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APPLICATIONS OF TETHERS IN SPACE – A REVIEW OF WORKSHOP RECOMMENDATIONS –

By Georg von Tiesenhausen, Editor

Advanced Systems Office
Program Development

May 1986

National Aeronautics and Space Administration

George C. Marshall Space Flight Center

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16. ABSTRACT

Well-organized and structured efforts of considerable magnitude involving NASA, industry, and academia have explored and defined the engineering and technological requirements of the use of tethers in space and have discovered their broad range of operational and economic benefits. The results of these efforts have produced a family of extremely promising candidate applications. The extensive efforts now in progress are gaining momentum and a series of flight demonstrations are being planned and can be expected to take place in a few years. This report provides an analysis and a review of NASA's second major workshop on Applications of Tethers in Space held in October 15-17, 1985, in Venice, Italy. It provides a summary of an up-to-date assessment and recommendations by the NASA Tether Applications in Space Program Planning Group, consisting of representatives of seven NASA Centers and responsible for tether applications program planning implementation as recommended by the workshop panels.

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FOREWORD

By Georg von Tiesenhausen
Advanced Systems Office
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Historically, the space flight community is most familiar with rockets that generate propulsive forces internally and whose trajectory is determined by gravitational fields. It is, therefore, understandable that a tethered system, which can move spacecraft in space based on angular momentum exchange or on electrodynamic forces, requires a nearly constant exposure to the space flight community in order to become an accepted element of space mission operations.

This effort has been in progress for an extended period of time. A major workshop on tether applications in space took place in 1983 that set the stage for intensive efforts to evaluate the most promising applications. A second international workshop was held in 1986 that reviewed the swift progress made in the years past and which addressed future directions for the years to come. This report represents a review of these last workshop recommendations by the NASA Tether Applications in Space Program Planning Group. This group was established in 1983 by the Office of Space Flight, the Director of Advanced Programs, Ivan Bekey, consisting of representatives of six NASA field centers and the Jet Propulsion Laboratory. The group has the responsibility of annually generating study, technology, demonstration, and science and applications plans for the following years based on workshop recommendations. This dedicated group's analysis and review of the second Tether Applications in Space workshop's recommendations are addressed to government, industry, and academia to assist them in evolving safer, more economical and novel approaches to future space missions.

Georg von Tiesenhausen.
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Assistant to Director
Advanced Systems Office
Program Development
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TECHNICAL MEMORANDUM

APPLICATIONS OF TETHERS IN SPACE
– A REVIEW OF WORKSHOP RECOMMENDATIONS –

1.0 INTRODUCTION

The second workshop on "Applications of Tethers In Space" took place in Venice, Italy on October 15-17, 1985. (The first workshop occurred in Williamsburg, VA on June 15-17, 1983). In his preface to the first workshop, Peter Banks said: "...Some of the topics are clearly more mature, in a technical and scientific sense, than others. Yet, this is the time to have speculative thoughts and novel ideas. The passage of time and confrontations with technical and fiscal reality will winnow the collection into a harvest of rich technical productivity." The about 800 pages of raw material generated at that workshop were handed over to a NASA Program Planning Group established by NASA's Office of Spaceflight, Office of Advanced Programs in 1983. Since that time, a well structured, logical, and consistent Tether Applications Program Plan evolved from that workshop and has been followed and implemented. Progress in recognizing specific and quantized benefits in various application areas was rather swift and efficient. Six NASA Field Centers and the Jet Propulsion Laboratory participating in the various aspects of tether applications have zeroed in on the most beneficial concepts and have approached the definition of a number of flight demonstration missions.

The perspective of the second workshop was a world apart from the first one: Swift and well organised progress has been achieved in all categories of tether applications, considerable growth in understanding the benefits and specific applications of tether operations has occurred, and the definition of critical issues particularly in technology and science has set the stage for their solutions.

This report constitutes a review of the various workshop panels' conclusions and recommendations as a basis for the planning activities of NASA's Tether Applications In Space Program Planning Group.

