

NON-PROPULSIVE ACCESS TO THE MARTIAN SURFACE

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ABSTRACT

When humans begin to systematically explore and settle Mars, the addition of rocket exhaust gases to the thin Martian atmosphere will irreversibly alter its composition, and its reactivity with exposed surfaces. Scientists on Mars will then be hampered by the challenge of distinguishing anthropogenic from pristine features of their objects of study, a fact that will erode the value of their contributions to comparative planetology. The problem can be avoided, or at least mitigated, by conducting as much activity as possible using emission-free vehicles and power sources. Transportation between ground and space can be accomplished without rocket propellants, either by shooting payloads into space with guns (mass drivers), or by transferring momentum to them through ultra-long cables (space tethers). The Gun Transportation System would consist of electromagnetic “coil guns” or conventional expanding-gas guns, either of which must be hundreds of kilometers long to achieve escape velocity at human-survivable accelerations. The Cable Transportation System would consist of skyhooks, space elevators, and other tether-based elements, hundreds or thousands of kilometers long. Both transportation systems would be easier to deploy at Mars than at Earth, due to its smaller size, lower gravity, and thinner atmosphere.

INTRODUCTION

The atmosphere of Mars is considerably thinner than Earth’s, and thus more vulnerable to alterations in its composition by human activity. Future studies of the atmosphere, its chemical effects on surface features, and its interactions with Martian biota (if any), may be hampered by such alterations. This paper identifies a major risk of human activity on Mars to the science of biology: the destruction of life forms unique to Mars before they are ever discovered. Restricting gaseous emissions on the Martian surface, especially rocket exhausts, would mitigate this risk by preserving the pristine atmosphere to which the hypothesized life forms have adapted. To this end, non-propulsive alternatives to rockets are proposed for launching payloads into space from the Martian surface.

Momentum can be transferred to payloads either by shooting them from the surface with guns¹, or by lifting them with tethers that reach the ground from orbiting satellites². Payloads are assumed to include human beings. Therefore accelerations must not exceed human physical endurance limits, a restriction that translates into minimum lengths of gun barrels and tethers on the order of 400 km to reach escape velocity. This is long for the gun but short for the tether. Building a 400-km gun on Mars would require a construction, earth-moving, tunnel-drilling

megaproject to produce a straight or near-straight support structure of that length. Three sites whose favorable terrain-slopes would minimize the amount of work are examined.

Tethers as short as 400 km must rotate end over end as they orbit Mars, in order for their rotation and orbital speeds to nearly cancel where they pick up payloads³. Such rotating tethers, which touch down many times per orbit, are called *asynchronous skyhooks* to distinguish them from *synchronous skyhooks*, or “space elevators”. The latter are much longer and corotate with Mars. The space elevator is essentially a building so tall that the centrifugal force of Mars’ rotation would keep it from falling down⁴. Skyhooks are usually perceived as operating only in the equatorial plane, serving only equatorial launch sites. Because Mars explorers and settlers would probably rule out options demanding long journeys to reach their launch facilities, we consider skyhooks capable reaching non-equatorial latitudes.

SEARCH FOR PRIMORDIAL LIFE

Of central interest to exobiologists is the search for *pre-bacteria*, the hypothesized missing links between nonliving chemical systems and the simplest known independent life forms, the bacteria. Terrestrial searches for them have yielded nothing, either in the modern biosphere or in the fossil record. The transition from known non-living organic molecules to the first bacterium is a gigantic leap in chemical complexity, inexplicable by evolutionary theory without intermediate forms. The lack of living bacterial precursors lends credence to *panspermia*, the hypothesis that bacteria fell to Earth from an extraterrestrial source, and the prediction that their ancestors can be found on their planet of origin. Following the recent discovery of bacteria-fossil-like structures in a Martian rock recovered from the Antarctic ice sheet as a meteorite⁵, some exobiologists regard as inevitable the transfer of bacteria between planets, aboard rocks dislodged from their parent bodies by asteroid or comet impacts. After the Earth, Mars is the second most likely birthplace of bacteria in the solar system, and therefore the next place to search for pre-bacteria. If pre-bacteria exist on Mars in a form that would be recognizable to science, they must be more fragile than bacteria and unable to survive in space. Otherwise they too would have survived the interplanetary journey aboard the impact ejecta that brought Martian bacteria to Earth. By this hypothesis, seekers of pre-bacteria should go to the Martian surface.

