

Unique Results and Lessons Learned From the TSS Missions

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The Tethered Satellite System (TSS) Space Shuttle missions, TSS-1 in 1993 and TSS-1R in 1996, were the height of space tether technology development in the U.S. Altogether, the investment made by NASA and the Italian Space Agency (ASI) over the thirteen-year period of the TSS Program totaled approximately \$400M—exclusive of the two Space Shuttle flights provided by NASA. Since those two pioneering missions, there have been several smaller tether flight experiments, but interest in this promising technology has waned within NASA as well as the DOD agencies. This is curious in view of the unique capabilities of space tether systems and the fact that they have been flight validated in earth orbit and shown to perform better than the preflight dynamic or electrodynamic theoretical predictions. While it is true that the TSS-1 and TSS-1R missions experienced technical difficulties, the causes of these early developmental problems are now known to have been engineering design flaws, material selection, and procedural issues that (1) are unrelated to the basic viability of space tether technology, and (2) can be readily corrected. The purpose of this paper is to review the dynamic and electrodynamic fundamentals of space tethers and the unique capabilities they afford (that are enabling to certain types of space missions); to elucidate the nature, cause, and solution of the early developmental problems; and to provide an update on progress made in development of the technology.

I. Background

SPACE tether systems can be classified as three types: dynamic, electrodynamic, and electrostatic. All types require dynamic stabilization, which can be achieved by gravity-gradient near a planet (in which case the tether is deployed in a vertical orientation) or by spin stabilization, which does not require a gravitational field or any particular orientation. Each type of tether system provides unique capabilities that have important potential applications in space.

A. Basic Concepts

A dynamic, gravity-gradient stabilized tethered system consists of two end-bodies connected by a tether. The end-bodies may be two satellites of equal mass, or one may be much more massive, as in the case of the Space Shuttle deploying the much smaller Tethered Satellite System (TSS) satellite. (The same system could also be spin stabilized.) For a gravity-gradient stabilized system, tether length can be anywhere from the order of 100m to the order of 100 km. Maximum length is ultimately limited by the tension created in the tether (which is proportional to length) and tensile strength of the tether.

Electrodynamic tethered systems include all of the characteristics of a dynamic system with the additional provision that the tether contains a conductor and the end-bodies provide the capability of collecting and emitting electrons—or, put another way, they are capable of establishing electrical contact between the ends of the tether and a conducting environmental space plasma. (Alternatively, the tether can be an uninsulated conductor so that electrons can be collected on its surface—augmenting or even replacing the electrical contact of the positive end body.) The orbital motion, \mathbf{V}_{orb} , of a conducting tether of length, $\mathbf{L}_{\text{tether}}$, moving through the geomagnetic field, \mathbf{B}_{geo} , creates an EMF, given by

$$\phi = q(\mathbf{V}_{\text{orb}} \times \mathbf{B}_{\text{geo}}) \cdot \mathbf{L}_{\text{tether}}$$

The motional EMF biases the upper end of the tether positive and the lower, negative. The capability to collect and emit electrons allows an electrical current to be driven through the tether and closed through the ionosphere, shown by the TSS functional schematic in Fig. 1. The end-bodies are typically designed to maximize current flow. The system can operate in either the generator mode (in which the motional EMF drives the current and orbital energy is converted directly to electrical power) or in the motor mode (in which a high-voltage power supply, typically operating on solar energy, drives the current in the opposite direction, creating a velocity-aligned thrust).

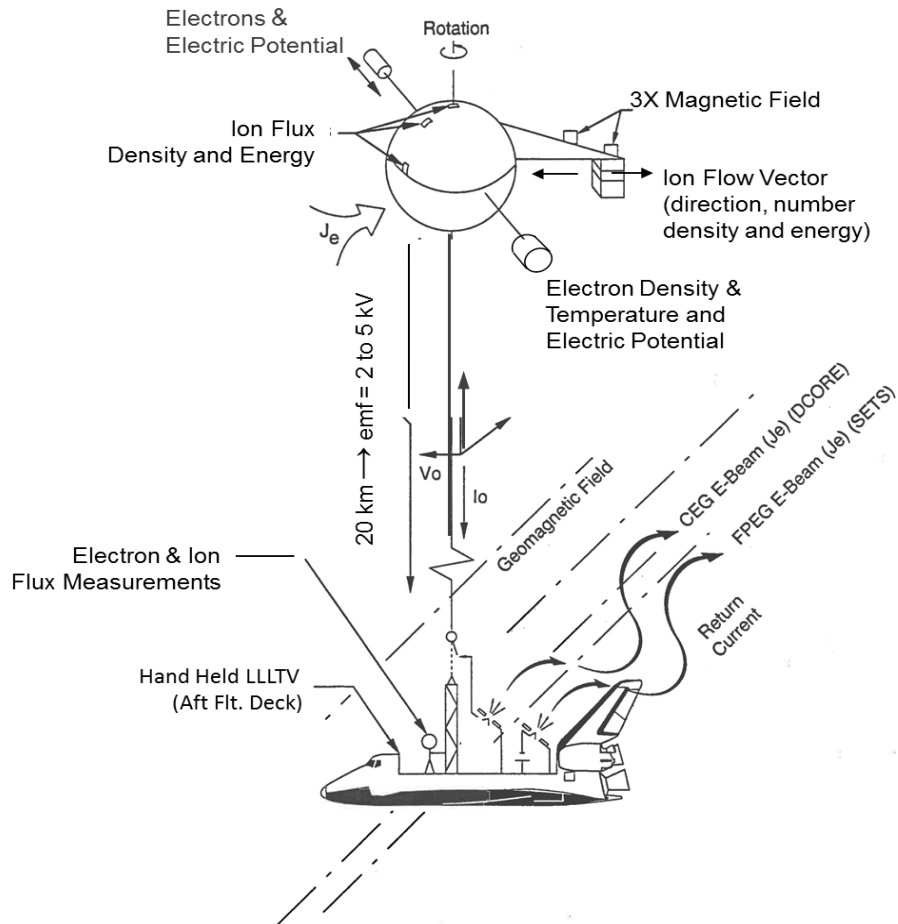


Figure 1. Functional Schematic of the TSS Electrodynamic Tether System¹.

The electrostatic tether system is similar to the electrodynamic system in that the tether includes a conductor and some charge control is required. The difference is that operations are designed to maintain a particular value of electric potential on the tether rather than to generate a current—which the system is designed to minimize.

