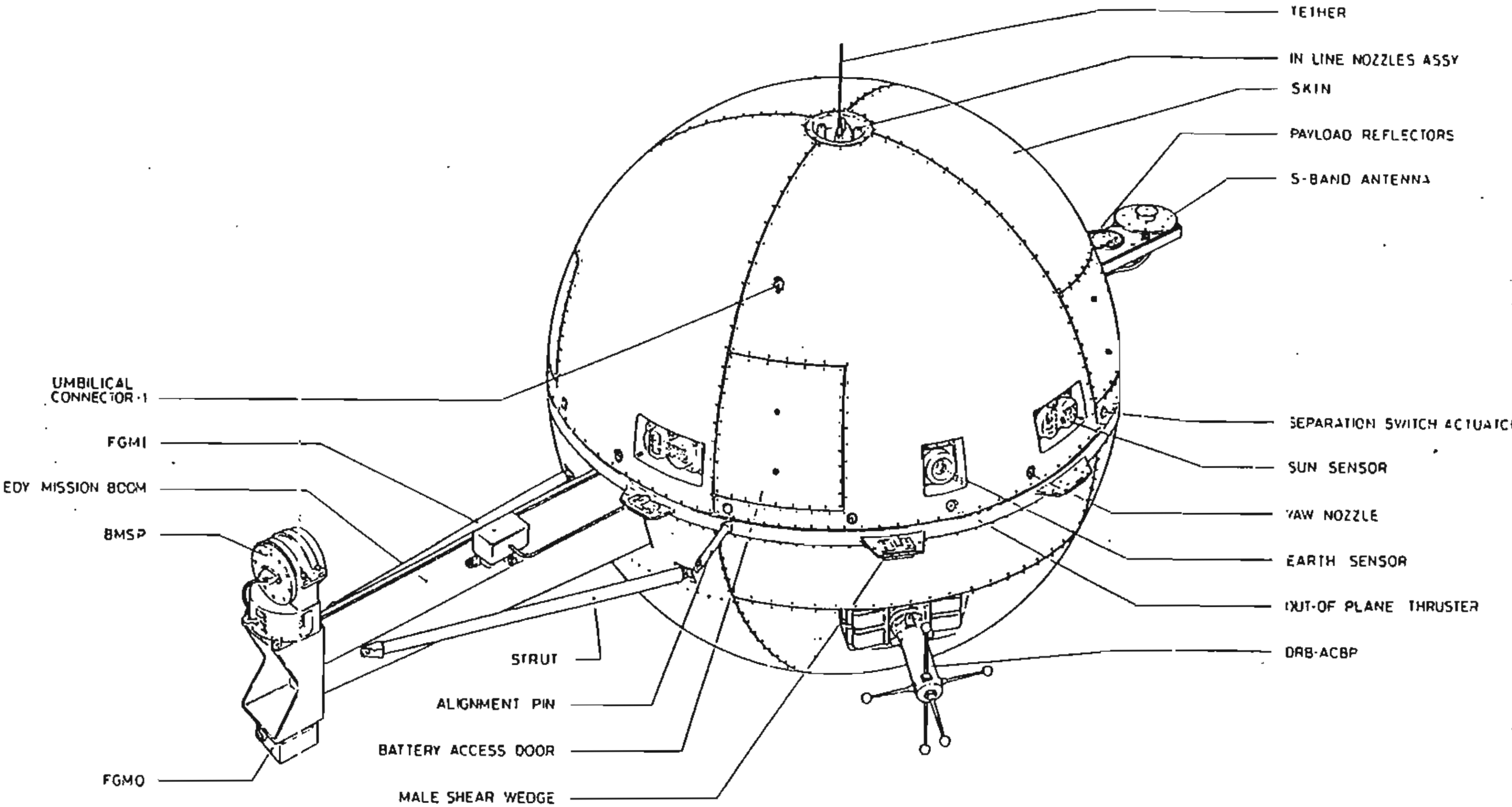
$f^{*} < f_{ci}$ ⟶ $D \gtrsim 40m$

TSS DESIGN OVERVIEW
DEPLOYMENT CONCEPT

TYPICAL ELECTRODYNAMICS MISSION SCENARIO

1. ORBITER ATTAINS 160 nmi (296 Km) ALTITUDE.
2. UNLATCH SATELLITE AND DEPLOY OUTWARD USING THE DEPLOYMENT BOOM (12 METERS).
3. RELEASE SATELLITE AND CONTROL UPWARD TRAJECTORY USING TETHER REEL MOTOR. 20 KM DEPLOYMENT REQUIRES APPROXI– MATELY 10 HOURS.
4. SATELLITE CONTROLLED ON-STATION APPROXIMATELY 20 HOURS.
5. RETRIEVE SATELLITE USING THE TETHER REEL MOTOR, DOCK ON BOOM, RETRACT BOOM AND LATCH DOWN SATEL- LITE. RETRIEVAL REQUIRES APPROXI- MATELY 4-6 HOURS.

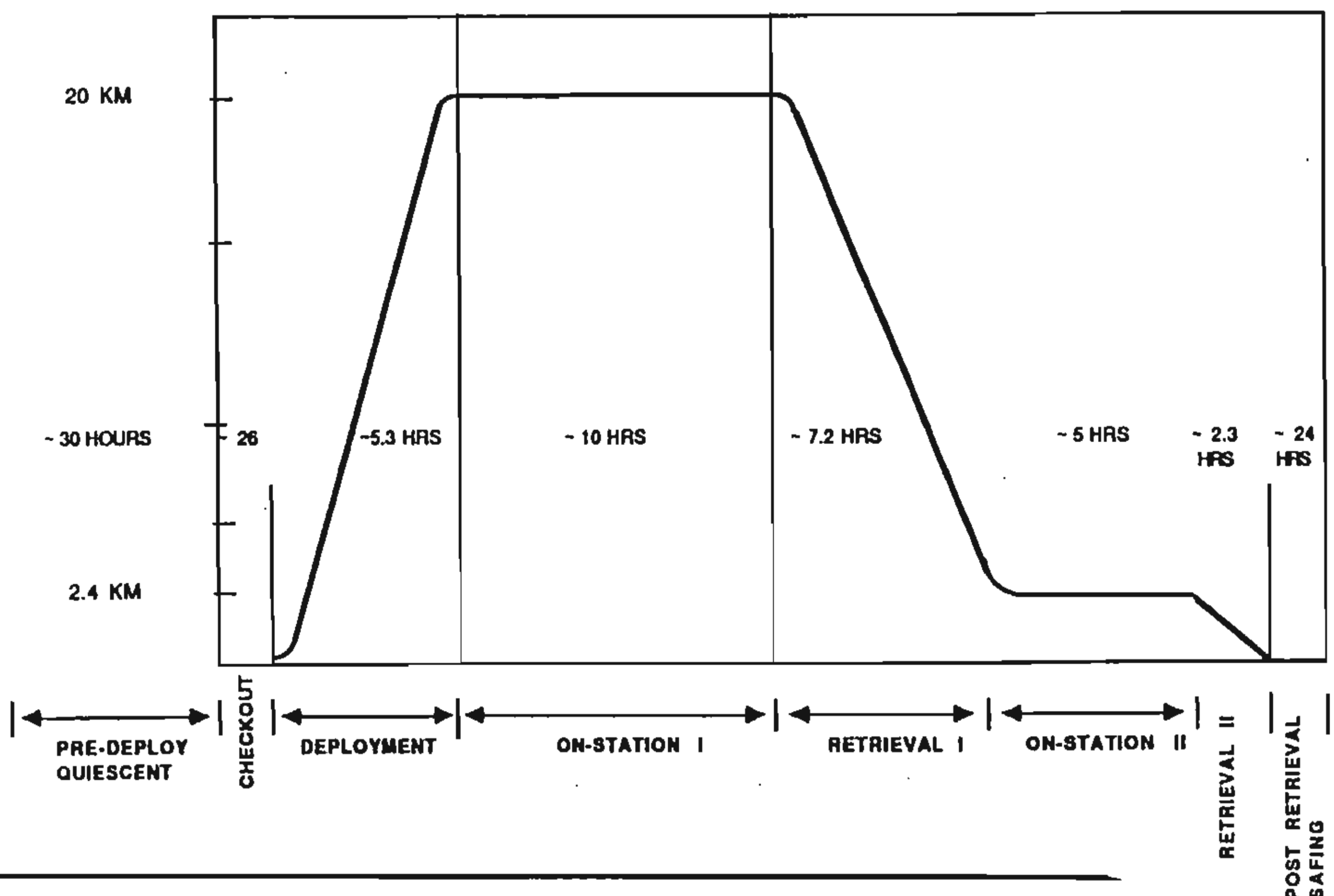



TETHER
IN LINE NOZZLES ASSY
SKIN
PAYLOAD REFLECTORS
S-BAND ANTENNA
UMBILICAL CONNECTOR-1
FGMI
EDY MISSION BOOM
BMSP
SEPARATION SWITCH ACTUATOR
SUN SENSOR
YAW NOZZLE
EARTH SENSOR
OUT-OF PLANE THRUSTER
DRB-ACBP
STRUT
ALIGNMENT PIN
BATTERY ACCESS DOOR
MALE SHEAR WEDGE
FGMO

