Table 1 Shuttle EVA involving the rotation of massive objects

| STS mission | EVA payload | Object being rotated | Moment of inertia $I$, kg m$^2$ |
|---|---|---|---|
| 61B | EASE | Single structural beam | 120 |
| 61B | EASE | Assembled structure, about external axis | 1,100 |
| 61B | ACCESS | Assembled structure, about internal axis | 1,500 |
| 51A | Westar | Satellite with stinger, MMU, EMU attached | 4,800 |
| 51I | Leasat | Satellite | 45,000 |

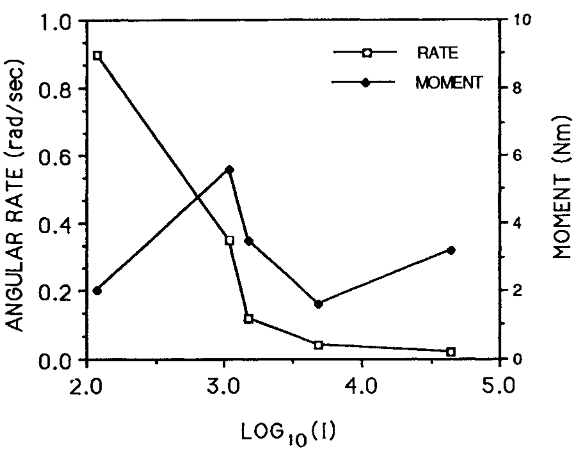


Fig. 2 Mechanical characteristics of the rotation of massive objects.

ping at rest. In each case, the EVA crew member performing the task was adequately restrained at the feet. No apparent motion or zooming of the camera was allowed. An object of known size a known distance from the camera must have been present to estimate the camera field of view. The resulting data set obtained from the available videotapes is summarized in Table 1. A rigid triangle was located on the object being rotated using identifiable features such as structural joints and corners. Size and mass properties were obtained from readily available mission documentation. Average angular rate was extracted by means of a sinusoidal fit to the trajectory. The appropriate moment of inertia $I$ of the object being rotated was used to estimate the moment applied by the crew member to complete the movement. Although the calculation of applied moment is straightforward to tasks performed in EVA, hydrodynamic effects greatly complicate matters in neutral buoyancy simulation. No neutral buoyancy tasks were included in this study.

## Results and Conclusions

The reconstructed angular rate and corresponding applied moment for five manual-handling cases identified earlier are shown in Fig. 2. The data indicate that as the moment of inertia of the object being rotated is increased, the angular rate is decreased so as to keep the applied moment relatively constant. This trend is demonstrated over nearly three orders of magnitude in moment of inertia. The applied moment averaged over all cases is $3.2 \pm 1.6$ Nm.

Because of limitations in both the amount and precision of the data, only preliminary conclusions can be supported. The relatively constant level of applied moment observed here indicates that applied moment is a reasonable determinant of purely rotational manual handling tasks performed by a foot-restrained EVA crew member. In the 1-$g$ environment, metabolic energy expenditure is frequently used to characterize the physical workload of repetitive manual-handling tasks. In terms of the data presented here, mechanical energy expenditure is the product of angular rate and applied moment. Over the range of manual handling tasks in the present study, energy expenditure does not appear to be as consistent a quantity and, thus, not as useful a task determinant as applied moment. This conclusion does not alter the fact that over extened time durations, metabolic energy expenditure must be considered to insure adequate life support capabilities.

The levels of applied moment observed in operational EVA appear to be small fractions of the corresponding physiological limits. Horizontal and vertical shoulder strength limits of greater than 50 Nm have been established for foot-restrained pressure-suited subjects in simulated weightlessness.[7] The reduced level in operational EVA is perhaps due to an unfamiliarity with manual control in true weightlessness, an effect that is not well simulated by neutral buoyancy training. It is, therefore, conceivable that for highly repetitive manual handling tasks such as extensive truss structure assembly, the natural learning process would result in significantly larger applied moments and correspond faster task completion times.

## Acknowledgment

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# Mars Tethered Sample Return

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## Introduction

ONE of the highest priorities in planetary science is obtaining samples from other planets in the solar system. Mars ranks high on the list of bodies proposed for sampling. Present concepts for obtaining samples from Mars center entirely on lander vehicles. Missions based on lander vehicles

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*inherently* involve very large launch vehicles, the emplacement of a large booster on the Martian surface, and automated rendezvous in Mars orbit. At present, the United States possesses none of these capabilities. It has been estimated that a lander sample-return mission could require 10-15 years to develop at a cost of $4-12 billion. As an alternative, samples of Martian soil suspended as dust in the Martian atmosphere can be obtained from an orbiting spacecraft by lowering a tethered sample-collection platform without need for a lander. Although dust samples alone cannot answer all of the first-order scientific questions about Mars, the importance of dust samples has been recognized in the planetary sampling strategies of the NASA Advisory Council's Solar System Exploration Committee.[1,2]

The advantages inherent to a Mars Tethered Sample Return (TSR) mission are that it obviates the requirement for the development of a lander and rover, it obviates the need for automated Mars orbit rendezvous, and it permits the use of a smaller (available) launch vehicle. TSR thus offers 1) quicker response time (no major new spacecraft/ELV developments); 2) lower cost (smaller launch vehicle, no lander/rover, no automated docking required); and 3) higher reliability (smaller number of vehicles, smaller number of mission steps, lower-order technology).