It is equally possible that bacteria evolved on Earth from ancestors so fragile that they left no fossils, and have since been wiped out by one or more global changes, such as oxygenization of the atmosphere. It has been argued that bacteria appeared much too early in Earth history to have evolved here⁶. The fact that bacteria have existed almost as soon as the environment became hospitable to them might mean that they evolved very quickly from fragile precursors. Chemical reactions can proceed rapidly when triggered by some high-energy event, producing mixtures far from thermodynamic equilibrium and rich in complex but unstable molecules, few of which persist as the energy dissipates. Some of these molecules might have become self-replicating on a time scale shorter than their mean lifetimes, and capable of evolving within their dynamic chemical environment from one generation to the next. It would only take a single bacterium to evolve in this primordial soup before it cools, for life to survive the aftermath of the triggering event and gain a toehold on the planet. The fact that nothing much more complicated evolved for almost two billion years⁷ testifies to the robustness and stability of the bacterium, the

most successful of life forms. By this hypothesis, bacteria could have evolved either on Earth or Mars, and spread via impact ejecta to the other planet. If on Earth, pre-bacteria may never be found. If on Mars, pre-bacteria may be found under the following conditions:

- (1) persistent pre-bacterial life forms exist,
- (2) global change has not wiped them out,
- (3) they are recognizable as life, and
- (4) they survive human intrusion into their environment.

Condition (4) may require the imposition of constraints on human activity within or near the hypothesized biosphere of Mars, especially activities such as rocket launches that pollute the atmosphere. If any rocket-plume constituent is lethal to pre-bacteria, it could be spread planet-wide by the winds of Mars, exterminating pre-bacteria before they are discovered by science.

Yet a third possibility is that bacteria evolved around some star other than the sun, and fell to Earth and/or Mars on meteors captured by the sun during a close passage of the star.⁶ This would be the only viable hypothesis if it took billions of years for bacteria to evolve, in which case the search for pre-bacteria would be just as fruitless on Mars as on Earth. But the current prevailing view of evolution, known as *punctuated equilibrium*, is that life evolves in bursts separated by long stretches of stability⁸. The first such burst might have been the giant leap from nonliving precursors to the first bacteria 3.5-4.0 billion years ago, perhaps triggered by an asteroid falling into the primordial soup in the final days of planetary accretion. Modern biologists need not invoke billions of years of evolution around some ancient star to accept the early appearance of bacteria on Earth or Mars.

Rocket Contamination Footprints

The Mars Society's proposal for human exploration, known as *Mars Direct*, calls for launching a new crew to the Martian surface at every launch window and returning that crew to Earth through the next launch window⁹. These windows are separated by one Earth-Mars synodic year, or 780 Earth days. The outbound rocket would inject little if any exhaust gas into the atmosphere of Mars, because deceleration would be accomplished by aerobraking. But the Earth Return Vehicle (ERV), a methane-oxygen burner, would inject almost its entire propellant load of 96,000 kg into the Martian atmosphere as water vapor and carbon dioxide. The effect of this injection on the Martian atmosphere can be grasped by noting the masses of water and carbon dioxide occurring there naturally. Table 1 gives the atmospheric compositions of Earth and Mars, along with other data needed to estimate the column densities of water and carbon dioxide above their surfaces. Figure 1 gives the corresponding relative humidity. From these it is clear that water vapor is a trace constituent in the Martian atmosphere, unlike carbon dioxide. The reverse is true in Earth's atmosphere, though both gases are trace constituents in the driest regions. Therefore in assessments of the environmental impact of hydrocarbon burning, water vapor must be regarded as the pollutant on Mars, and carbon dioxide the pollutant on Earth.