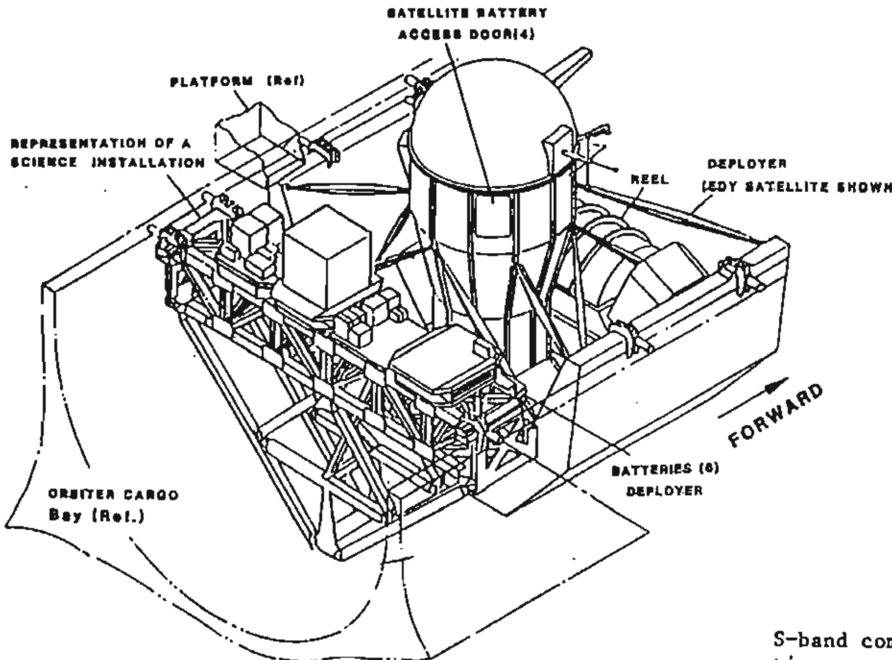
TSS DEMONSTRATION FLIGHT(S) CAPABILITIES

Parameter	Satellite	Deployer
Maximum Total Mass (kg)	500	2100
Scientific Payload Mass (kg)	60-80	500
Payload Volume	Negotiable (1.5m Diam)	Negotiable (Spacelab MDM Pallet)
Temperature (°C)	-10 to +50	Negotiable
Thermal Control (Watts)	50 (Passive)	2 Coldplates @ 1500 Each
Power @ 28 ± 4 VDC		
Average (Watts)	50	500-1000
Peak (Watts)	100	1500
Energy (Watt-Hrs)	900-2000	36,000
Data		
Telemetry (KBPS)	6-12	300-400
Commands (KBPS)	2	Flexible
Operational Altitudes (Km)	130 and Above	Up to 100 km Tether
Orbital Inclination	Any	Any
Mission Duration (Hrs)	36	36
Position Determ.(Rel.to Orbiter)		
Range	±1%	-
Angular	±2°	-
Attitude Control		
Pitch, Roll	±2°	-
Yaw	±3°	-
Attitude Measurement	±0.1 to ±0.3°	-

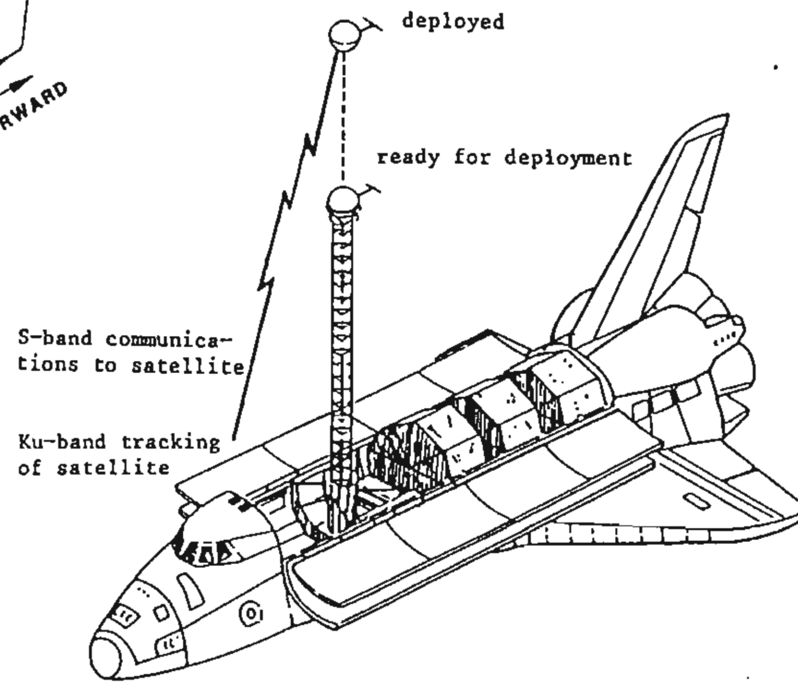
TSS Mission Profile



TSS CONFIGURATION



STOWED

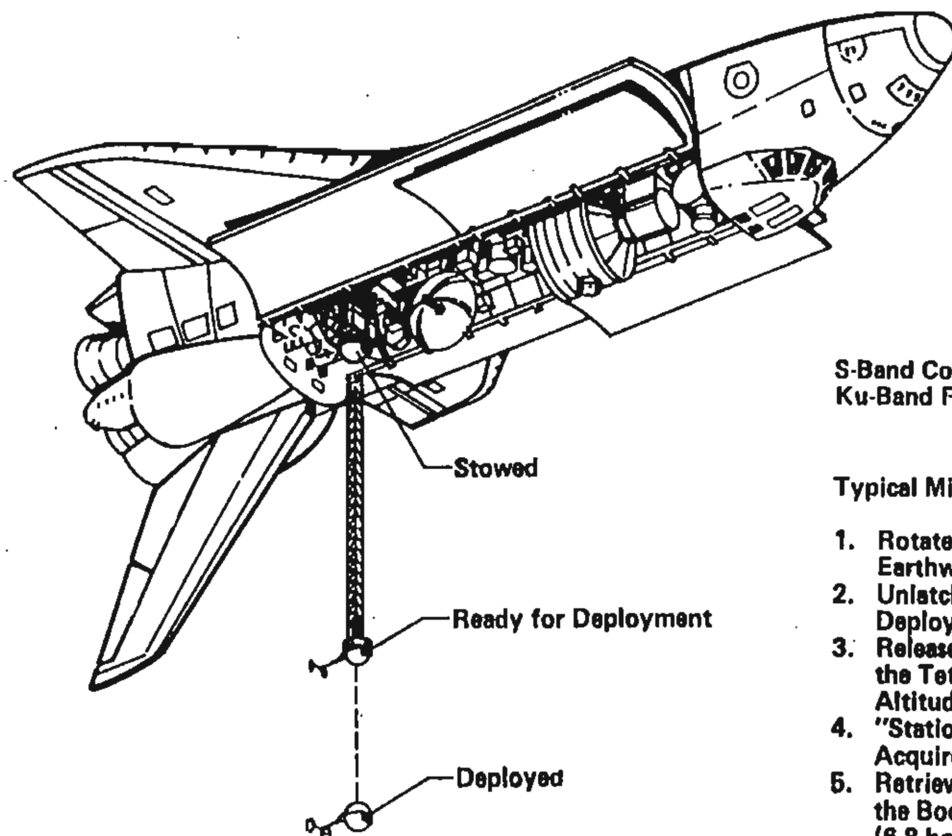


TSS ATMOSPHERIC MISSION

Second TSS mission about two years later for atmospheric studies. Satellite to be lowered to 130 Km altitude to reach region previously probed only by sounding rockets.

- Earthward satellite deployment
- 100 Km long, non-conductive tether
- Satellite upgraded for aerodynamic effects.