## Scientific Rationale

The Mars TSR cannot supplant more complex and thorough lander and manned sample returns. It can, however, provide the United States with options for 1) a fast "grab" sample in response to a national goal, or 2) a "contingency" sample obtained in conjunction with a lander mission to ensure against lander/rover/launcher/rendezvous failure, or 3) a "precursor" sample as a part of a logical series of building-block sample returns (tether, lander/rover, manned mission).

TSR can either be performed before or as a part of a more complete lander sample-return mission. Furthermore, TSR offers scientific advantages over lander missions. It 1) obtains a global (rather than local) sample, and 2) is well-suited to in situ aeronomical studies.

The importance of obtaining a global sample is high.[3] Fine-grain particulates suspended in Mars' upper atmosphere are thought to be derived from essentially all of the major geologic units on the planet, including the layered polar deposits. These particulates cover the surface and will be observed by the sophisticated NASA Mars Observer (MO) remote sensing mission. Thus, obtaining a sample of suspended dust will also provide an important "ground truth" measurement to anchor the context of MO and future orbital remote sensing.

The Solar System Exploration Committee (SSEC) of the National Academy of Sciences Space Science Board specifically cited the importance of dust samples to a complete understanding of the Martian surface geochemistry, surface/atmosphere interactions, and weathering processes. Typical particle sizes in Martian dust storms are in the range 0.4-3 $\mu$m, with some particles as large as 10-80 $\mu$m.[4] This dust 1) may be analyzed to determine the primary and trace chemical, isotopic, and mineralogical compositions of the Martian regolith; 2) contains information about the mechanical, petrological, and geochemical properties of the Martian regolith and crust; 3) can be age-dated using accelerator techniques; 4) preferentially samples the regolith aeolian zone; 5) contains a record of surface weathering, surface/radiation, and surface/atmospheric interaction processes; 6) directly affects the radiative transfer and chemistry of the Martian atmosphere, and 7) is a key factor in planning for Martian aerobraking.

This list demonstrates that a rich variety of scientific applications can be achieved with collected Mars dust.

The deployment of a tethered sample platform into the Martian upper atmosphere also provides the unique opportunity to make in situ investigations of Martian aeronomical environment. The report of the Science Working Team for the Mars Aeronomy Observer (MAO) mission[5] ranked the measurement of high-altitude neutral and ion composition and temperature profiles as key objectives. Vertical and meridional composition and temperature profiles, as well as low-altitude magnetic surveys, atmospheric/solar wind-interaction studies, and plasma wave investigations can be directly obtained from a tether platform suspended into the Mars atmosphere.

## Technical Feasibility

Having cited the scientific rationale behind a Mars TSR mission, we now examine several key issues relating to its technical feasibility. First among the issues examined here is the applicability of current tethered satellite technology to the Mars sampling problem. The key factors in determining the aerothermodynamic environment in which a Mars tethered sample platform will operate are the dynamic pressure regime and drag deceleration. Drag effects will be discussed later in this section. Dynamic pressure at altitude $z$ is given by

$$P_{dyn}(z) = \rho(z)v^2 \tag{1}$$

where $\rho(z)$ is the atmospheric density at altitude $z$ and $v$ is the circular orbit velocity. To reduce $P_{dyn}$ (as well as other factors, such as tether length), one prefers to collect dust from as high an altitude as is feasible. Viking and Mariner 9 Orbiter data[6] have shown that dust is present during the annual Martian dust storms at altitudes up to 40-60 km. Adopting the mean-annual Mars reference atmospheric density[7] of $7 \times 10^{-6}$ kg/m$^3$ at 50 km for $\rho$ and the circular orbital velocity at that altitude ($v$ = 3.5 km/s), one finds $P_{dyn} = 8.7 \times 10^1$ kg m$^{-1}$ s$^{-2}$. Adopting the Jacchia standard reference Earth atmosphere,[8] one finds that the same dynamic pressure is achieved at an altitude of ~93 km for a tether in Earth orbit (the exact correspondence altitude depends upon solar activity and season). Using onboard guidance and aerodynamic surfaces for attitude and trajectory control, the present NASA Tethered Satellite System (TSS) is designed to operate in the terrestrial atmosphere as low as 90-100 km. Thus, the present technology appears to be functionally adaptable to the Mars TSR.