B. Inception and Early Development

A fanciful concept of a gravity-gradient stabilized “space tether elevator” dates back to the 1960’s.² However, in the 1970’s, the dynamics of space tethers was developed by Prof. Giuseppe Colombo of the University of Padova, Italy³, while the fundamental electrodynamic was investigated by Dr. Mario Grossi, of the Harvard-Smithsonian Center.⁴ The work of Prof. Colombo and Dr. Grossi placed the concept of space tethers on a firm engineering footing and showed it to be a technically viable concept.

In 1980, the Tethered Satellite System Facility Requirements Definition Team, a science advisory team for the NASA Office of Space Science, recommended that NASA develop a Space Shuttle-based tether deployment system or Tethered Satellite System (TSS).⁵ The team was convinced that a space tether system could (1) enable a new class of active space experiments; (2) permit the scientific investigation of previously inaccessible regions of space; and (3) provide new engineering capabilities. Example applications from the report of the TSS Facility Requirements Definition Team are listed in Table 1. The scientific and technological potential of space tether systems, in which either solar-electric energy or orbital kinetic energy can be coupled to the planetary rotational motion via the geomagnetic field was viewed as unique and extensive. Expectations ran high for the future of the technology and the advances it could afford in our ability to explore and exploit space.

In 1983, NASA entered into a bi-national program with the Italian space agency, ASI, to develop a TSS system designed to be carried on the Space Shuttle. NASA would develop the tether and tether deployer system and ASI would develop a satellite that was specifically designed for deployment on an electrodynamic, gravity-gradient-stabilized tether (Fig. 2).

Table 1. Science and Technological Applications of the TSS⁵

<p>Science Applications</p> <ul style="list-style-type: none">- Direct observation of magnetospheric-ionospheric-atmospheric coupling processes in the 125-150 km region of the lower thermosphere- The in situ generation and study of large-amplitude hydromagnetic waves and magnetic field-aligned currents in space plasma—allowing simulation of celestial body electrodynamics including induced field-aligned currents and rf production in the Jovian magnetosphere.- The generation of high-power VLF and ELF electromagnetic waves within the ionosphere-magnetospheric system- New, global observation and mapping of crustal geomagnetic phenomena- The observation of important atmospheric processes occurring within the lower thermosphere <p>Technology Applications</p> <ul style="list-style-type: none">- The investigation of hypersonic, transition flow aerodynamics- Controlled investigation of spacecraft-space plasma environmental dynamics- Long-wire antennas coupling with the ionospheric plasma- Electrical Power Generation- Propellantless Propulsion Generation
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Eleven science teams from the US and Italy were jointly selected on a competitive basis by the two agencies to develop a suite of flight instruments to measure the electrical characteristics of the TSS and its local interaction with the magnetized ionospheric plasma; to observe the generation and propagation of various wave modes with remote, ground-based measurements; and to theoretically model the electrodynamic tether's behavior. In addition, a team from ASI would develop core equipment required for electrodynamic operations. This included a high-current electron gun that was designed to emit electrons collected at the satellite back into the ionosphere at the Orbiter (Fig. 1).

II. What Have We Learned?

Prior to the TSS missions, there were at least three “truths” involved in the TSS system design and operation that were held as common knowledge. Despite their general acceptance, all three were shown to be incorrect by the TSS results—as discussed below.

A. Tether Dynamics

The TSS system was completed and first flown on the STS-46 flight of the Space Shuttle that was launched on July 1992 into a 300-km circular orbit at 28.5° inclination. During what was designated the TSS-1 mission, the shuttle-tether-satellite system was configured for electrodynamic operations (Fig. 1) and the profile for the planned deployment to 20 km would result in some 30 hours of deployed operations, including 15.5 hours on station at various deployment lengths for science experiments. Unfortunately, the mission was terminated shortly after TSS operations began, with the satellite deployed only 268 m, because the tether reel jammed (discussed in a later section).

Despite the shortened deployment, this mission was ground-breaking in that it was the first attempt to place a gravity-gradient stabilized tether system in orbit and any data obtained would, by definition, be unique. In fact, the results

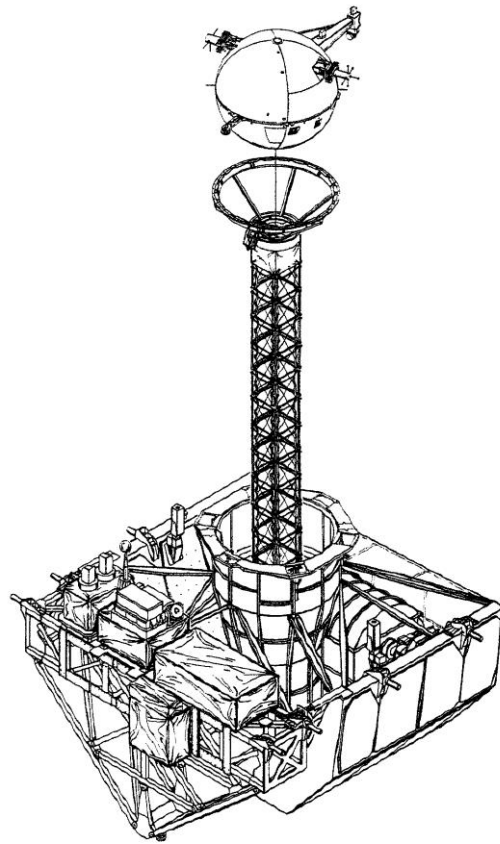


Figure 2 Isometric drawing of the TSS.⁶

obtained were highly significant. The challenges for tether dynamics occur in early deployment and late retrieval when the tether is short and tether tension is very low. As a result, the most critical, fundamental tether dynamic questions were exercised—and far more severely than would have been allowed under planned operations.

To appreciate the significance of the TSS-1 results, it is necessary to review the pre-mission understanding of tether dynamics as predicted by the best existing dynamic models. These models, which were developed independently at several different institutions, agreed on two basic and well-founded limitations.