One can quantify the environmental impact of rocket exhaust by expressing the mass of each exhaust gas in terms of the natural abundance of that gas in the atmosphere. For this purpose, let us define the *footprint* of a gas source to be the surface area on a planet above which

the mass of an atmospheric constituent would be doubled by emission from the source. Thus the *water footprint of an ERV launch on Mars* would be the surface area on Mars above which the natural atmosphere contains 43,200 kg of water, which is the mass of water expelled by the ERV. Numerically, the footprint is simply the mass of the constituent gas in the rocket exhaust divided by the column mass of that gas in the undisturbed atmosphere.

The water and carbon dioxide footprints of an ERV launch are shown in Table 2 for both planetary atmospheres. The water footprint on Mars is by far the largest number in the table, due in part to the extreme dryness of the Martian atmosphere. To illustrate how much drier Mars is than Earth, the volumetric water abundances in Table 1 were converted to curves of relative humidity vs. temperature. The results, shown in Figure 1, suggest that it never rains on the Red Planet, and snows or frosts only on extremely cold nights or at high latitudes. Any cloud condensing from water vapor in the ERV rocket plume would quickly evaporate as the plume diffuses into the dry Martian air. The average relative humidity within the plume will exceed twice that of the pre-launch air until the plume has diffused to a cylinder 2.06 km² in cross section around the rocket path. At that point the carbon dioxide in the plume, by contrast, will have dropped to within 0.016% of its density in the undisturbed atmosphere.

Precautionary Principle

Atmospheric oxygen, vital to most life forms on Earth today, is known to have caused a mass extinction of anaerobic bacteria some two billion years ago. Might water vapor do the same to Martian pre-bacteria? A handful of ERVs poses no risk, but as the exploration of Mars leads to settlements and commerce with Earth, rocket launches could become a significant source of water vapor in the Martian atmosphere. The result could be a dramatic global increase in relative humidity. How this change would affect the hypothesized pre-bacteria will remain a completely open question until somebody either discovers pre-bacteria or develops a scientific theory of pre-bacteria with some predictive power.

Given our state of ignorance of the roots of the tree of life, the *precautionary principle* should be given great weight as we venture beyond the home planet. Although this principle has been stated in various ways, it always expresses the need to err on the side of caution when science cannot provide the knowledge needed to perform traditional risk assessment and management. A recent summary of the precautionary principle reads as follows¹³:

When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically.

Generalized from humans to entire biospheres, this principle has already motivated NASA's efforts to protect other planets from terrestrial microbes by sterilizing interplanetary spacecraft. It should now motivate efforts to preserve the natural composition of Mars' atmosphere by developing alternatives to rockets.

MASS DRIVERS

Many mass drivers have been proposed over the years for launching payloads from planetary surfaces. All are basically linear accelerators, applying a force to the payload as it

moves along an upward-inclined linear guide, or *rail* (*barrel* for gas guns). Whatever the nature of the force, electromagnetic, gas pressure, or psychic, we assume it is uniform along the rail and vanishes thereafter. To launch ERVs, the mass driver must produce muzzle velocities of at least Mars escape (5.03 km/sec), with acceleration low enough to avoid injuring the passengers, and with enough velocity margin to compensate for aerodynamic drag along the post-muzzle flight path through the atmosphere. The payload may include onboard rockets to reach higher speeds than the mass driver can deliver, but these would be fired far beyond the Martian atmosphere. The acceleration limit must account for the reduced tolerance of individuals whose physiologies have adapted to Mars gravity (0.38 gees). Here we assume a 3-gee limit, which achieves Mars escape velocity after 430 km, if applied continuously along the rail. This length can be reduced to 390 km for launchers near the equator and pointing eastward, since payloads start with Mars' rotation velocity at the loading end of the rail.