The workshop was divided into seven work panels and the following reviews and analyses are structured accordingly. For each area, it lists the responsible planning group representative and the panel members. This is followed by an abstract of each panel's subject coverage and recommendations.

2.0 TETHER MISSIONS IN SUPPORT OF SPACE SCIENCE AND APPLICATIONS

Program Planning Group Representative: Dr. William A. Webster, NASA Goddard Space Flight Center

Panel Members:

Franco Mariani	University of Rome
Donald Coble	Los Alamos National Laboratory
George Carignan	University of Michigan
Robert Hudson	NASA Headquarters
Alberto Anselmi	Airitalia
Martin Hechler	European Space Operations Center

Paul Dickinson	Rutherford Appleton Laboratory
William Baracat	General Research Corporation
Angelo Bonanni	Carlo Gavazzi Controls
Giacomo Modugno	Rome
Maurizio Candidi	IFSI/CNR
Harris Mayer	JPL
Charles Tang	JPL
Antonio Moccia	University of Naples
Sergio Vetrella	University of Naples
Nobie Stone	NASA-MSFC
Paul Coleman	University of California
Leonardo Gagliardi	PSN

Panel Proceedings Summary

This truly international assembly of scientists addressed the new opportunities which tethered operations can provide with considerable enthusiasm. They considered early as well as far future science missions.

The panel emphasized the following needs:

(1) Understanding the electric and magnetic environment requires tethered satellites (or platforms) clean from the standpoint of electric and magnetic contamination to keep undesired noise below the expected level of significant measurements.

(2) Understanding the dynamics of the tether and improving atmospheric models is another essential goal, since accurate knowledge in this field is also essential to making possible some of the most interesting applications (among them, studies on gravity and geomagnetic anomalies) near Earth and/or to plan future advanced TSS missions or tether applications to space stations.

(3) Improve the EMC/EMI properties of tethered satellites or platforms.

(4) Improve their DC magnetic cleanliness.

(5) Complement the payload with sensitive, low-power dynamical packages (accelerometer, tensiometers, etc.).

(6) Stimulate close cooperation between dynamicists and aeronomists to get reliable dynamical and atmospheric models.

Panel Recommendations – General

(1) Low altitude measurements (90 to 130 km) of the neutral and ionized atmosphere/ionosphere given the highest priority.

(2) Magnetic and gravity measurements were given second priority. The panel recommended all possible efforts to improve EMC/RFI over DC magnetic cleanliness of tethered vehicles.

Panel Recommendations – Broad Categories of Experiments for TSS-2

(1) Ambient ion and neutral species.

(2) Electron, ion temperature and energy balance.

(3) Magnetic and gravitational field.

(4) Electric field.

(5) Electrostatic and electromagnetic waves.

(6) Stereoscope remote sensing of the Earth's surface.

(7) Dynamics of tethers (and satellites).

(8) "Open wind tunnel" experiments at low altitudes.

NOTE: Important developments are necessary in order for a tethered satellite to be deployed to lower altitudes.

Panel Recommendations – Measurements Below 130 km

- Atmospheric transition from diffusive separation to turbulent mixture of components.
- Atomic oxygen to molecular oxygen.
- Higher order terms of gravity and magnetic fields.

Challenges:

- Shock waves generated by a vehicle disturb the ambient atmosphere.
- Conventional instruments may not work (for example mass spectrometers).
- Measurement body (i.e., TSS) to be an aerodynamic body.
- New techniques to be developed (resonance fluorescence, laser fluorescence, etc.).

Advanced Science Missions:

- Tethered satellites suspended from spacecraft to study planetary atmospheres.
- Sample collection during comet or asteroid rendezvous missions.
- Stereoscopic observations from tethered platforms (solid-state array detectors and synthetic aperture radars placed vertically on a single tether).
- Communication links using tethered satellites.
- Tethered space compass for field measurements.
- Tethered penetrator for comet/asteroid samples.