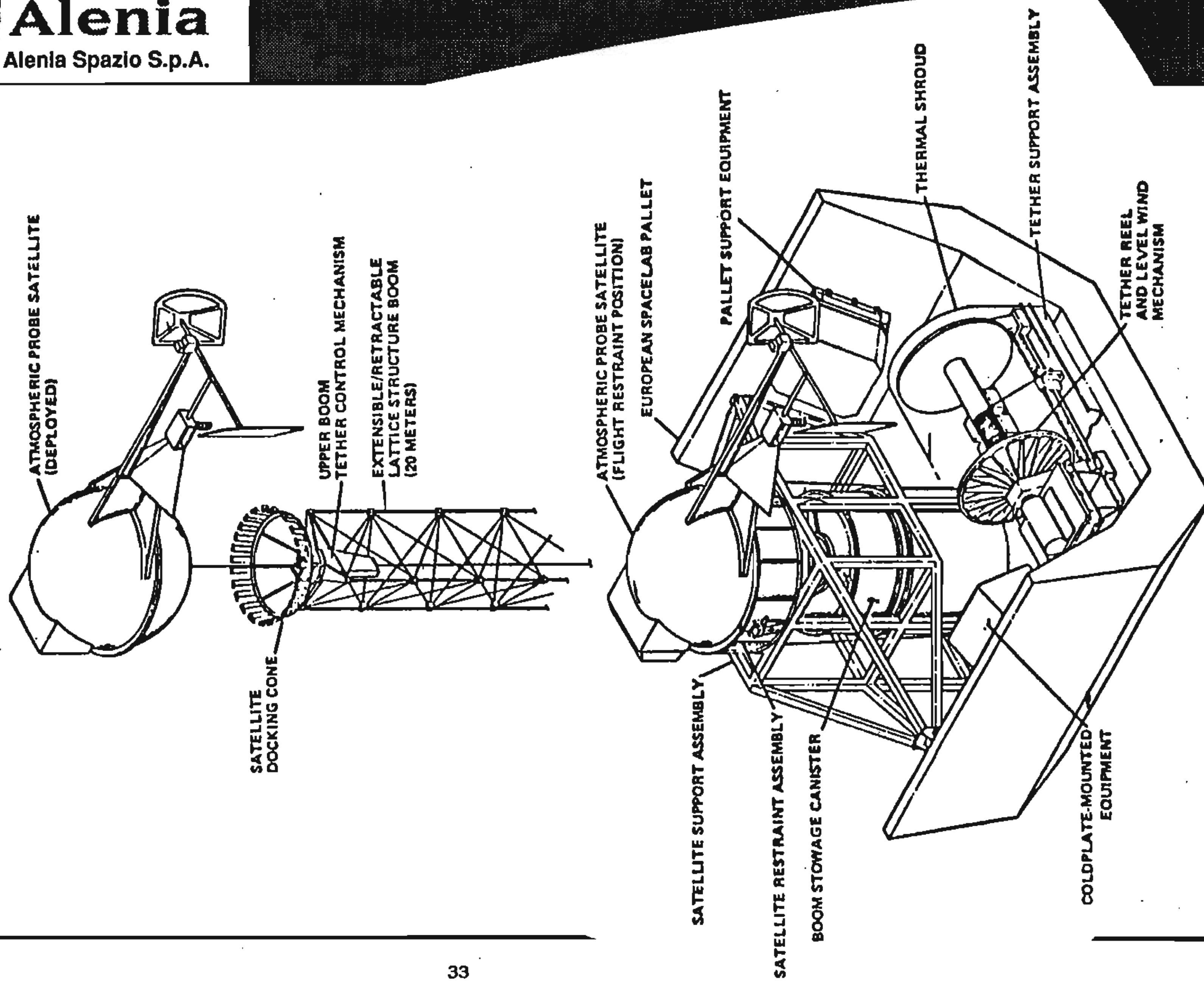
TSS DESIGN OVERVIEW - DEPLOYMENT CONCEPT



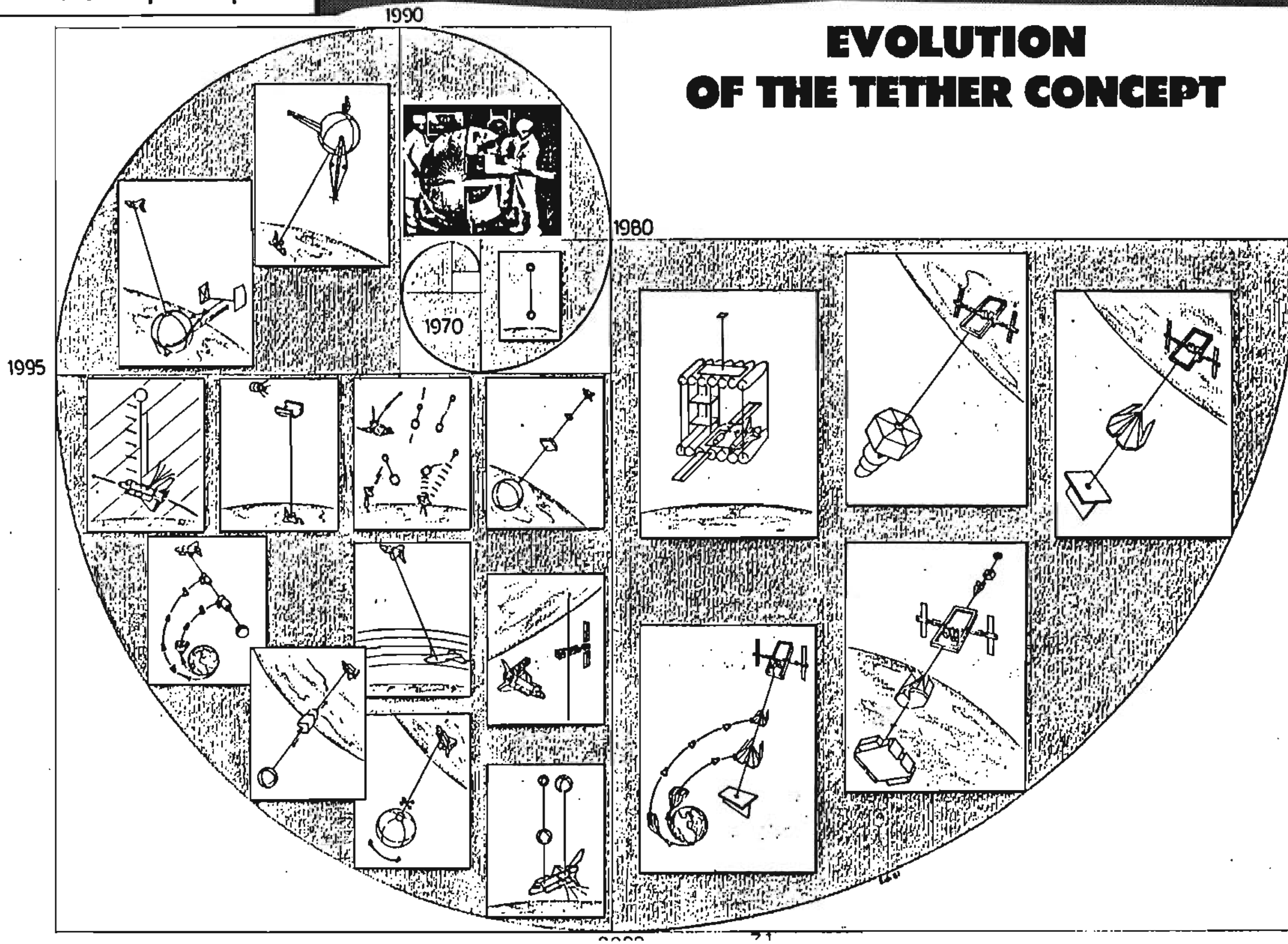
S-Band Communications to Satellite
Ku-Band Radar Tracking of Satellite