Based on the preceding considerations, we identify the following criteria for mass-driver sites, listed in decreasing order of importance:

1. Terrain elevation increases uniformly over a very long distance (minimizes acceleration).
2. Terrain elevation is as high as possible at the muzzle end (minimizes air drag).
3. Terrain is near equator and slopes up toward the east (maximizes boost from Mars' rotation).

With these criteria in mind, cursory inspection of a topographic map of Mars¹⁴ uncovered the potential mass-driver sites listed in Table 3. The listed length at each site represents the longest uninterrupted stretch of uniformly sloping terrain, and therefore the longest straight section of rail possible at that site. Calculations of atmospheric drag loss at each candidate site are shown in Table 4. They are based on an assumed ERV mass of 20,000 kg, which is about the mass of the Mars Direct ERV minus propellant and items to be left on the Martian surface.⁹

The last row in Table 4 shows how aerodynamically streamlined the ERV must be to keep drag losses below 100 m/sec. Clearly the Olympus Mons site outshines the others in this respect, because it would require little if any streamlining to give the ERV an effective cross section of 4.39 m². Unfortunately, Table 3 shows that it is the worst of the three sites when rated by rail length, subjecting passengers to accelerations almost double the safety limit. One way around this problem would be to guide the ERV along a curved section of rail before feeding it to the straight section on the slope of Olympus Mons. Figure 2 illustrates this idea with a 3-stage idealized model, in which the terrain slope jumps abruptly from 0° to 5.44° at the base of the Olympus Mons cinder cone. Over the base, a curved section of launch rail with length S and uniform radius of curvature R_C (Stage 2) is installed to connect a horizontal section (Stage 1) to the main inclined section (Stage 3). R_C is driven by the need to keep centrifugal forces within passenger comfort and safety limits. This in turn determines the length of the curved section between its points of tangency with horizontal and sloped terrains ($S \approx 0.0949R_C$ is the flat Mars approximation in this case). The more sharply Stage 2 curves, the less supporting structure must be built to hold it up over the terrain, but the more jarring will be the ride for passengers due to centrifugal force. Figure 3 shows the acceleration required along Stage 3 and the speed of arrival from Stage 2, for several assumed centrifugal-force limits. Also shown is the height of the rail above the base of Olympus Mons, which is where the gap between rail and terrain is greatest. Choosing a design involves a tradeoff between reducing the cost of the rail and increasing the margin of safety for passengers, an exercise beyond the scope of this report. One plausible compromise, shown by arrows in Figures 2 and 3, is obtained using an upper limit of 1 gee on

centrifugal force in Stage 2 (solid curves in graphs). It has a 16.7-km curved section with a 185.3-km radius of curvature, allowing the ERV to enter Stage 3 at 1.348 km/sec, a speed that can be boosted to escape velocity without exceeding the 3-gee linear acceleration limit. This curved section crosses over the base of Olympus Mons at a height of 188 meters.

Our attention has focused on the Olympus Mons site because its superlative elevation places it above so much of the atmosphere that aerodynamic drag can be ignored. The two other candidate sites, Tharsis Montes and Hellas Planitia, would be more suitable for launching highly streamlined ERVs. If power is abundant at these sites, imparting extra velocity to payloads to compensate for drag would permit the launching of less streamlined shapes. With a 500-km stretch of uniformly sloping terrain to accommodate it, a straight-rail mass driver could produce muzzle velocities of 5.4 km/sec without exceeding the 3-gee safety limit.