- (1) *The gravity-gradient induced tension in the tether was predicted to be insufficient to stabilize the tether-satellite system until deployment had reached a minimum distance of 1 km.*
- (2) *Because the dynamic control law was based on feed-back from a positive tether tension measurement, if the tether ever became slack (so that the tension measurement went to zero) it would be impossible to regain control and the satellite would have to be jettisoned.*

The as-flown deployment profile, given in Panel 2 of Fig. 3, shows that the satellite was deployed only 268 m (including the 8-m boom) at which point the deployer jammed. Moreover, the jam created an impulsive jerk, violated the flight rules for deployment, and exposed the system to an extremely severe dynamic upset. The satellite was thrown into violent yaw gyrations and bounced many meters so that the tether became slack—violating the most fundamental conditions of the dynamic control law. Clearly, according to the pre-mission understanding of tether dynamics, recovery would be impossible and the satellite and tether would have to be jettisoned.

Yet, as shown by the flight data in Fig. 3, within minutes, the system stabilized in a vertical orientation with the tether taught and straight and the satellite almost motionless. Notice that the satellite-mounted magnetometer x, y, and z-axis measurements shown in Panel-1 suddenly transition from straight lines to $\pm 45^\circ$ oscillations at the instant of the jam (1992/218/01:57) and back to almost straight lines within a period of 5 minutes (02:02). (The gyrations at 01:48 resulted from slack tether which developed when the tether was reeled out too fast at the initiation of deployment.) Additionally, the tether tension was observed to have spiked suddenly when the jam occurred, followed by alternating periods of tension and slack (zero tension) as the satellite bounced multiple times, and then transitioned to a steady tension approximately equal to the initial pre-jam value. Again, the event damped within five minutes, leaving the satellite-tether system rock-solid, as shown in the photograph of Fig. 4, which was taken after the event. The damping of this event was the result of the combined action of the satellite attitude control system, the Shuttle ACS thrusters, and the natural dynamic damping of the tether system.

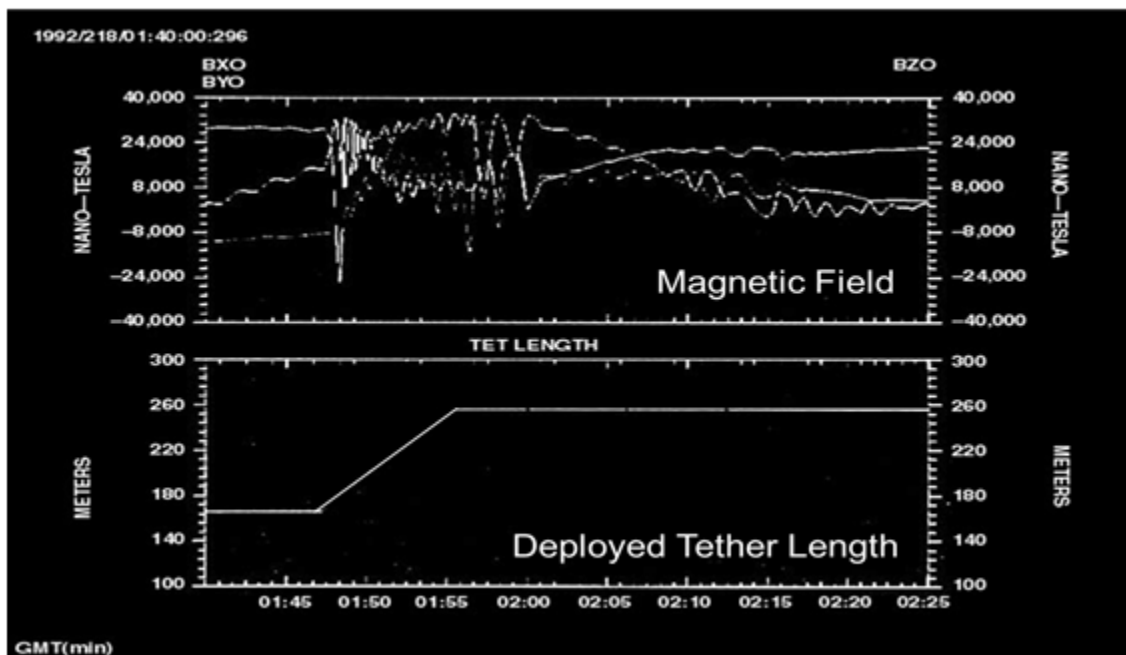


Figure 3. TSS-1 Magnetometer and Tether Length Data. Note disturbances to attitude at the sudden deployment start and stop (~ 1:47 and ~1:56)

Long deployment and system control were subsequently demonstrated by the TSS-1R and the Small Expendable Deployer System (SEDS) missions. During TSS-1R, the 500 kg satellite was stably deployed to a length of 19.7 km with no dynamic issues. During the SEDS-1 mission, which was intended only to validate long deployment, a small payload was deployed downward 20 km and the tether cut as it swung down through the vertical. SEDS-1 was totally successful. The goal of SEDS-2 was to demonstrate stabilization of the system following deployment. (Orbital mechanics causes the lower tethered body to move ahead of the upper body during deployment.) The payload was deployed downward 20 km and stabilized by a pre-programmed control law for the tether deployment rate. The goal of the mission was accomplished successfully. However, four days after deployment, the tether broke (discussed in a later section).

In the most fundamental sense, these missions have shown that long tethered systems are both feasible and far more stable and easily controlled than could have been expected pre-mission on any theoretical grounds. Moreover, it proved tethers to be safe—even under extreme dynamic upsets at short deployments. *It is significant that, after the TSS-1 event, and with the satellite still tethered only 268 m from the Space Shuttle, the crew turned in and went to sleep for eight hours.*



Figure 4. Restabilization of the TSS-1 Satellite. Credit: NASA

B. Tether Electrodynamic

Three and a half years after the TSS-1 mission, the TSS was re-flown under the mission designation, TSS-1R. The reflight was launched into a similar orbit with the same hardware and experiments and with the same planned deployment profile as TSS-1, and was, again, configured for electrodynamic operations. Deployment proceeded nominally for approximately five hours and reached a distance of 19.7 km. At this point, the tether suddenly broke. Again, the mission was terminated early—again, the result of an engineering design flaw (discussed in the following section).