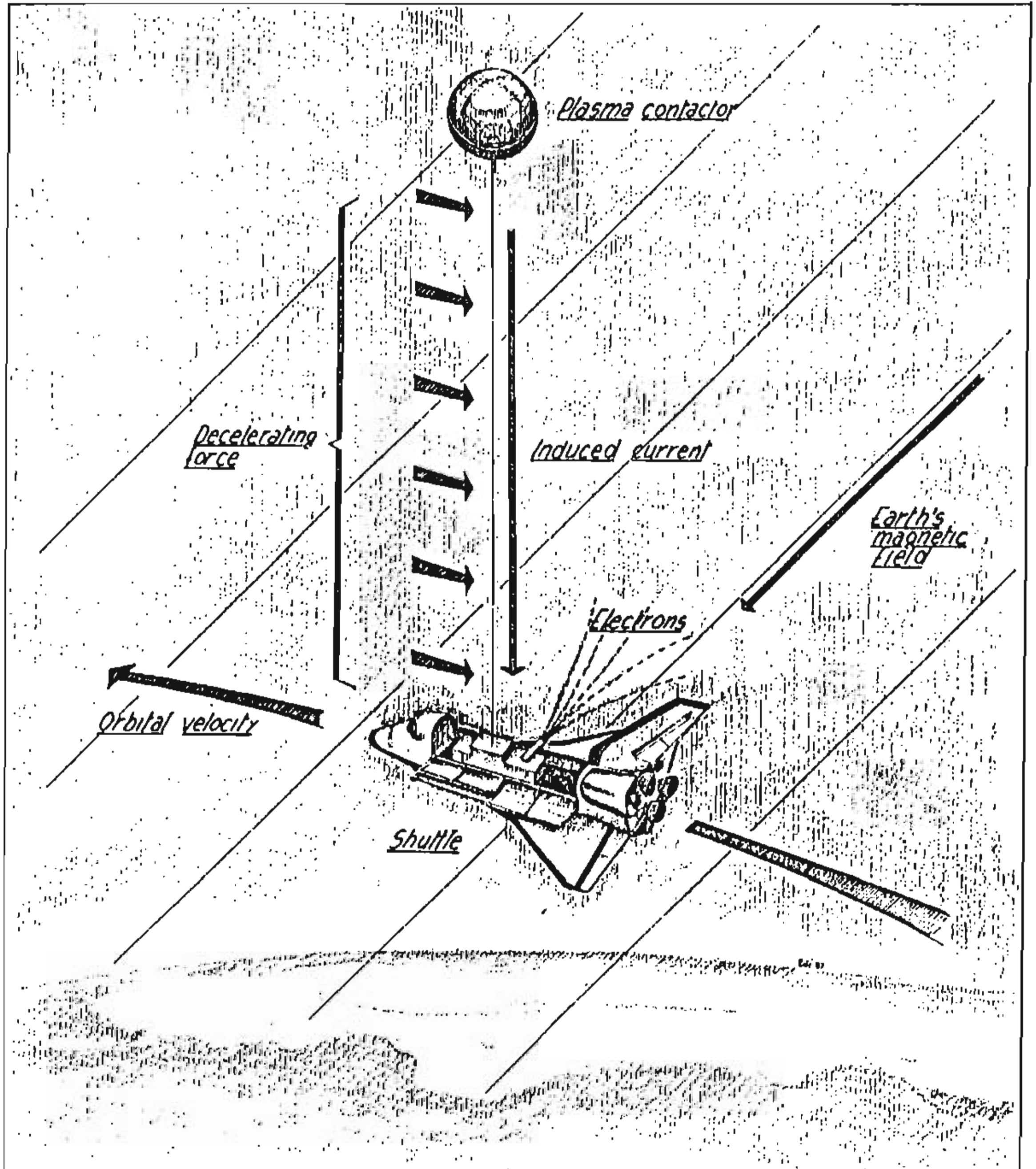
Typical Mission Scenario

1. Rotate the Orbiter Such That the Cargo Bay Is Facing Earthward (Altitude 230 km)
2. Unlatch Satellite and Deploy Outward Using the Deployment Boom
3. Release Satellite and Control Downward Trajectory Using the Tether Reel Motor. (Deployment 100 km to A 130 km Altitude Requires Approximately 6-8 hours).
4. "Stationkeep" the Satellite At the Desired Altitude and Acquire the Scientific Data (10-20 hours Typical).
5. Retrieve Satellite Using the Tether Reel Motor, Dock At the Boom, and Restow Satellite in the Orbiter Cargo Bay. (6-8 hours).


ATMOSPHERIC PROBE SATELLITE (DEPLOYED)
SATELLITE DOCKING CONE
UPPER BOOM TETHER CONTROL MECHANISM
EXTENSIBLE/RETRACTABLE LATTICE STRUCTURE BOOM (20 METERS)
ATMOSPHERIC PROBE SATELLITE (FLIGHT RESTRAINT POSITION)
EUROPEAN SPACELAB PALLET
PALLET SUPPORT EQUIPMENT
THERMAL SHROUD
TETHER SUPPORT ASSEMBLY
TETHER REEL AND LEVEL WIND MECHANISM
SATELLITE SUPPORT ASSEMBLY
SATELLITE RESTRAINT ASSEMBLY
BOOM STOWAGE CANISTER
COLDPLATE-MOUNTED EQUIPMENT

EVOLUTION OF THE TETHER CONCEPT

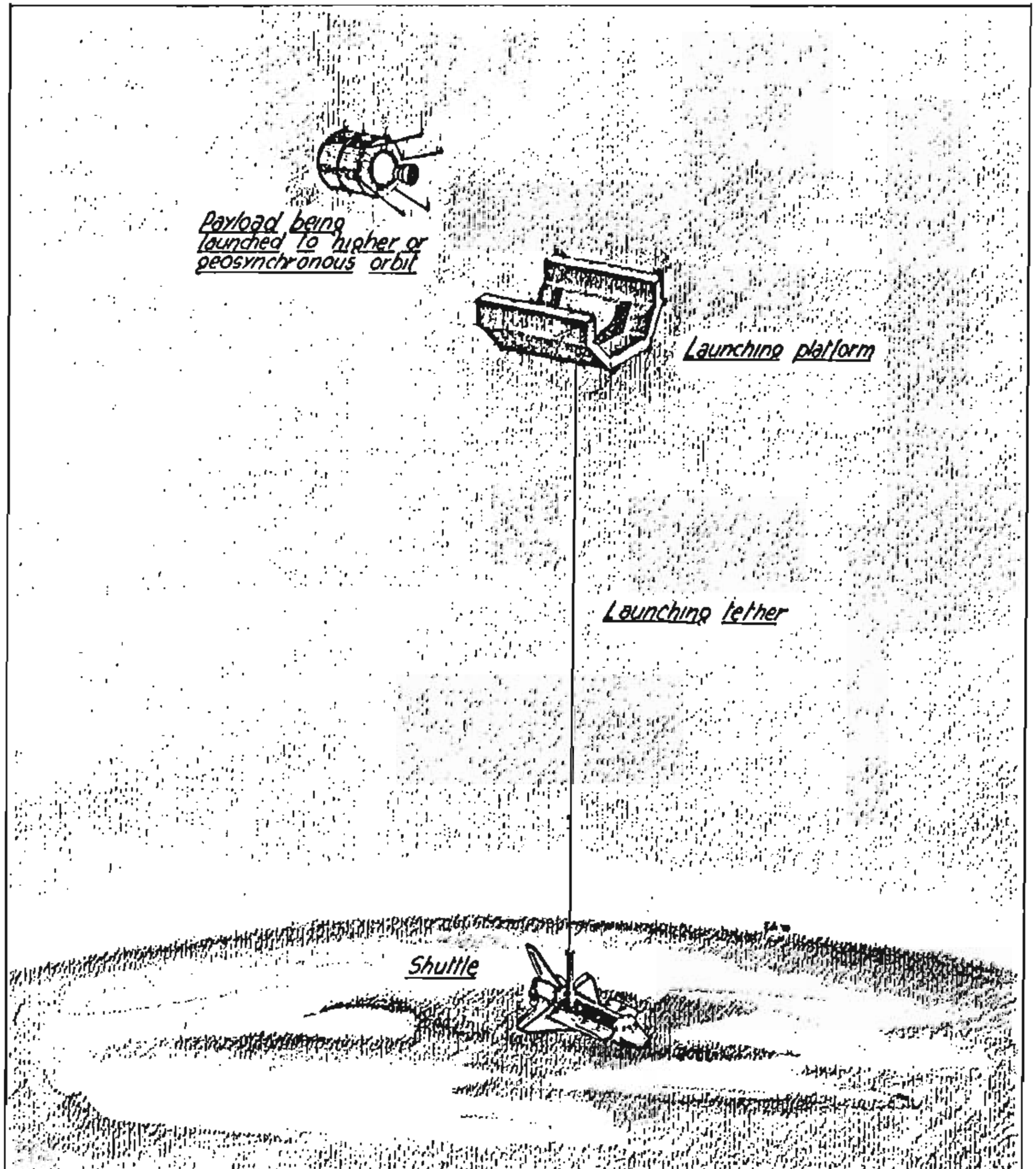




POWER/THRUST GENERATOR

Generation of electromagnetic propulsive thrust to boost the orbit of a spacecraft, and generation of DC electrical power to supply primary power to on-board loads.