3.0 POWER AND THRUST GENERATION THROUGH ELECTRODYNAMIC TETHERS

Program Planning Group Representative: Joseph C. Kolecki, NASA Lewis Research Center and Dr. James E. McCoy, NASA Johnson Space Center

Panel Members:

Joseph C. Kolecki	NASA/LeRC, USA
Marino Dobrowolny	IFSI/CNR, Italy
Carlo Bonifazi	IFSI/CNR, Italy
Paul J. Wilbur	Colorado State University, USA
Don Parks	S-Cubed, USA
William J. Miller	Aeritalia, Italy
Kevin Rudolph	Martin Marietta, USA
John R. Beattie	Hughes Research Labs, USA
Jay Hyman	Hughes Research Labs, USA
James E. McCoy	NASA/JSC, USA
Bob Estes	Smithsonian Astrophysical Observatory, USA
Giorgio Tacconi	University of Genoa (DIBE), Italy
Emilio Banfi	Laben Si El, Italy
Ludwik Celnikier	Observatoire De Paris-Menfon
J. P. Lebreton	SSD/ESA/ESTEC, The Netherlands
Jean Sabbaugh	CNR/PSN, Italy
Efrem Rsuconi	Carlo Gavazzi Controls, Italy
Wolfgang Westphal	AEG, Germany
Manual Martinez-Sanchez	MIT, USA
Andrea Lorenzoni	PSN, Italy
Francesco Giani	Aeritalia SSG, Italy

Panel Proceedings Summary

The Electrodynamic Interactions working panel focused on issues involving electrodynamic power and thrust generation applications, space experiments and demonstrations, and electrodynamic tether antenna signal generation and detection. Applications were identified in the areas of:

- Multikilowatt to megawatt power/thrust generation.
- Communications.
- Planetary exploration.

Additionally, many issues and concerns were identified in each area including:

- Hardware characterization.
- Environmental interactions and characterization.
- Design tradeoffs.
- Development of better models and theories.

A unanimous recommendation was drafted to fly a hollow cathode on the Shuttle Orbiter as part of the upcoming TSS-1 mission. (See the following.)

Finally, a number of short and long term flight demonstrations and applications were identified including:

- Early proof of function flights.
- Low impedance current collection by means of hollow cathode or hollow cathode based plasma sources.
- Drag makeup and orbital maneuvering of Space Station and other large space systems.
- Multikilowatt to megawatt power generation.
- ULF/ELF/VLF antenna applications.
- Planetary exploration to include the Jovian magnetosphere and Saturn ring system.

<u>Panel Recommendations</u>

- Multikilowatt to megawatt power and thrust generation
  - Understanding plasma contactor operation in space for currents up to 50 A.
  - Identifying and understanding the effects of instabilities.
  - Characterizing the ionospheric/magnetospheric closure path.
  - Understanding environmental impact due to operations of large electrodynamic systems, and associated effects upon other space vehicles.
  - Assuring long term insulator survival and understanding performance impacts due to insulator defects.
- Electrodynamic Tether ULF/ELF/VLF Antenna
  - Characterizing the various wave propagation media involved with the ULF/ELF/VLF transmissions.
  - Analyzing background noise sources and noise statistical structure.
  - Determining optical locations for ground receivers.
  - Correlating signals received at different locations to subtract off noise.
  - Characterizing instabilities and waves due to large current densities in the Alfven wings.
  - Putting theoretical work on firmer footing than it is at present.
- Plasma contactors, hollow cathodes
  - Performing laboratory and analytical characterization of contactor operation including magnetic field effects.

- Developing a plasma contactor technology for electron currents up to 50 A.

- Flying hollow cathodes or hollow cathode based plasme contactors on (i) the Shuttle Orbiter for the TSS-1 mission and (ii) Both ends of the tether in future TSS missions.

- Short and long term flight demonstrations

  - Early proof of function flights to involve current collection by means of plasma contactor devices.

  - Power generation and orbital maneuvering (of Space Station and other large space systems).

  - ULF/ELF/VLF antenna applications demonstrations.