First and foremost, the long deployment provided the first opportunity for high-voltage electrodynamic operations. The TSS-1R mission validated the performance of an electrodynamic tether in space—including the generation of a significant level of current as orbital kinetic energy was directly converted to electrical power. Although none of the planned science experiments were conducted, almost five hours of “calibration” operations were obtained over a wide range of electrodynamic conditions. In addition, the tether-break event, itself, provided a significant experimental opportunity that would not have occurred under the pre-planned set of investigations. The resulting observations were unique and ranged from surprising to totally unexpected.^{1,7-11}

Perhaps the most fundamental finding from the TSS-1R mission was that the most trusted theoretical current collection model in use, the Parker-Murphy (PM) model, does not include the full range of physical process by which an electrically biased ionospheric satellite interacts with its space plasma environment. In 1967 Parker and Murphy¹² modified the 1923 Langmuir-Blodgett model¹³ (which described current collection in stationary unmagnetized laboratory plasma) to account for the fact that the ionosphere has an embedded magnetic field that

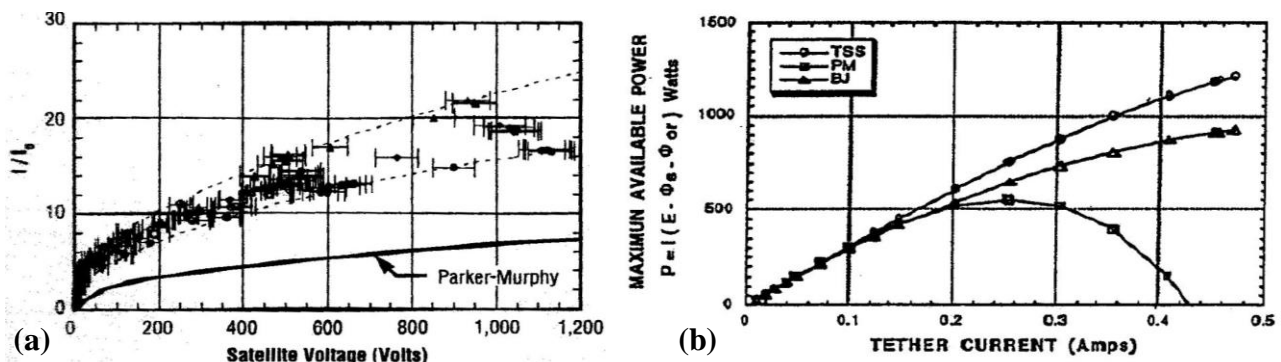


Figure 5. Comparison of the TSS-1R Data with Models.⁹ Comparison of measured (a) current with the predictions of Parker-Murphy; and (b) usable power with the predictions of Beard-Johnson and Parker-Murphy.

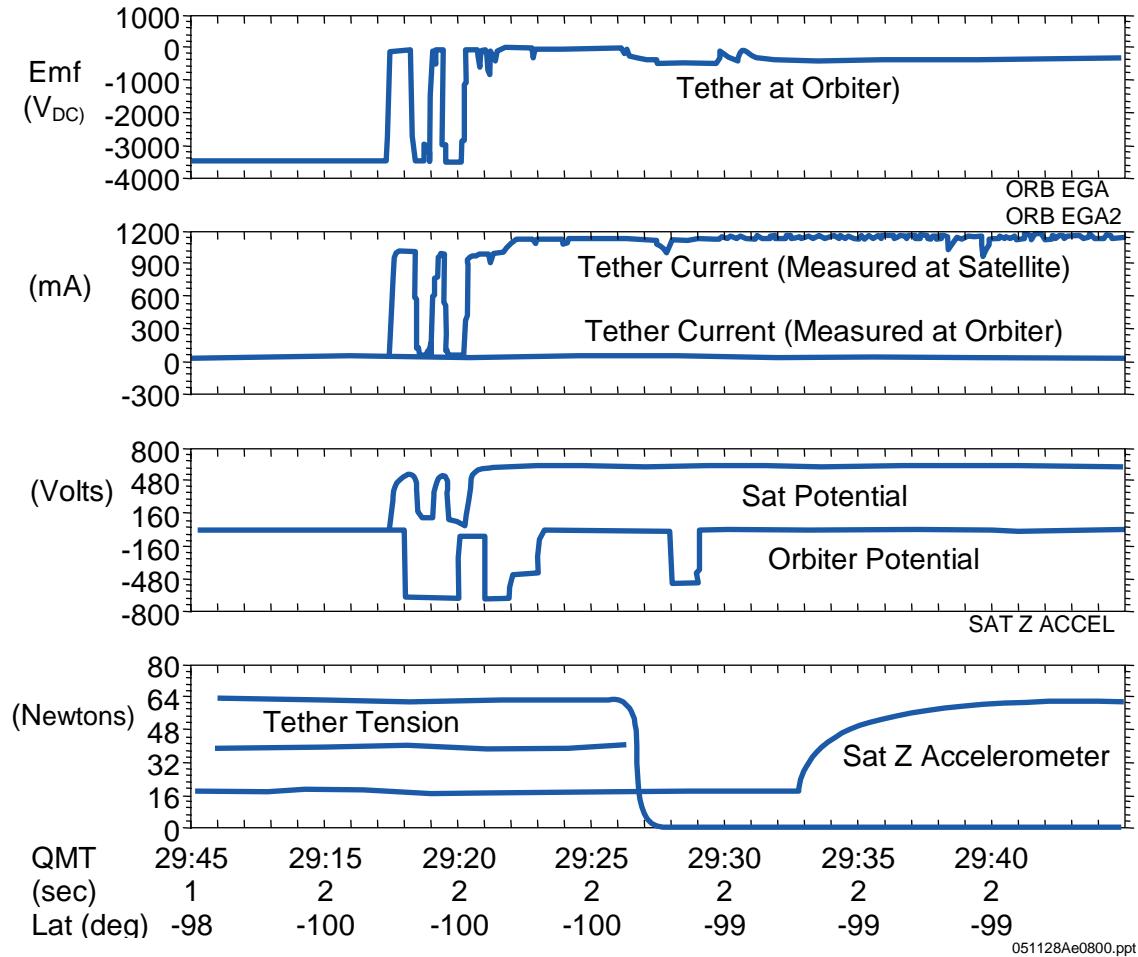


Figure 6. TSS-IR Mission Data.¹⁴ Data recorded at time: 1996/057/01:29:09:997.18.

restricts cross-field electron mobility, limiting current collection approximately to a flux tube. The PM model had been validated by rocket-borne measurements and used for more than thirty years to predict electrical behavior of satellites in ionospheric and magnetospheric environments. It was, therefore, confidently used to predict the current expected to be collected by the electrically biased TSS satellite. However, as soon as electrodynamic operations began, it became obvious that serious differences existed between the PM model and the measured results,^{1, 9-10, 15} as shown in Fig. 5a. Moreover, the measured current and usable power generated were higher at any given bias potential than the unrestricted, electrostatic Beard-Johnson model, which should have given the maximum possible current (Fig. 5b).