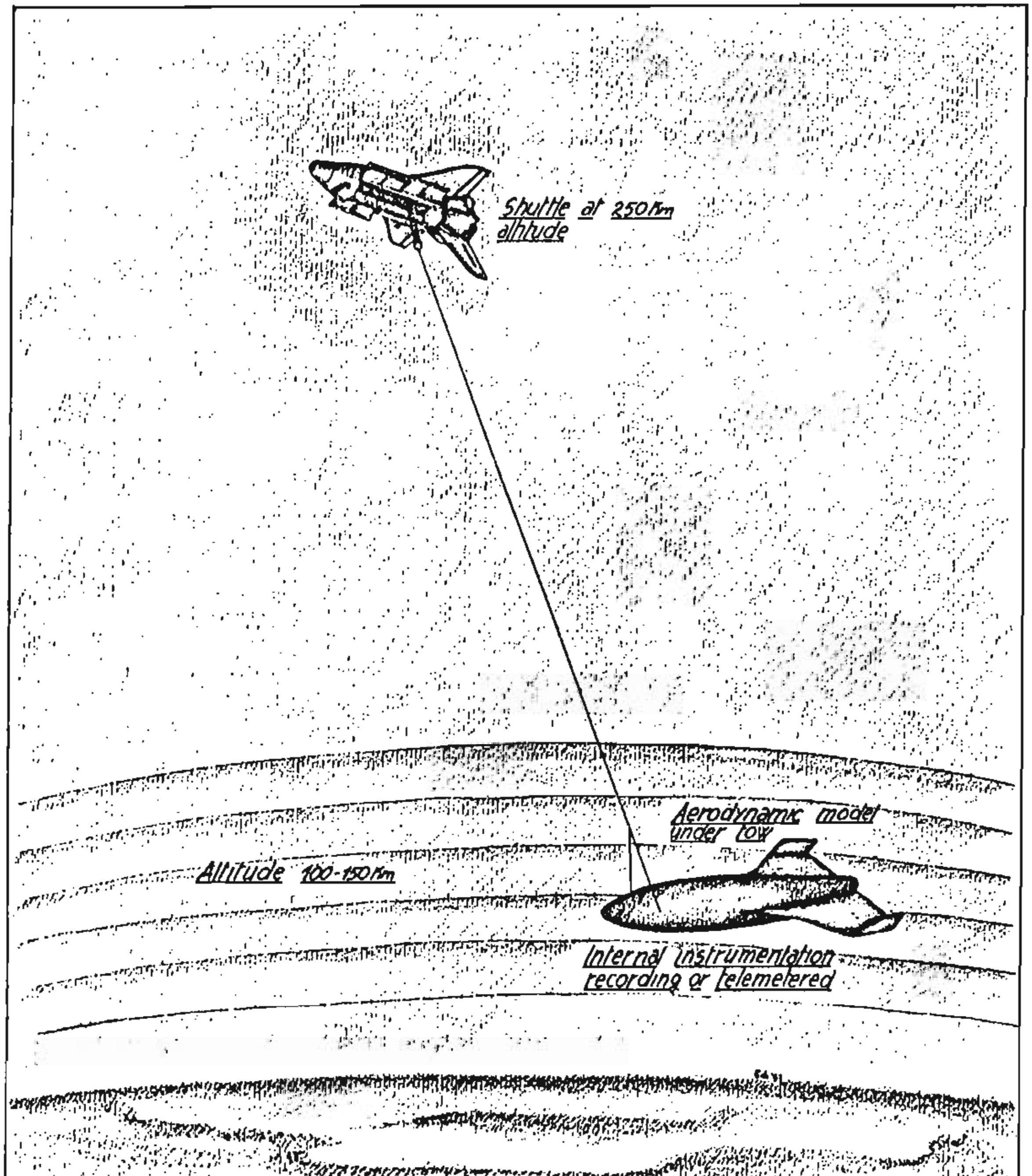
- *Plasma contactors*
- *10-20 Km tether length*
- *Aluminum/teflon materials*
- *Up to 20.000 Kg subsatellite mass*
- *Up to 1 MW power required/produced*
- *Up to 200 n thrust produced*
- *90% efficiency.*



TETHERED LAUNCH SYSTEM

Implementation of a launching platform with a payload release service to perform tether assisted orbit transfer to higher or geosynchronous orbit.

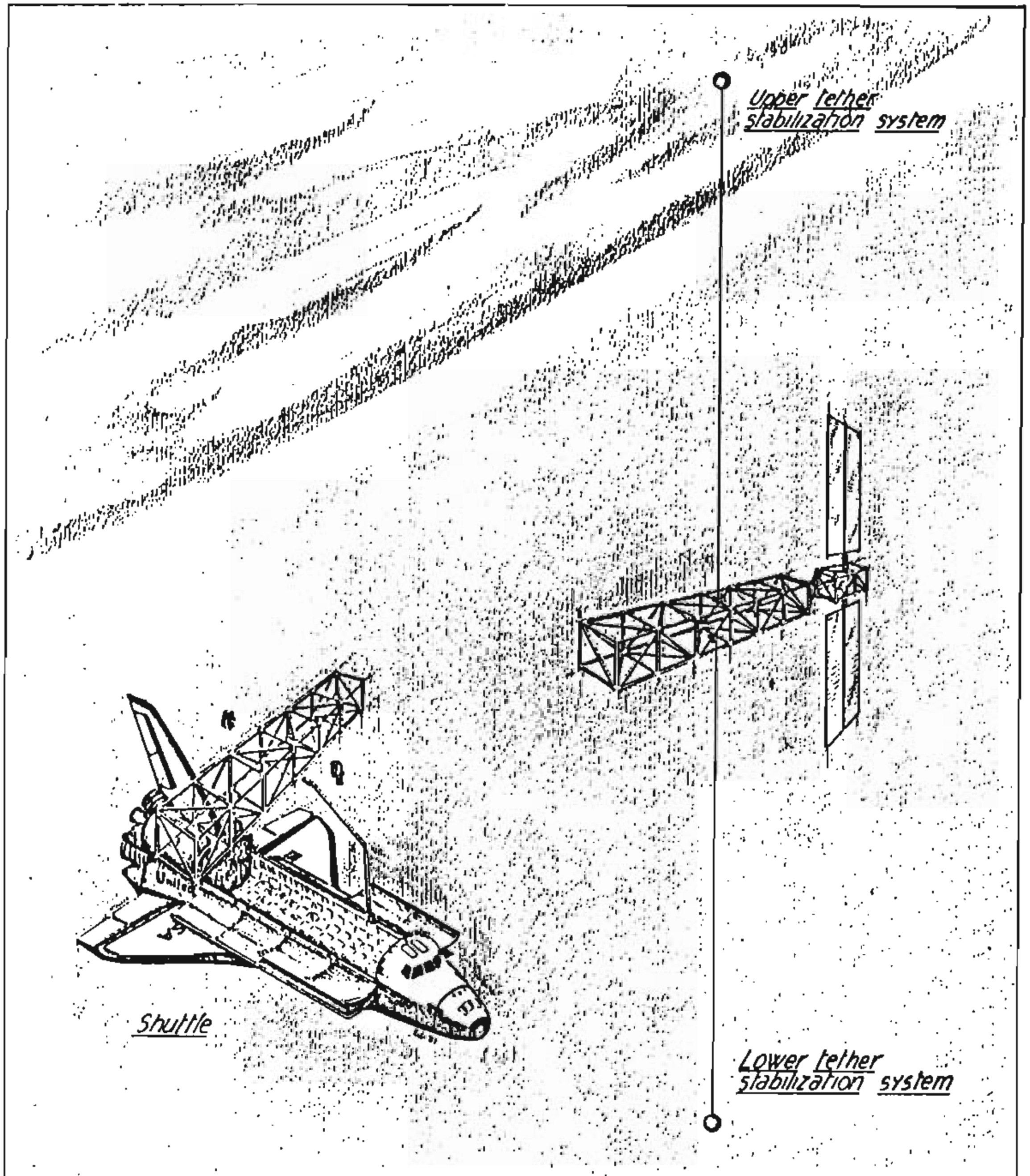
- *Launching tether (variable length)*
- *Launching platform*
- *Upper stage motor*
- *Momentum transfer from Shuttle to upper stage*
- *Spinup capability may be required.*



TETHERED «WIND TUNNEL»

A tethered fixture attached to the Space Shuttle provides a Wind Tunnel facility by towing aerodynamic bodies through the atmosphere.