4.0 TETHERED TRANSPORTATION SYSTEMS (MOMENTUM EXCHANGE)

Program Planning Group Representative: Georg von Tiesenhausen, NASA-MSFC

Panel Members

Chris Purvis	JPL/Cal Tech, USA
Ed Bangsund	Boeing Aerospace, USA
Joseph Loftus	NASA/JSC, USA
Mark Henley	General Dynamics/SSD, USA
Tom Stuart	NASA/HQ, USA
Joe Carroll	Energy Science Labs, USA
Ernesto Vallerani	Aeritalia, Italy
Dave Moruzzi	Italian Advanced Industries, USA
Terry Reese	General Research Corporation, USA
Maxwell Hunter	Lockheed/MSC, USA
Mario Galantino	PSN/CNR, Italy
Harris Mayer	JPL, USA
Martin Hechler	ESA/ESOC, West Germany

Panel Proceedings Summary

The panel arrived at a prioritized list of tethered transportation missions listed below in descending order of priority:

1. The Small Expendable Deployment System for boosting payloads from the Shuttle.

2. Electrodynamic propulsion for small and large orbit changes within LEO

3. Boosting of OTVs from the shuttle, to reduce the deltaV needed to reach GEO.

4. Launch vehicle capture and release by tethers hanging from permanent facilities.

5. Artificial gees on manned deep-space expedition vehicles during transit.

6. Multi-pass remote aerobraking of planetary orbiters, to simplify navigation.

7. An equatorial "staircase" or "fire brigade" to high orbits and escape.

8. "Slings" of various sorts:

   a. Spinning lunar-orbiting rock collector/prospector.

   b. Lunar-surface-based sling to throw rocks into low lunar orbit.

   c. Asteroid-based sling (to throw rocks, or to move the asteroid itself).

   d. Hoops or solenoids with electromagnetic assist to the tether strength.

5.0 TETHER CONTROLLED GRAVITY LEVELS

Program Planning Group Representative: Kenneth R. Kroll, NASA-JSC

Panel Members:

Charles A. Lundquist	University of Alabama, USA
Luigi G. Napolitano	University of Naples, Italy
James R. Arnold	University of California, USA
Giovanni Ahersini	Case, Mileu
Dale E. Fester	Martin Marietta, USA
Faduesco Giani	Aeritalia GSS, Italy
Vincero Guarnieri	Aeritalia GSS, Italy
Jack W. Slowey	Smithsonian Astrophysical Observatory, USA
Rodelf Monsi	University of Naples, Italy
Kenneth Kroll	NASA/JSC, USA
Ethu Outsua	Politecuis of Tonius
Alberto Passerone	Iciam-CNR, Italy
Giacomo C. Moduano	Eye Clinic, Rome University, Italy
Paul A. Penzo	JPL, USA

Panel Proceedings Summary:

The panel covered two aspects of its area of responsibility: Potential scientific use of variable gravity levels and variable gravity systems concepts.

Scientific Values:

- Biological responses to different fixed or varying magnitudes of gravity and threshold values for different phenomena.
- Effect of gravity levels on fluid mechanics.
- Threshold of crystal growth.
- Search for optimum gravity levels.

Operational Values:

- Disturbance isolation.

The following matrix summarizes the objectives and uses of controlled gravity systems as seen by the panel:

	TSS ERA PRE-IOC	IOC ERA FOR SPACE STATION	POST-IOC ERA
Objectives and Uses	Objective is to master the concept and technology of gravity control. Gravity control would be applied to: Life Sciences Materials Science Fluid Science Engineering Uses	Gravity Controlled experimentation in Space Station applied to: Life Sciences Materials Science Fluid Science Engineering Uses	Fully exploit gravity control in Space missions.
Demonstrations and Experiments	Demonstrate gravity profile generation, measurement and use, including appropriate analysis and evaluation. Recommended Opportunities for early demonstrations: Spinning Orbiter Mission Orbiter experiments during tether missions. Elevator on a tether.	Science and application experiments, possibly using TSS deployer.	Processes and applications.

Panel Recommendations:

Disposable Deployer Mission (1987). This mission may allow a measurement of the acceleration field change and particularly the associated acceleration noise at positions in the Shuttle while the tether and payload are deployed. Appropriate instrumentation for these measurements needs to be identified and scheduled for the mission.