During nominal preplanned operations, the current was deliberately limited to 500 mA. However, during the tether-break event, the current controller was circumvented. The electrical discharge initially shorted the tether directly to Orbiter ground and, following the tether break, the bare end of the tether made direct contact with the ionosphere. In both configurations, a maximum current of 1.1 Amps was generated at 3400 volts (as shown in Panels 1 and 2 of Fig. 6)—producing approximately 3.5 kW of electrical power.⁷ It was not the purpose of TSS-1R to generate large amounts of power and the system was not optimized for this purpose. Still, this is a very respectable level for space power systems. Clearly, TSS-1R operations validated the concept of closing the tether circuit through the conducting ionosphere, which allowed the current in the tether to interact with the geomagnetic field, independent of the return current, and generate a net EMF. Moreover, the ability of the conducting ionospheric medium to conduct significant levels of current was demonstrated. In fact, the ionospheric saturation level was never reached.

Finally, it can be argued that the generation of a propulsive force was indirectly validated, based on the fact that the only difference in generating power and thrust is the direction of current flow in the tether. In the “motor” mode, a power supply must be added to reverse the polarity of the tether circuit. However, all other processes are exactly

equivalent. In fact, power generation produces a drag force (directed in opposition to the orbital velocity vector) of an equivalent magnitude to the propulsive mode force any given current. *The TSS-1R results directly validate the electrodynamic generation of electrical power (at the expense of orbital kinetic energy) and, indirectly, the production of a propulsive, velocity-aligned force in the motor mode.*

Moreover, the Plasma Motor Generator (PMG) experiment,¹⁶ a secondary Space Shuttle payload, directly demonstrated the bi-polar operation of an electrodynamic tether. The PMG configuration included a 500 m conducting tether with a hollow cathode plasma generator at each end. The current generated was small—in the range of 300 mA—but polarity was successfully reversed by a power supply and the current made to flow in the opposite direction—*directly the demonstrating the propulsive “motor” mode circuit.*

III. What Went Wrong?

The common knowledge today is that space tethers do not work, that they are complex, and they have fundamental faults. This perception is based on three anomalous events—three.

One is reminded of a story about Thomas Edison. On the grounds of his winter home in Ft. Myers, Florida are dozens of varieties of bamboo. Mr. Edison had studied the characteristics of bamboo fibers as he searched for a suitable filament for his light bulb. A reporter was interviewing him one day and, noting the bamboo, he commented, “Mr. Edison, it is reported that you have tried more than three hundred materials for you electric light—without success. Are you not becoming discouraged?” Thomas Edison is reported to have replied, “Not at all. I have now learned three hundred things that will not work.” The great inventor discarded the failed materials, which opened up new possibilities, and pressed on—never losing sight of the goal of an electric light.

The present characterization of space tethers based on three anomalous events is not an accurate assessment of the technology. This is not to suggest that this assessment must wait until three hundred failures have been endured—but three? And those three not even proper failures? As discussed above, tethers have been clearly shown to work. Now, to show that they are not fundamentally flawed, we will analyze the three anomalous events and the issues they raise.

A. The TSS-1 Tether Reel Jam

The Deployer, developed by Martin Marietta Astronautics Group (MMA) under the direction of the TSS Project Office at NASA-Marshall Space Flight Center, was a reel-type capable of both deployment and retrieval (Fig.2). The Deployer was complex and massive because it was a “facility” class device for multiple missions designed to accommodate a 500-kg satellite and had a reel sized to handle either 20 km of conducting tether or up to 100 km of non-conducting tether. Fundamentally, the design was sound. However, two months before launch and after delivery and integration into the STS payload, the Shuttle landing load margins were increased—significantly. As a result, the TSS Deployer system had to be either stiffened or removed from the mission.

Faced with a probable two-year slip and possible cancellation of the program if TSS were removed, the Project Management at Marshall decided to stiffen the Deployer. This was accomplished by adding an adjustable shim, or wedge. A wedge design was developed by MMA and approved by the TSS Project but, unfortunately, at the recommendation of the STS Safety Office, an alternate design that had not been approved was actually mounted and flown. The Deployer included a level-wind mechanism that was intended to prevent tether pile-up during retrieval—similar to that on a casting type fishing reel. The wedge was adjusted with a ¼-inch screw that was, later, found to intrude ¾-inch into the envelop-of-motion of the level-wind. As a result, during the TSS-1 flight, after deploying the 268 m of tether on the first layer of windings, the level-wind moved to the position of the wedge and jammed against the adjustment screw—terminating deployment with a sudden jolt.

Fault Resolution: This situation could easily have been avoided by (1) applying the standard engineering practice of checking for any intrusions into envelopes of motion of the deployer mechanisms by the added hardware; and (2) better communication among the two NASA centers and the prime contractor. *It should be noted that the deployer jam had nothing to do with the viability of space tether technology itself. Moreover, this problem was resolved before the launch of TSS-1R.*

B. The TSS-1R Tether-Break Event

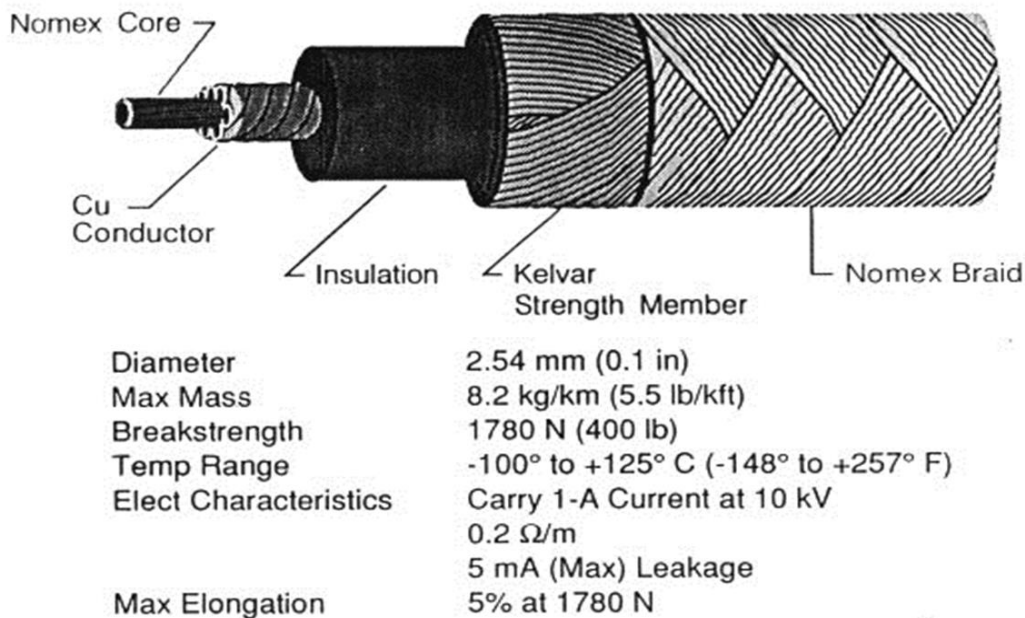
The tether-break event of the TSS-1R mission occurred about five hours into deployment during a day pass, approximately three minutes before local sunset, as the satellite approached within 300 m of the planned maximum deployment distance of 20 km. Operations at the time were three minutes into the sixth step of an IV24 Ops Cycle (defined in Dobrowolny and Stone¹). This step is passive, so that there had been no current flow in the tether for approximately three minutes prior to the break. As a result, the tether was grounded to the ionosphere at the upper end