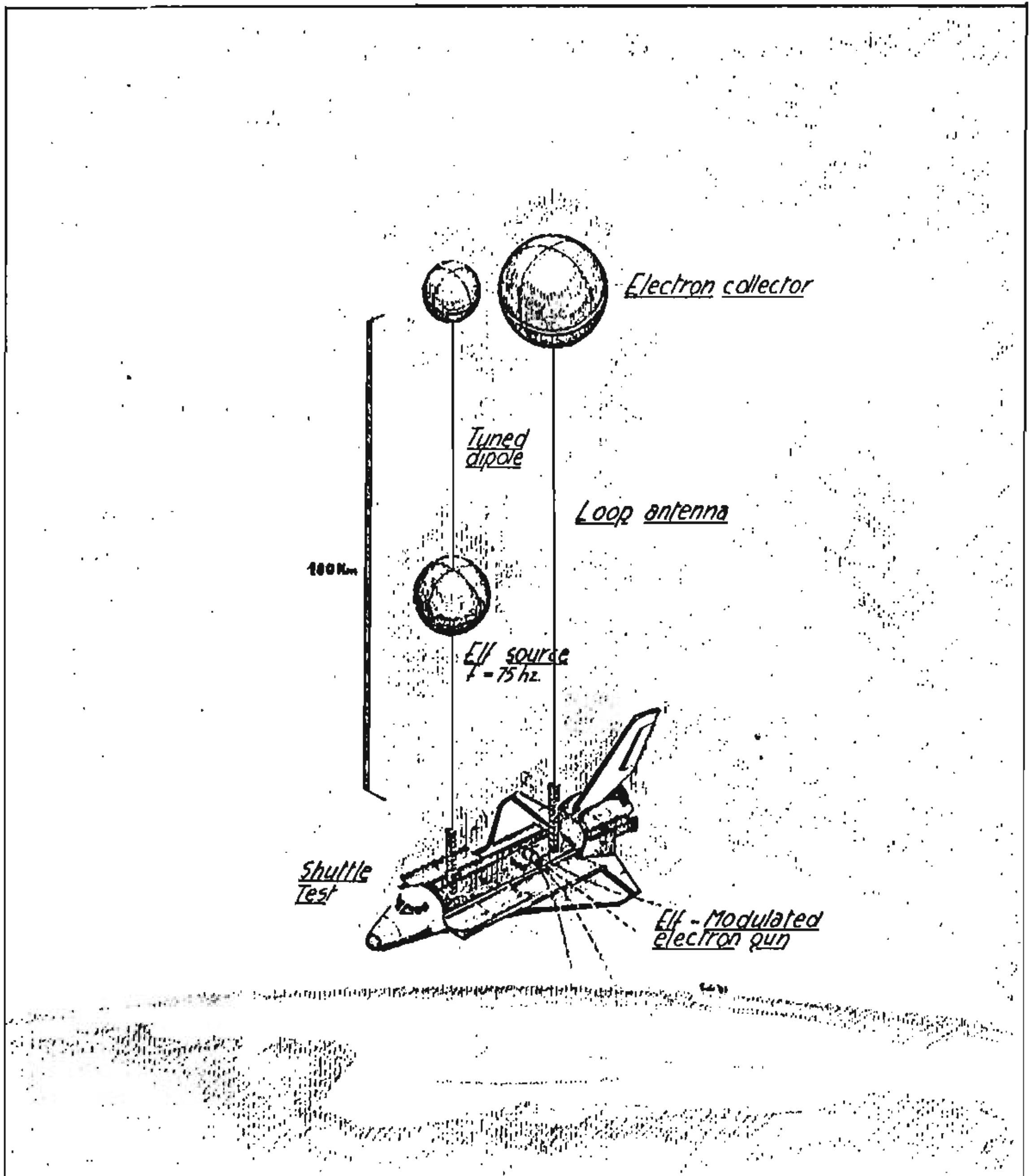
- 100 Km tether length
- Long testing time
- Heat transfer coefficients measure
- Drag coefficient measure
- Air flow and turbulence measure
- Low Reynolds number regime
- Large mach number regime.



TETHER AIDED ASSEMBLY

Implementation of tether stabilization systems to maintain the correct orientation of space structures during assembly by passive gravity-gradient stabilization.

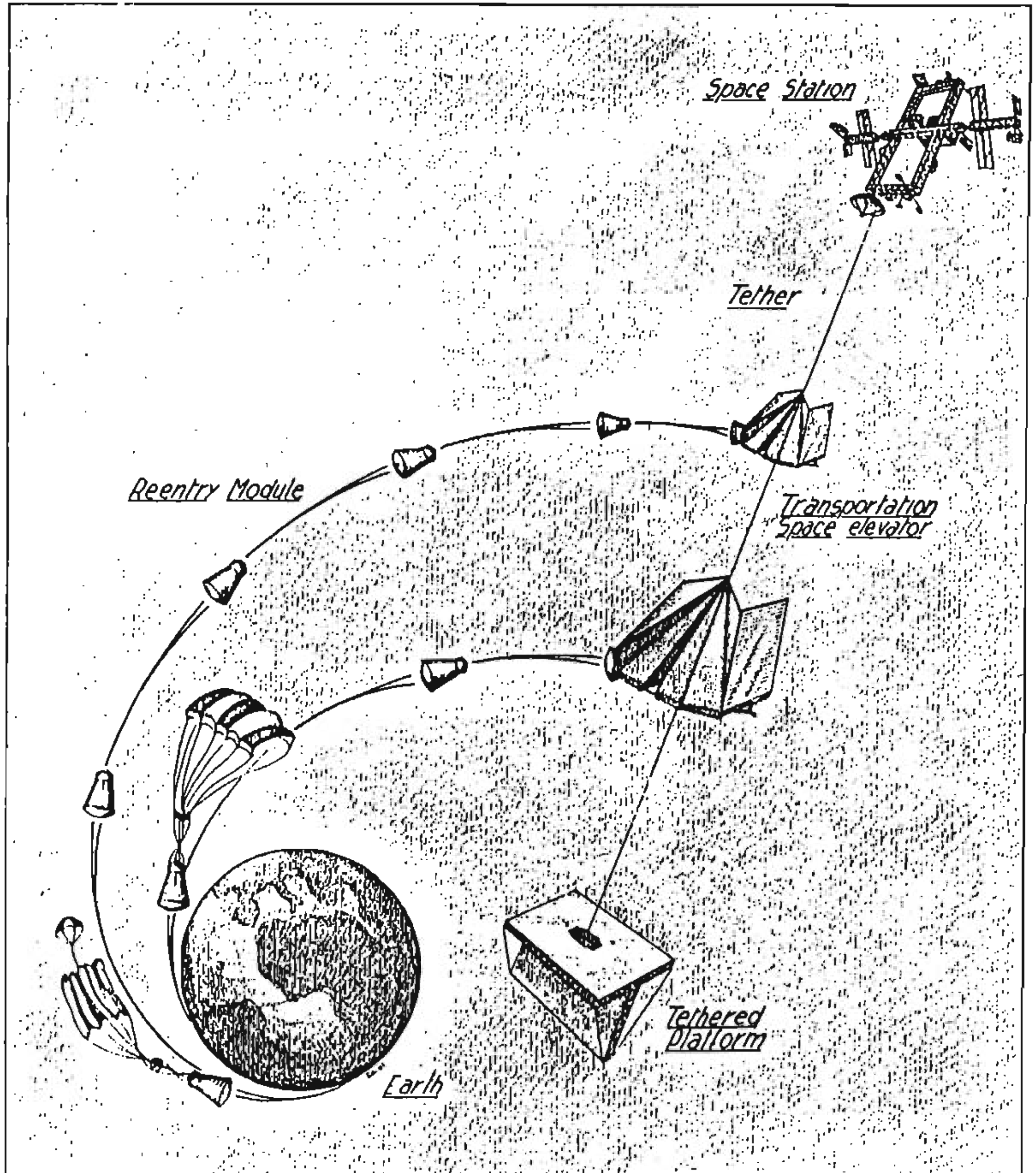
- *Single or double tether stabilization system*
- *Simple one-way deployer (tether expendable)*
- *1-2 Km tether length*
- *Up to 2.000 Kg mass of tether length*
- *Small tether control capability may be required.*



LONG ANTENNA

Generation of ULF/ELF/VLF waves by an orbiting electromagnetic tether for worldwide communications.
Electromagnetic waves can be generated by an on-board transmitter or by electron gun modulation.

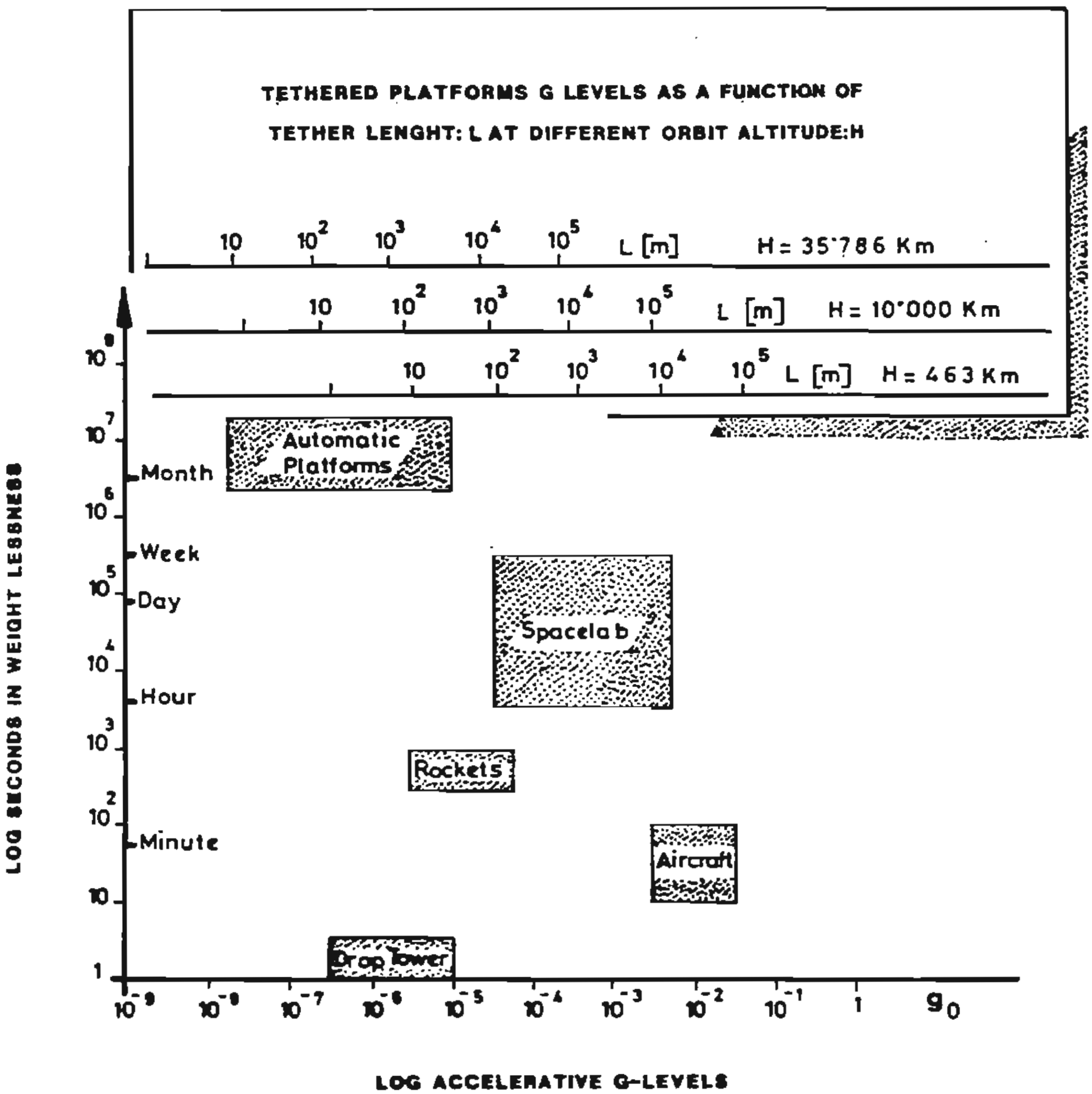
- *Tether length 20-100 Km*
- *10 A tether current*
- *ULF(3-30 Hz), ELF(30-300 Hz), VLF(3.000 Hz) bands*
- *1 W by night power*
- *0,1 W by day power*
- *Tuned dipole by on-board transmitter*
- *Loop antenna by electron gun modulation.*