Spinning Shuttle Mission (1987-8). This mission provides the first opportunity to begin investigations of controlled gravity and threshold phenomena in the low gravity range (10^{-1} to 10^{-4}). Although a tether is not involved in this demonstration, the rotation principles for achieving low gravity are the same as for a rotating threshold system. Fluid science and applications are particularly pertinent for this mission. Necessary instrumentation and demonstration equipment should be planned.

TSS-1 (1988). The resulting acceleration field on the Orbiter including the associated acceleration noise, should be correlated with other data such as accelerations on the satellite, tether length, and tether tension. This mission should provide the necessary information to extrapolate performance of a tether gravity system for Space Station.

TSS-2. The controlled gravity experiments on the Orbiter for TSS-1 should be repeated and expanded. This mission may provide an opportunity to test an "elevator" that moves along the tether.

KITE. The disturbance isolation aspects of this proposed mission may make it particularly suited to studies of the uncertainties or noise levels that accompany the obtained acceleration fields.

TSS-3. The controlled gravity objectives for this mission would be similar to those for TSS-2, except that improved demonstrations should be expected based on experience with earlier missions.

6.0 TETHER CONSTELLATIONS

Program Planning Group Representative: Georg von Tiesenhausen, NASA-MSFC

Panel Members:

Enrico Lorenzini	Smithsonian Astrophysical Observatory
Franco Bevilacqua	Aeritalia, Italy

Panel Proceedings Summary

The panel divided the constellation concepts into three parts:

(1) Pre-Space Station IOC-Era

(2) IOC-Era

(3) Post-IOC-Era

Pre-IOC-ERA

1. Demo flight for the micro-g/variable-g (space elevator) with a modified TSS system (e.g., adding a down-scaled elevator to the TSS).

2. Shuttle-borne, multi-probe 1-D system for simultaneous data collection (e.g., measurement of spatial geophysical gradients with good time correlation).

IOC-Era

1. Micro-g/Variable-g Lab (space elevator) Space Station-borne

2. Space Station c.o. (orbital center $\simeq$ center of mass) management

3. Space Station-borne multi-probe system.

Post-IOC-Era

All the following applications are supposed to be free-flying systems.

1. Quadrangular 2-D constellations electrodynamically stabilized.

2. Quadrangular 2-D constellations stabilized by differential air drag.

3. Pseudo-elliptical 2-D constallation, electrodynamically stabilized.

4. Centrifuge for low-g application $>10^{-3}$ g.

5. Torquing of a spinning station (or vehicle) for controlling the precession rate of a spin axis.

Conclusions

1-D vertical constellations provide unique capabilities (1st priority)

- 3-mass system (space elevator) can provide variable-g environment from microgravity level to 10^{-2} g.
- More than 3-mass system provides simultaneous data collection at different locations.
- 3-mass system (SS in the middle) for SS orbital center management allows simultaneous micro-g experiments and other tether assisted experiments.

2-D Constellations (2nd priority)

- Stable configurations proposed for providing a separation of functions among physically connected platforms.
- Pseudo-elliptical constellations provide an external 2-D frame for stabilizing light structures (e.g., reflectors, solar sails).

Panel Recommendations

- Improve the fidelity of dynamics models, especially with regards to tether dynamics.
- Tether construction
  - multi-function tether concept to be further developed.
  - tether physical characteristics; effects on the system dynamics.
- Ingenius design of crawling systems.
- Improve the knowledge of micro-g/variable-g requirements.

7.0 TETHERED OPERATIONS ON THE SPACE STATION

Program Planning Group Representative: The entire group.