by the satellite, shifting the full motion-generated tether EMF of 3400 volts to the bottom of the tether. The TSS configuration and parameters during the break event can be seen in Figs. 1 and 2 in Stone and Bonifazi.¹ The TSS-1R Mission Failure Investigation Board¹⁷ found, from Post-flight analysis and testing, that *the tether break resulted from an electrical discharge that ignited between a flaw in the insulation around the high-voltage tether conductor and the deployer hardware that was grounded to the Orbiter. The discharge generated sufficient heat to melt the tether.*

To better understand the nature of this problem, we first consider the construction of the tether and the design of the tether-control boxes on the deployer—both of which were flawed. As the tether came off of the reel, it passed over a series of pulleys contained in the Lower Tether Control Mechanism (LTCM). The LTCM box was vented according to the STS requirements (concerned only with stress release and mechanical integrity of the box) but did not meet venting requirements for high-voltage when exposed to an external vacuum. As a result, the residual gas pressure within the LTCM, coupled with the small separation of the tether from grounded components of the tether control system, resulted in almost ideal conditions for igniting an electrical discharge—as determined by the Paschen curve.

The tether consisted of five layers. At the center was a core of Nomex fibers. Around this were wrapped ten strands of 34 AWG copper wire. The core with the wrapped copper wires was then insulated by an FEP Teflon jacket. The Teflon jacket was surrounded by the strength member, a layer of braided Kevlar 29. Finally, an outer layer of braided Nomex was added to mitigate the corrosive effects of atomic oxygen. This construction is shown in Fig. 7. Pertinent to the discharge problem are the facts that: (1) the inner core of Nomex was highly porous—something like a cigarette filter, and (2) the FEP Teflon insulating jacket was an unbroken, air-tight sleeve. As a result of its porous core, the air-tight insulating jacket, and the fact that this complex coaxial system was assembled under ambient atmospheric conditions, a large volume of air at 1 Atm pressure was trapped within the 21-km long tether. Any flaw or puncture of the Teflon jacket, once uncovered by the deployment action and exposed to the high-vacuum environment of space, would allow the trapped gas to rapidly escape.

After extensive analysis of the available flight data and tether fabrication techniques, methods, and conditions, the TSS-1R Failure Analysis Board concluded that the flaw in the insulation was probably the result of debris included in the Kevlar braid which, under pressure of outer windings on the reel, would have punctured the Teflon jacket. This conclusion was supported by numerous examples of trapped debris in samples taken from the tether remaining on the reel after the mission. The Failure Investigation Board found, “...sufficient evidence from test and analysis to establish foreign object penetration, or damage to the FEP insulation layer in manufacturing or handling, as the probable cause of the breach of the insulation layer.”¹⁷ Moreover, Teflon is known to cold-flow



7. TSS Electrodynamic Tether Construction. The inner core of Nomex is very porous. The Nomex core and copper wire strands are sealed in an air-tight Teflon insulating sleeve. The outer layers are braided Kevlar for strength and braided Nomex for atomic oxygen resistance. Credit: Martin Marietta

over time so that, over the period of three and a half years that the tether remained on the reel between the TSS-1 and TSS-1R missions, even a slight pressure between windings would have been sufficient to press any included debris into the Teflon jacket.

Fault Resolution The tether-break failure could have been prevented simply by (1) the use of proper clean-room assembly practice for flight hardware by the tether manufacturer, which would have eliminated any debris; (2) the use of good high voltage and high vacuum engineering practice—for example, avoiding trapped gasses in the tether by the use of individually insulated conductors where the insulation is bonded directly to the wire, and proper venting and spacing of high-voltage elements from ground points in the tether control boxes; and (3) the use of an insulation material that does not have the cold-flow characteristics of Teflon.

Again, it should be noted that the tether-break had nothing to do with the viability of space tether technology, itself, but everything to do with good engineering practice. In fact, the Failure Investigation Board concluded, “...the tether failure is not indicative of any fundamental problem in using electrodynamic tethers...”¹⁷

C. The SEDS-2 “Micrometeoroid Problem”

Although it successfully met its mission objectives, the fact that the tether broke during the SEDS-2 mission raised a concern that has haunted tether technology since. Even the question as to why the SEDS tether broke is unresolved. At first, it was *assumed* that it was severed by a micrometeorite or by space debris—and this is still believed by some. However, subsequent testing showed that the Spectra material, from which the very thin tether was fabricated, is highly subject to erosion by atomic oxygen and that the strength of a tether of the diameter used (comparable to dental floss) would have been greatly compromised within four days—so that a break due atomic oxygen erosion should have been expected. Whatever the case, however, the sensitivity to a possible tether-break event and the potential deleterious effects of such a failure had been raised and remain a concern.

Fault Resolution Assuming, as the test data suggest, that the Spectra tether was eroded by atomic oxygen to the point that it broke under tension, the problem can be avoided by selection of a tether material that is resistant to atomic oxygen. It should also be noted that this is only a problem for low-altitude orbits. At higher altitudes, the density of atomic oxygen falls off so that the flux is reduced to a level that no longer presents a credible problem. The micrometeoroid concern can be mitigated by tether design, as discussed later.