Next on the list of issues addressed here is the sample collection method itself. To minimize sample damage, one prefers inlet designs with the entrance apertures located tangent to the oncoming streamflow. In such a configuration, boundary-layer turbulence is employed to capture and decelerate dust particles into the collection orifice. This approach dramatically reduces both vehicle drag and sample damage (if the collector platform exterior is made rough to increase the boundary-layer scale length), but requires the continuum flow regime. The disadvantage of this approach is that it reduces the maximum effective collecting area to approximately half the frontal cross section of the boundary layer. For the 1-m diam current TSS spacecraft, a 0.10-m thick e-folding scale length on the boundary layer implies an annular capture cross section (of width one e-folding length and circumference $2\pi$ meters) of 0.63 m$^2$ effective collecting area.

Based on this collecting area, we can estimate the collected sample mass as a function of stay time in the atmosphere. The sample mass $m$ intercepted by a collector of entrance aperture area $A$ over $N$ orbits is

$$m = (2\pi Na)\rho_d A \tag{2}$$

where $a$ is the orbit radius of the circular orbit, and $\rho_d$ is the mass density of dust at the orbit altitude. At Mars, the maximum atmospheric dust density occurs during the annual global dust storms.[5] Pollack et al.[5] demonstrated from Viking lander measurements that the vertical optical depth of a dust storm implies an atmospheric mass loading of $1\text{-}5 \times 10^{-2}$ kg m$^{-2}$. Taking the dust/gas ratio to be uniform over this altitude range[4] gives a lower limit to the dust density at 50 km of $\rho_d = 2.3 \times 10^{-9}$ kg m$^{-3}$. Thus, for collection at an altitude of 50 km over the Martian surface, one expects a 0.63-m$^2$ collector to nominally intercept a dust load of $m = 0.03$ kg/orbit. Therefore, the time to collect a sample of mass $m$ is

$$t = \left(\frac{m}{\eta \rho_d A}\right)\sqrt{\frac{a}{GM}} \tag{3}$$

where $\eta$ is the dust collection efficiency, $M$ the mass of Mars, and $G$ the universal gravitational constant. Taking the collection rate at 50 km estimated previously and $\eta = 10\%$, Eq. (3) gives a 100-g collection time near 55 h, or about 33 orbits. Because present analytical sample analysis techniques typically require $\leq 0.001$ kg of material,[9] a 0.1-kg sample would supply numerous investigator teams. Higher collection efficiencies could reduce the collection time requirement by a factor of 2–5.

It is important to note that tethered sample collection involves a loss of orbital energy (a drag term) due to the sampling process, thereby limiting the residence time of the collector. To estimate the altitude lost to drag we adopt a 3200-kg orbiter vehicle based at 105 km with a 500-kg tethered platform of cross section 3.1 $m^2$ and drag coefficient $C_d = 2$ suspended by a tether with cross section of 10 $m^2$. In this calculation, the tether was assumed to be 0.01 m thick, and the cross section more than 10 km above the collection platform was ignored since it lies at substantially lower atmospheric densities than does the collection platform. Equating drag energy lost to an orbit altitude loss reveals that once the collector is deployed to 50 km in the Mars atmosphere, such a system would suffer less than 5 km of orbit altitude loss for each kilogram collected. Below 40 km, the exponential density increase of the atmosphere causes the vehicle to sink rapidly. An issue for future study is the degree of tether and collection platform erosion due to dust impacts, which may ultimately limit the deployment lifetime and/or minimum penetration altitude of the collection platform more severely than vehicle drag.

We now address the two basic mission design issues relating to a Mars TSR. The first of these is whether the length of the "sampling window" is sufficiently long to conduct a mission. As previously discussed, the most efficient time to collect a tethered dust sample is during Mars' annual (i.e., every two Earth years) global dust storm. Martian dust storms display rise times of 4–14 days[5] and then decay over 60–75 days.[5] Therefore, it appears there is sufficient time to plan and conduct a sampling sortie if an Orbiter/Tether Platform has been placed into Mars' orbit in advance.

The final issue to be examined is the Orbiter/Tethered Platform spacecraft mass and launch vehicle requirements. The following simple analysis is designed to scale these requirements. Adopting the 2130-kg Mars Orbiter as a reference spacecraft bus, the 500-kg mass of the NASA/Italian TSS spacecraft, a 200-kg deployment mechanism, 250 kg for a 250-km-long tether, 580 kg for Earth-return propellant,[2] and a 210-kg Earth return vehicle[2] gives a total vehicle weight of 3870 kg. This is not dramatically different from the 3408 kg Viking '76 Orbiter/Lander spacecraft. These Viking missions were launched using Titan 3/Centaurs. The Titan 4/Centaur ELV now in development has a Mars-injection payload capability of over 3900 kg. For comparison, options devised by the Solar System Exploration Committee for Mars lander/rover sample return missions range from 8157–26,990 kg in mass.[1,2] This analysis shows that a Mars TSR mission has lower injected-mass requirements than other proposed Mars sample return missions, and that it can be carried out by available launch vehicles.

## Conclusion

In summary, tethered sample return appears to be both technically feasible and scientifically interesting. Detailed studies of this promising concept appear warranted.

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