Panel Members:

Gianfranco Manarini	PSN/CNR, Italy
Georg von Tiesenhausen	MSFC/PS01, USA
Donald L. Jones	Ball Aerospace, USA
Bill Nobles	Martin Marietta, USA
B. Bishof	MBB/ERNO
N. W. Spencer	NASA/GSFC, USA
Pietro Merlina	Aeritalia, Italy
Fernando Grego	Selenia Spazio
Silvio Bergamaschi	Un. Padova, Italy

R. Ciardo	Aeritalia, Italy
Philip Chaneller	DFVLR/Koln-Porz
Dana Andrews	Boeing Aerospace, USA
Guiseppe Moneti	Martin Marietta, USA
Tom Mayfield	Martin Marietta, USA
Filippo Sciarrino	Contraves Italiana
Pietro Gervasini	Laben
Wolfgang Westphal	AEG, Germany
Gerald J. Whitman	American Embassy, Rome, Italy
E. Antonia	Politechnics di Torino, Italy
James Arnold	University of California, USA

Panel Proceedings Summary:

This panel followed a prepared agenda in order to accommodate a great variety of tether operations, their effects on the space station, and their priorities. The agenda covered the following major items in considerable detail.

Tether Applications to Space Station

Space Station Benefits From Tether Applications

Flight Demonstrations

Required Technology Emphasis

Impact on Space Station Configuration and Operation

Space Station Tether Applications Priorities

Future Tether Applications

Panel Recommendations

Proposed IOC Capabilities:

- Tethered Space Station C.G. Vernier (CG Management)
- Electrodynamic Reserve Power
- Electrodynamic Thrust (Drag Make-up)
- Tethered Platform (short mission)
- "Zero G" Laboratory (soft suspension)
- Tethered Elevator (soft suspension)
- Deboosting Small Cargo Modules
- Electrodynamic Tether (Research)
- Multi-Probe (beads on string) (short mission).

Proposed Flight Demonstrations:

- Tether Shape Measurements
- KITE/Scaled-SATP
- Disposable Tether System Verification
- Fluid Transfer Experiments Under Various DC and AC Accelerations
- Experiments Already Made to be Repeated Under Different G-Levels
- Needed: Tether Mediated Rendezvous Demonstration
  - P/L Deployment and Subsequent Retrieval
- Elevator/Crawler Demonstration (Gravity Field Mapping and Perturbation Determinations)
- Verifying and Refining Dynamic Models in Flight Demos
- Attachment/Detachment of Crawler to Tether
  - RMS
  - EVA
- Drive Mechanism for Crawler
  - Electromechanical
  - Electromagnetic
- Variable/Minimum Gravity
  - Accuracy
  - Duration
- Attitude Control
  - Rotation About Tether
  - Stabilization for Instrument Pointing
- Power Generation/Dissipation
- C.G. Location and Maintenance for P/L's and Experiments Attached to Crawler
- Degree of Automation/Robotics
- Internal Suspension System

Required Technology Emphasis:

- Tether Technology
  - Materials and Configurations
  - Maintainability
  - Tension Control
  - Damping Characteristics
  - Environmental Compatibility
- Deployer Technology
  - Motor/Generator
  - Motor/Reel Coupling
- Electrodynamic Technology
  - Plasma Contactors
  - High Voltage Insulation
  - High Voltage Conversion and Control
  - Specific Tether Construction
  - Environmental Compatibility
- Engineering Instrumentation
- Science Instrumentation
- Critical Systems Hardware (Mechanisms, Devices, etc.)

Space Station Tether Applications Priorities:

Criteria:

- IOC Space Station Applicability
- Improved Operational Capability
- Solution to Space Station Problems

Priorities:

- Variable Gravity Laboratory (Controllable)
- Deboosting Small Cargo Modules
- Electrodynamic Reserve Power

- Tether Space Station C.G. Control (Vernier)
- Tethered Orbiter Deboost
- Tethered Remote Docking of Orbiter
- Tethered Science/Applications Platform

8.0 TETHER TECHNOLOGY AND TEST FACILITIES

Program Planning Group Representative: Paul M. Siemers III, NASA-LaRC

Panel Members:

Paul M. Siemers III	NASA-LaRC
Edmondo Turci	Aeritalia
Giovanni Carlomagno	University of Naples
John Anderson	NASA-Headquarters
Piergiovanni Magnani	FIAR SPA, Milano
G. Marone	SIA SPA, Torino
Dun Crouch	Martin Marietta
L. M. Palenzona	ESA-ESTEC
Carlo Boccaato	Augusta SPA, Milano
Vittorio Giavotto	University of Milano
Pete Bainum	Howard University
Virod Modi	University of British Columibia
George Wood	LaRC
John Hoffman	University of Texas, Dallas
Dick Diller	NASA-Headquarters
G. Bianchini	University of Padua

Panel Recommendations:

- STARFAC: Initiate design development testing activity with emphasis on atmospheric/aerothermal instrumentation and high temperature tethers and components. Initiate TSS capability extension studies.
- TSS-2: Define mission; implement design and development of mission to optimize capabilities of present configuration.
- Electrodynamics: Include hollow cathode (plasma contactor) as part of TSS-1 baseline. Initiate advanced development relative to tethers and components.
- Tethers: Establish coordinated program to define requirements and initiate development and test of tether concepts and materials.
- Tether Dynamics: Expand dynamics working group/establish review function to evaluate capabilities and recommend future development.

9.0 SUMMARY

The workshop inputs were generated by about 105 panel members from eight countries: United States, Germany, Italy, Netherlands, Canada, Belgium, England, and France. There were seven panels, one more than in 1983 - the space station panel. A summary of each panel's output is provided in a convenient matrix format. A separate matrix covers the Science and Applications panel.

The first matrix shows project status, technology requirements, major issues, engineering questions, demonstration missions, and panel recommendations.

The Science and Applications matrix concentrates on specific recommendations, development problems, and overall recommendations.

The combined panel recommendations are the basis for NASA's Tether Applications in Space Program Planning Group's future plans and tasks. Each aspect of the recommendations is covered in the 1987 Program Plan.

The high level of the second workshop activities has indicated the great strides made since 1983 and provides confidence for advances in the years to come when the first demonstration flights will take place.

WORKSHOP PANEL SUMMARY APPRAISALS OF TETHER CONCEPTS

CATEGORY / PARAMETERS	ELECTRODYNAMIC INTERACTIONS	TRANSPORTATION	GRAVIT UTILIZATION	CONSTELLATIONS	SPACE STATION TETHER OPERATION	TECHNOLOGY AND TEST
•FEASIBILITY •COST/BENEFIT POT. •OPERAT. POTENT.	DRAG MAKE–UP SYST. KILO/MEGA WATT SY. ULF/ELF ANTENNA	SEDS ORB. LAUNCH S/C SS DEPL. ORB/OTV PLATFORM	TORF VAR. G. MODULE CRAWLER PLATFORM	1–D VERTICAL 3–MASS SYSTEM MULTI–MASS SYSTEM	C. G. VERNIER ELECTROD. POWER & THRUST REENTRY CAPSULE PLATFORM & VAR. G. LAB	STARFAC
•PRINCIPAL TECHNOLOGY REQUIRE–MENTS	CONDUCTORS INSULATORS POWER MGMT. & CTRL. HOLLOW CATHODE	MIN. RECOIL TETHER MULTIPLE REUSE LIGHT W. DEPLOYER	NONE	CRAWLER DEV. SIMULATION MODELS	SEE TECH & TEST SEE TRANSPORT–ATION	INSTRUMENT–ATION MATERIALS DYNAMICS AEROTHERMAL ANAL.
•MAJOR ISSUES	HARDWARE DEF. ENVIR. INTER–ACTIONS DESIGN TRADE–OFFS MODELS & THEORIES	DEBRIS COLLISION SS ORBIT PERT. LTD. SIM. CAP.	POWER SUPPLY PROX. OPS. REMOTE DOCKING G–LEVELS	COMPAT. OF CRAWLER WITH FIBER OPT. LINK	SEE TRANSPORT–ATION	CRAWLER PLATFORM CONTROL TECH. AVAILABILITY
•CRITICAL ENGINEERING QUESTIONS	ENERGY STORAGE HIGH POWER APPL. ULF/ELF INSUFFIC. ENERGY TRANSM. FAC.	OPT. DEPLOYER S. ENERGY MGMT SS IMPACTS	FLUID MOTION TSS–1 RESULTS	POWER TRANSM. COMMUNICATION	SEE TRANSPORT–ATION SEE ELECTRODYN.	ENVIRONMENT–AL EFFECTS ON MEASURE–MENTS
•DEMONSTR–ATION MISSIONS	PROOF OF FUNC–TION HOLLOW CATHODE. TSS–1 MISS. UTILIZ.	SEDS KITE REENTRY CAPS. TETHER SHAPE MEAS	KITE ELEVATOR (TSS–1)	TETHERED CRAWLER MULTIPLE PROBE SYST.	DEPLOYER KITE CRAWLER REENTRY CAPSULE FLUID TRANSFER	TSS–2 ELEVATOR KITE
•RECOMMEN–DATIONS	POWER & THRUST GEN SEE DEMO. MISS. ULF/ELF ANTENNA WARM PLASM TH. SYSTEM DEFIN.	SEDS DEVELOP SIM. PROG. DEV. KITE DEV. PLATFORM DEF. STRATEGY FOR S.S.	LIFE SCIENCE APPL. LONG DUR–ATION EXP ROTATING SY. DEV. MICRO–G REQU.	IMP. MODEL FIDELITY DEV. MULTI–FUNCT. TETH. TETH.CHAR. EFFECTS CRAWLER DESIGN MICRO/VAR–G REQU.	VAR G. LAB REENTRY CAPSULE ELECT POWER/ THRUST C. G. CONTROL PLATFORM ORB/OTV DEPLOY	DYNAMICS PANEL INSTR. & HIGH TEMP COMPONENT STUDIES EVAL OF TSS–1