D. A Change in the NASA “Culture”

The final reason for the diminished interest in space tether technology is related to the loss of the two Space Shuttles and their crews, which greatly affected the culture at NASA. It has fundamentally changed from the days of the agencies’ inception when, in the “old” NASA, it was acceptable to take reasonable risks in order to advance technology and explore the new space frontier.

Faced with the first major set-back of the Space Shuttle era, the “new” NASA failed to embrace risk and withdrew into a three-year hiatus in which no Shuttle was launched. With the loss of the Shuttle came the loss of any willingness to take risks. There was an aversion, not only to any risk of human safety, but even to the risk of not achieving goals that is inherent to all experimentation. The reaction was ironic in that, although the cause of neither Shuttle accident had anything to do with the payloads, the increased restrictions, more demanding validation, and unreasonable levels of documentation imposed on Shuttle payloads increased costs by factors of twenty or more. Experiments, accordingly, became too costly to fail and in the attempt to avoid failure, were made even more expensive. It is the authors experience that, ironically, these new regulations, documentation, and endless reviews added little if anything to the probability of success achievable under the old system. To the contrary, they interfered with real functional and environmental testing required to uncover problems and achieve a proper validation.

Hence, the TSS, which had begun under the old culture, now had to contend with the sensitivities of the new. It was the heightened sensitivity for safety that resulted in the addition of the “stiffing wedge” that ultimately caused the TSS-1 deployer to fail and the three-year hiatus in Shuttle launches exacerbated the conditions that led to the tether-severing electrical discharge on TSS-1R—this in two respects. First, the imposed three-year extension of the program greatly increased its total costs in order to maintain the required technical army—which led to the cost-driven decision not to purchase a new tether for the reflight mission. Secondly, given that the TSS-1 tether was going to be used, the three-year storage enabled cold flow of the Teflon sleeve that likely resulted in the compromised tether insulation.

In addition, ProSEDS, the only reasonably funded and instrumented tether mission planned since the TSS program, was canceled after being integrated for launch because of a hypothetical risk to the International Space Station that would have required multiple failures of the ProSEDS system, including a broken tether, combined with a series of very special circumstances regarding the location, altitude and state of the ISS.

In the post Columbia environment the *perception* of failure associated with the TSS missions was deemed unacceptable and, subsequently, there has been no real funding or serious interest in major tether missions. Despite this, however, there have been several smaller missions that tested aspects of tether technology and several concepts have been developed up through the level of laboratory simulation testing and modeling. These advances have, technically, moved space tethers beyond the initial developmental glitches.

IV. Are the Problems Resolved?

What progress has been made toward resolving the developmental technical issues that arose in the initial tether missions and what issues, if any, remain open and require further work before space tethers can be considered a viable addition to space technology?

A. TiPS—A Decade on Orbit

The SEDS-2 tether break uncovered the only real fundamental problem for tether technology—the potential effect of micrometeoroids on tether life expectancy. Though small in diameter, tethers are long and have a sizable total area. Micrometeoroid flux models, therefore, present a rather negative picture of the viability of tethers. While impact probabilities are relatively straight-forward, the assessment of probable damage is not. Moreover, the Naval Research Office (NRO) Tether Physics and Survivability (TiPS) mission suggests a different view.

The TiPS experiment used a 4-km long, non-conducting tether with two small end-bodies of similar mass¹⁸ It was launched into a 1000-km, high-inclination orbit and *remained there, intact, for more than a decade*. The tether was of a braided tubular design with its center filled with a compressible “yarn” that would expand the tube to its full diameter (~2 mm) once deployed. This represents a significant increase in diameter over that of the SEDS tethers.

The purpose of the TiPS mission was to investigate tether dynamics. But the primary contribution of interest here is that its longevity calls into question the micrometeorite impact models used to predict tether lifetime on orbit—the same models that have called into question the fundamental practicality of tethered systems. The increased tether diameter resulted in a longer predicted life on orbit, but TiPS far exceeded even this longer prediction. The “micrometeoroid problem” has received much attention and other technological solutions have been developed—but not to the level of flight validation. The survival of TiPS, however, presents more than ten years of on-orbit experience that remains an enigma and suggests that tethers may, in fact, be more robust than the models predict.

B. Other Technical Developments

1. Impact-Resistant Tether Designs

The TiPS expandable tubular tether represents the first attempt to remedy the micrometeoroid impact problem—and it appears to have accomplished this goal. However, a second approach has also been developed that may provide even longer on orbit lifetimes. The Hoyt multi-string tether, shown in Fig. 8, uses multiple, smaller diameter tethers that are interconnected by cross-hatching that spreads out once deployed.¹⁹ The multi-string design has obvious advantages. However, this robustness is further enhanced by the cross hatching. If a string is severed at some point, both the tension and electrical current carried by that string will be detoured into adjacent strings by the cross hatching. This design is not flight validated, but the rather straight-forward calculations suggest it increases tether life on the order of 90 percent.

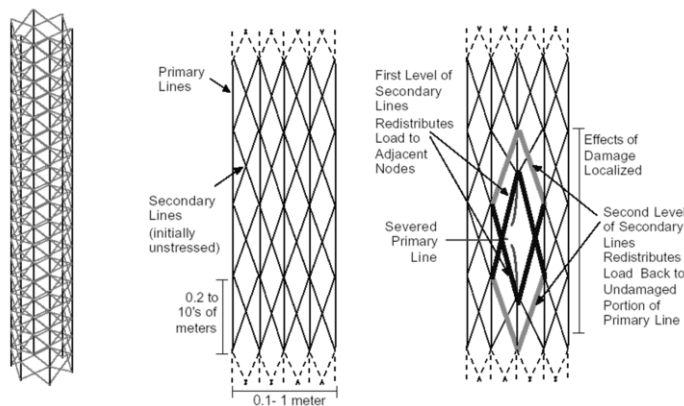


Figure 8. Hoyt Multi-String Tether Design.²¹

2. Enhance Plasma Contactor Techniques

One potential limitation of the TSS involved the limited current capacity of the *designed* contact between the Shuttle and the conducting ionospheric plasma, as well as the high level of input power required by the electron gun. Two approaches to enhancing contact capacity have been developed. A solid expellant plasma generator (SOLEX), shown in Fig. 9, was inspired by the TSS-1R tether break event in which a self-sustaining electrical discharge at the end of the broken tether carried more than an amp of current.^{20,21} SOLEX uses a solid expellant (as opposed the use of a gas in state-of-the-art devices) which allows large amounts of expellant to be contained in a small volume without pressure vessels, valves, plumbing or heaters (Fig. 9 insert). Moreover, SOLEX has been shown to be capable of conducting upwards of ten amps of current, and can operate directly on the un-regulated high-voltage power generated by an electrodynamic tether.²¹