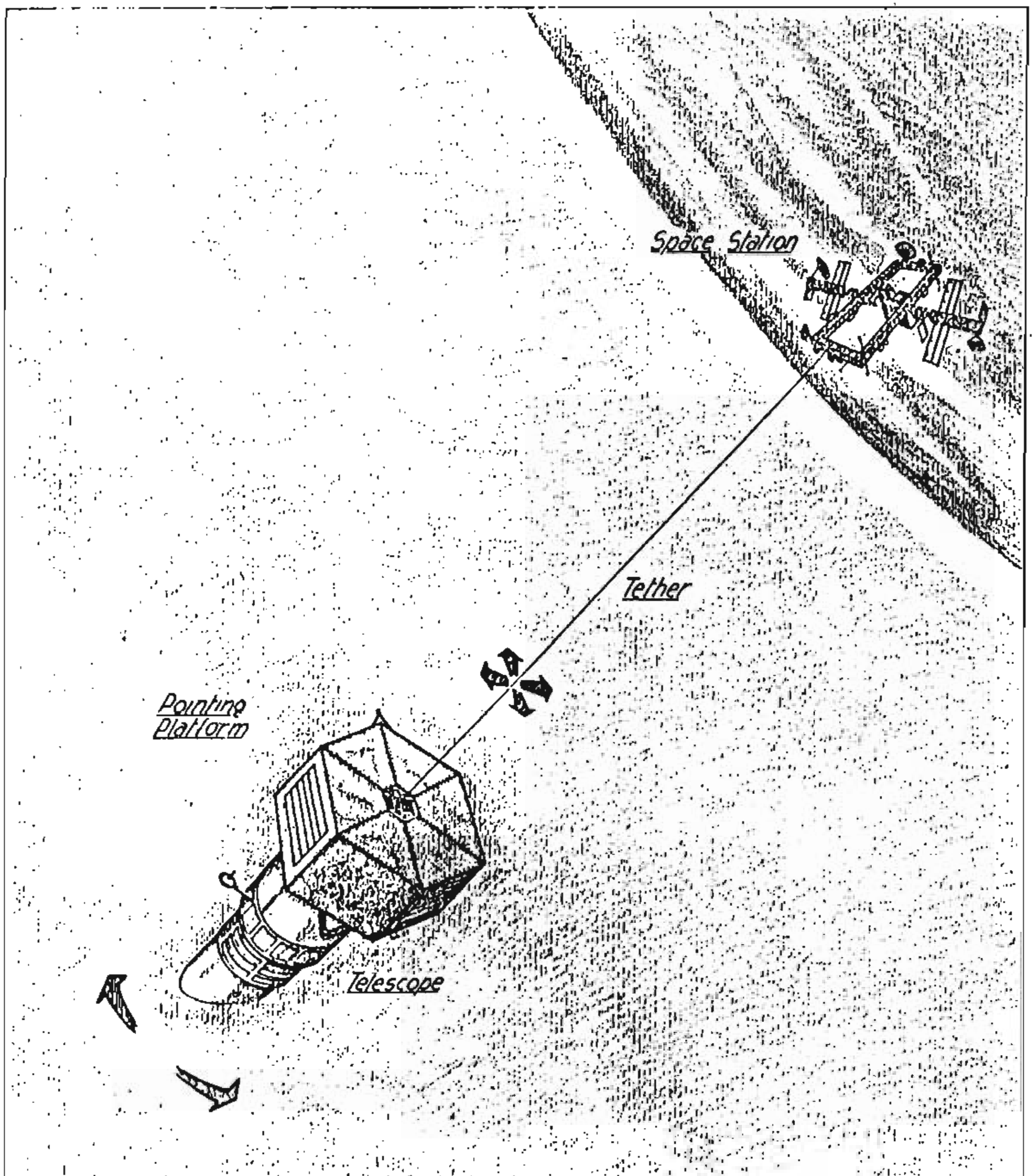
ELEVATOR RELEASED REENTRY SYSTEM

Allowing finely tuned adjustments of the reentry trajectory to ferry materials to earth and destroy residuals during reentry into the earth's atmosphere.

- *Up to 70 Km. tether length*
- *7 ton elevator system mass*
- *Controlled release capability*
- *Reentry module*
  - *— up to 3 ton mass*
  - *— parachute system*
  - *— thermal protection system*
- *Disposal module*
  - *— up to 3 ton mass*
- *Fuel and cost savings*
- *Quick reentry capability.*



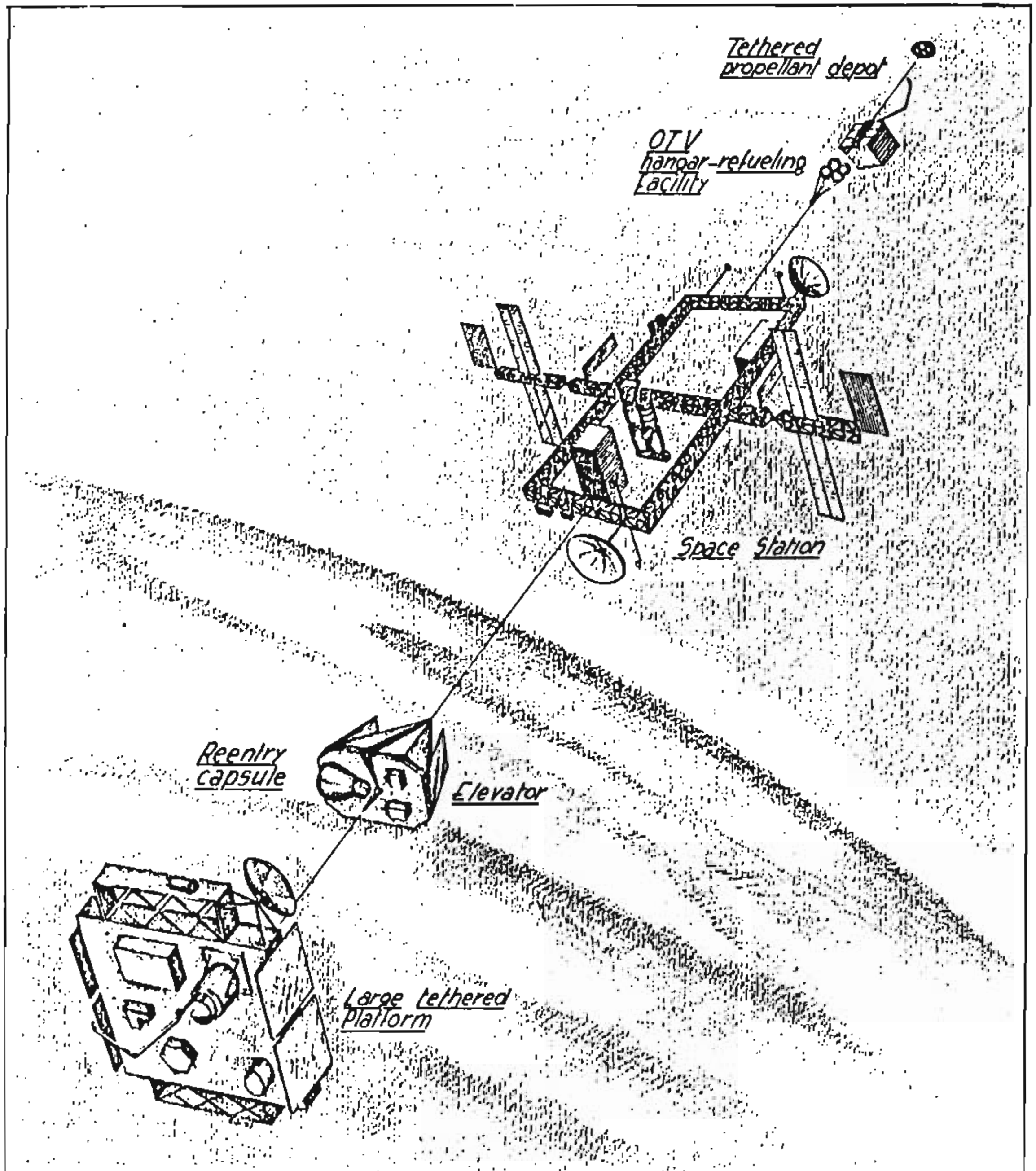
NOMINAL GRAVITATIONAL LEVELS AS A FUNCTION OF DURATIONS ACHIEVABLE WITH THE MAIN AVAILABLE MICROGRAVITY PLATFORMS COMPARED WITH TETHERED PLATFORMS.