WORKSHOP PANEL ON SCIENCE AND APPLICATIONS APPRAISAL SUMMARY

SPECIFIC RECOMMENDATIONS		DEVELOPMENT PROBLEMS	OVERALL RECOMMENDATION
TSS–2 EXPERIM.	BELOW 130 km EXP.		
• AMBIENT AND NEUTRAL SPECIES • ELECTRON, ION TEMPERATURE AND ENERGY BALANCE • MAGNETIC AND GRAVITATIONAL FIELD • ELECTRIC FIELD • ELECTROSTATIC AND ELECTROMAGNETIC WAVES • STEREOSCOPE REMOTE SENSING OF THE EARTH'S SURFACE • DYNAMICS OF TETHERS (AND SATELLITES) • "OPEN WIND TUNNEL" EXPERIMENTS AT LOW ALTITUDES	• ATMOSPHERIC TRANSITION FROM DIFFUSIVE SEPARATION TO TURBULENT MIXTURE OF COMPONENTS • ATOMIC OXYGEN TO MOLECULAR OXYGEN • HIGHER ORDER TERMS OF GRAVITY AND MAGNETIC FIELDS	• SHOCK WAVES GENERATED BY A VEHICLE DISTURB THE AMBIENT ATMOSPHERE • CONVENTIONAL INSTRUMENTS MAY NOT WORK (FOR EXAMPLE, MASS SPECTROMETERS) • MEASUREMENT (TSS) TO BE AN AERODYNAMIC BODY NEW TECHNIQUES TO BE DEVELOPED (RESONANCE AND LASER FLUORESCENCE, ETC.)	• IMPROVE THE EMC/EMI PROPERTIES OF TETHERED SATELLITES OR PLATFORMS • IMPROVE THEIR DC MAGNETIC CLEANLINESS • COMPLEMENT THE PAYLOAD WITH SENSITIVE, LOW–POWER DYNAMICAL PACKAGES (ACCELEROMETER, TENSIOMETERS, ETC.) • STIMULATE CLOSE COOPERATION BETWEEN DYNAMICISTS AND AERONOMISTS TO GET RELIABLE DYNAMICS AND ATMOSPHERIC MODELS

10.0 REFERENCES

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APPROVAL

APPLICATIONS OF TETHERS IN SPACE
– A REVIEW OF WORKSHOP RECOMMENDATIONS –

By Georg von Tiesenhausen, Editor

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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