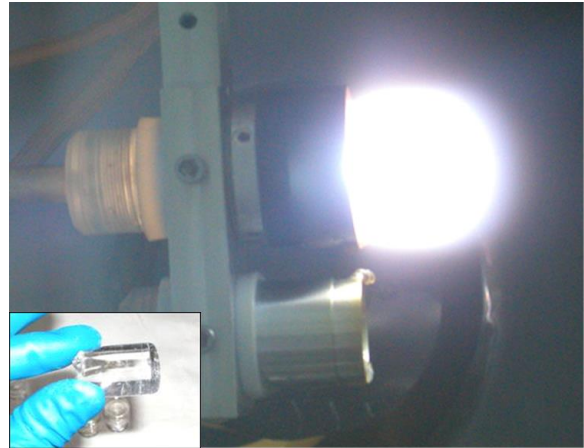


Figure 9. SOLEX Plasma Contactor. Operating at 1.8-amp discharge current level.²¹

The second approach to increasing contact current capacity uses a grid-sphere electrode (based on the 1960-era Eco satellite technology²²). The grid design minimizes the area for dynamic drag while providing a large effective electrode area for electron collection as a result of the electric field in the sheath that extends out around the wires of the grid.²³

3. Electrostatic Tether Applications

Whereas electrodynamic tethers require a significant magnetic field and operations are therefore restricted to the volume of planetary magnetospheres, electrostatic tethers have extended tether applications into interplanetary space. The electrostatic tether does not depend on current flow in the tether to develop an EMF. Rather, it maintains the tether at a sufficient voltage to repel and deflect solar wind protons. The resulting momentum transfer from the solar wind (which moves radially away from the Sun at speeds of 300-700 km/s) to the tether develops a small propulsive force that can, over a period of months, accelerate an attached space probe to extremely high speeds without the use of a propellant. This can significantly reduce the initial mass that must be placed in Earth orbit for deep-space missions.

V. What is the Future of Space Tethers?

The good news for space tethers is that there appears to be no technical reason not to press forward. It has been shown that (1) all problems experienced during early development of the technology now have solutions; and (2) the technology has been matured by advances made in the robustness of tether materials and designs, high voltage engineering in the space environment, tether health and status monitoring, and techniques for mitigating the broken tether hazard. Moreover, space tethers offer powerful and far-reaching technological and economic advantages. The potential applications of space tethers of all types have been discussed in numerous papers and will be further explored in this conference. The mention of three examples here will be sufficient to show the fundamental advantages that space tethers bring to space science and technology.

First, science missions to the outer planets require travel to such extreme distances from Earth and the Sun that chemical rocket propulsion and the conversion of solar energy to electrical power are marginal-to-unsuitable for missions that require an extended stay and multiple orbit adjustments. However, all of the gas giants have a significant magnetic field and, within the resulting magnetosphere, electrodynamic tether systems offer the possibility for essentially unlimited propulsion and power. This is particularly appealing in the case of Jupiter, where the magnetosphere extends beyond the orbits of its major moons.

Secondly, multiple electrostatic tethers, deployed to form an “electric sail” that obtains a propulsive force from momentum exchange with the protons of the solar wind, can reduce transit times to the heliopause from 33 years, that was required for Voyager 1, to approximately seven years—significantly faster than any other current or developing propulsion technology.

The third example is the reboost of the International Space Station (ISS). Because of its large cross-sectional area, dynamic drag on the ISS is significant. It decays from its maximum orbital altitude of approximately 475 km to its minimum reboost altitude of approximately 375 km in about six months. Without reboost, ISS would deorbit in 6 to 10 months and as a result, up to eight refueling flights are required each year. At approximately \$500M per

Shuttle flight, this was formally a staggering yearly operational expense. Now that the Shuttle is no longer available and the Russian space agency is being paid by NASA to perform this service, it is likely even more expensive. In 2001 MSFC teamed with several industrial partners to investigate the possibility of reboosting the ISS with an electrodynamic tether. The study affirmed that a tether reboost system capable of sufficient thrust to raise the ISS orbit and designed to have a minimum lifetime of five years in space is feasible, could be developed and launched for considerably less than the cost of reboosting ISS for one year and could be operated remotely from ground control. The result is that no ISS servicing flights would be required for up to a year at a time. The savings to NASA could be several billion dollars per year. Yet, there was little interest within NASA in making the necessary initial investment.

The new culture is in stark contrast to that of the “old” NASA. There has probably never been another period of such rapid technological advance in a peace-time environment as that of the early days of NASA; and arguably, humanity has never been closer than the day Neil Armstrong stepped onto the surface of the Moon and uttered those now immortal words, “...one giant leap for mankind.” It was, indeed, a human triumph.

This period of unparalleled success was not without risks. It was, in fact, *enabled* by a willingness to accept reasonable risks and to learn from failures. After the Apollo-1 accident—in which the crew was lost on the launch pad—the old NASA corrected the problem, determined the risks going forward to be acceptable, and pressed on. During the Apollo program, because the goals required technical capabilities that did not exist, new technology was developed in parallel with, and immediately incorporated into the mission. The technical spin-offs to society were beneficial and numerous. For example, the Euro-American Trans-Atlantic Cable was set aside in favor of worldwide satellite communications.

NASA is now at a crossroads. The Space Shuttle is no more and we are, therefore, presented with an opportunity to begin anew with a clean slate. America exists because of exploration and a pioneering spirit. Today, America does not appear to have lost her adventuring spirit or her interest in exploration. The enthusiasm of the American public for the planetary missions that have allowed us to see the nature of Earth’s sister planets and for the observations made of the cosmos by the Hubble space telescope has shown that America is willing to commit to a program that visibly and significantly increases human understanding. NASA needs to join with its ESA and industrial partners, embrace the public’s spirit, and step out into new endeavors that fire the imagination and offer the prospect of real advancement in understanding and in the unity of mankind.

The success of these new endeavors will, however, depend critically on a parallel and real commitment to the advancement of enabling technologies.

Acknowledgments

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