ASTROPHYSICAL AND EARTH SURVEY FACILITY

A fixed or highly accurate pointing platform attached to the end of a tether would accommodate and support a wide range of astrophysical and earth survey payloads.

- *Periodical payload reconfiguration*
- *10 ton mass*
- *5 ton mass payload accommodation capability*
- *15 KW power via tether power line*
- *20 Mbps data rate via optical fiber link*
- *3 degrees-of-freedom displacement mechanism*
- *Tens of arc seconds pointing performance*
- *Provision for different emergency conditions.*



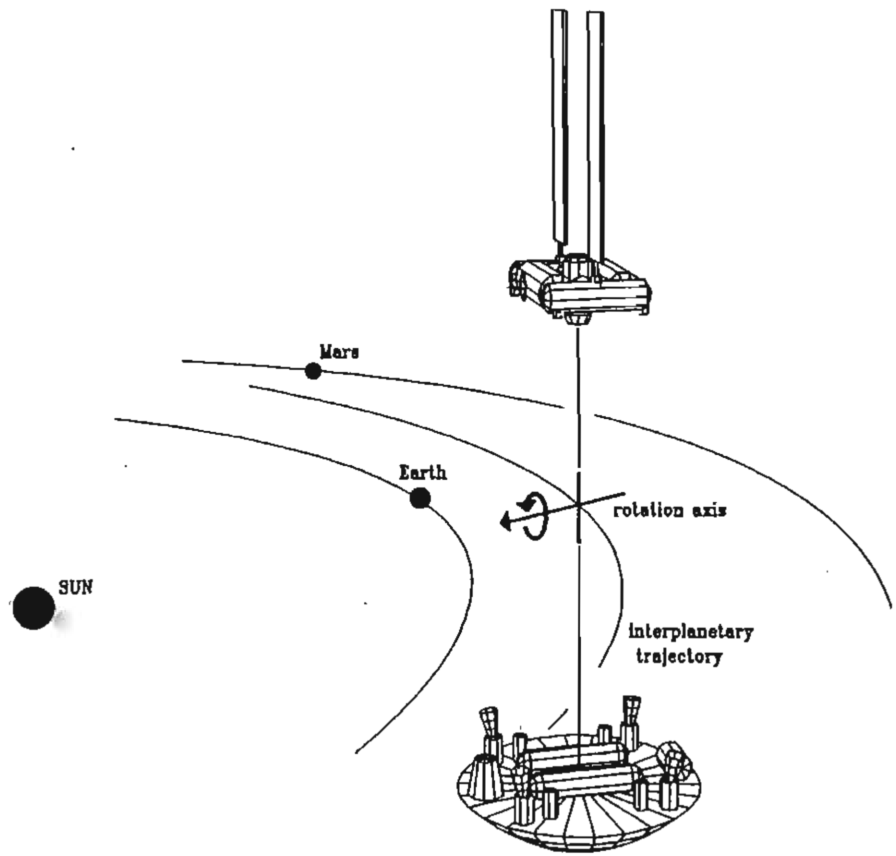
MULTIPLE TETHER APPLICATIONS FOR LONG TERM SPACE STATION CAPABILITY ENHANCEMENT

Upward tether system.

- *OTV hangar/refueling facility intermittently deployed*
- *Second tether reeled out from hangar for momentum transfer of OTV*
- *Propellant depot for spacecraft refueling*
- *Retrieval of OTV hangar with the second tether deployed.*

Downward tether system.

- *Large tethered platform for science and technology (50 ton mass)*
- *Tethered space elevator for platform servicing, microgravity laboratory, re-entry application, tether inspection and repair.*


Mars
Earth
SUN
rotation axis
interplanetary
trajectory

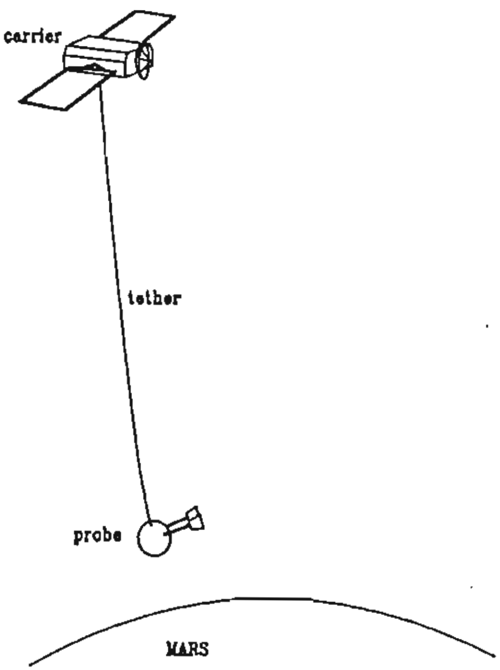


Fig. 10 TSS concept for Martian low atmosphere exploration

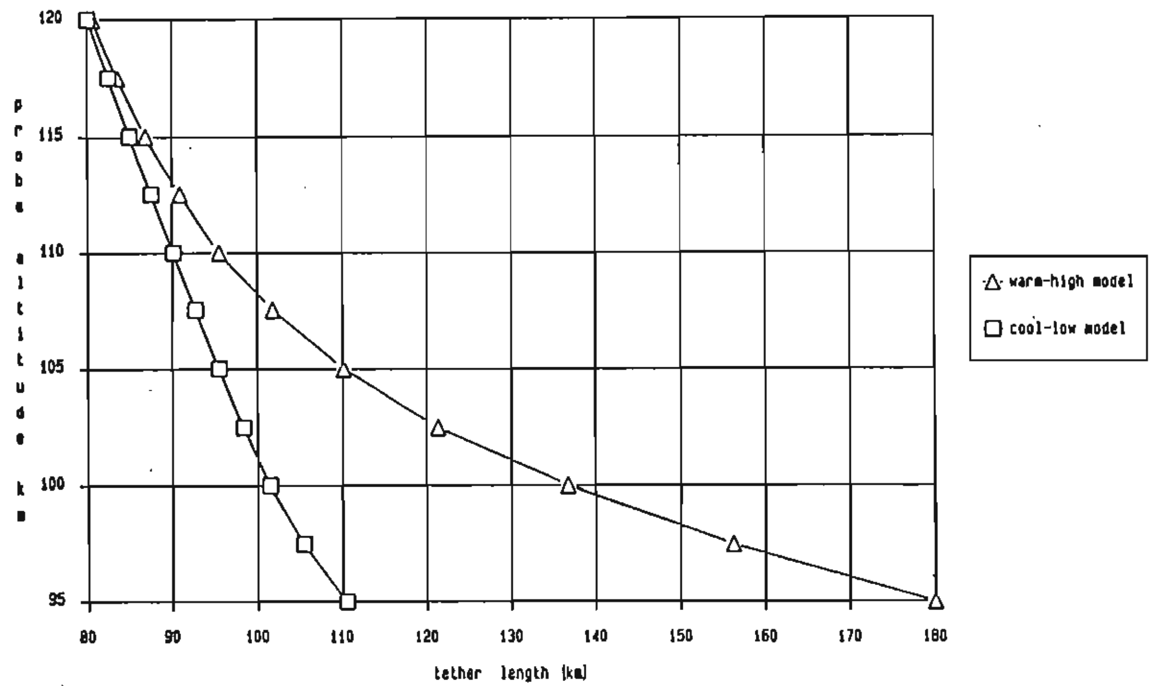


Fig. 11 Tether lenght required to deploy the probe at a given altitude from a carrier flying at 200 km


Thank You