SKYHOOKS

The *Skyhook* is a satellite whose function is to transport payloads to and from a terminal on the surface of a planet around which it orbits, using a space tether. Figure 4 illustrates both synchronous and non-synchronous types operating in the equatorial plane. For a payload to be picked up (or dropped off) easily as the satellite passes overhead, the tether tip must come to a complete halt after its descent to the terminal, before proceeding on its way with (or without) the payload. Kinematically, the ground and tether tip velocities must match at the moment of touchdown. For a circular orbit, the tether would behave like the spoke of a giant wheel rolling around the planet. The synchronous skyhook can be regarded as a special case in which touchdown is a permanent condition, i.e. the giant wheel is stopped dead with its spoke standing on the terminal. This is the immensely long *space elevator*, exemplified in science fiction by Arthur C. Clarke's "orbital tower".¹⁵ The shorter non-synchronous skyhook, or *pinwheel*, is much closer to physical realization.¹⁶ Of the two types, only the pinwheel could conceivably be developed in the near future to reach non-equatorial sites. For the space elevator to do so would require anchoring it to the ground, which would balance the component of gravity normal to the equatorial plane and prevent it from wobbling between hemispheres. The enormity of such an anchor places it in the unforeseeable future of global engineering megaprojects, where space elevators will figure prominently, as shown in Figure 5.

In designing pinwheels to launch ERVs from Mars, we follow the mathematical notation of Moravec³ but extend his analysis to nonzero latitudes. For a touchdown point at latitude λ , the velocity-matching condition is expressed in terms of the planet's radius r_p , orbital radius r_o and angular velocities of the skyhook spin ω_s , its orbital motion ω_o and the planet's rotation ω_p :

$$(r_o - r_p) \omega_s = r_o \omega_o - r_p \omega_p \cos \lambda. \quad (1)$$

This equation contains the implicit assumption that the satellite is moving due east at touchdown if the planet is rotating. This is true for all touchdowns from an equatorial satellite, but from a non-equatorial satellite with orbital inclination i , it is only true at the latitude extremes of the satellite ground track, where $\lambda = \pm i$. If the tether tip were to touch down at intermediate latitudes, the ground velocity component transverse to the orbital plane would not be cancelled, and the tether would be subjected to extremely high aerodynamic drag through the corotating

atmosphere. Therefore to reach high latitudes, the skyhook must be long enough to touch down only once or twice per orbit. Figure 6 illustrates the permissible types of pinwheels, and defines the parameters needed to compute their lengths as functions of touchdown latitude.

Pinwheel lengths are determined by synchronizing touchdowns with overflight of ground stations. This involves the following steps:

- ♣ Relate angles swept by orbiter and ground station:

$$\omega_o T_{PASS} = \omega_p T_{PASS} + 2 \pi J \quad (2)$$

- ♣ Relate angles swept by orbiter and pinwheel arm:

$$\omega_s T_{TD} = \omega_o T_{TD} + (2 \pi / N) K \quad (3)$$

- ♣ Express angular velocities in terms of radii and the gravitational constant of Mars:

$$\omega_s = (r_o \omega_o - r_p \omega_p \cos \lambda) / (r_o - r_p) \quad \text{where } r_p = 3390. \text{ km} \quad (4)$$

$$\omega_o = (G M_p / r_o^3)^{-1/2} \quad \text{where } G M_p = 42828. \text{ km}^3/\text{sec}^2 \quad (5)$$

- ♣ Compute the integer number of orbits per day and spins per orbit:

$$J = \text{int}(\omega_o / \omega_p) \quad (6)$$

$$K = \text{int}(\omega_s / \omega_o) \quad (7)$$

- ♣ Obtain orbital radius vs. touchdown latitude for N-armed pinwheel by solving:

$$T_{TD} - T_{PASS} = 0 \quad (8)$$

By solving Equations (2) and (3) for T_{TD} and T_{PASS} , we can write Equation (8) as

$$(\omega_o - \omega_p) K / N - (\omega_s - \omega_o) J = 0 \quad (9)$$

Solutions for 1- and 2-arm pinwheels were found by substituting Equations (4) through (7) into Equation (9), and numerically searching for zeroes of the left-hand side. Results are plotted in Figure 7. Note that only the “1-arm, 2-orbits/day” curve represents true pinwheels. The other two curves are at synchronous orbit and therefore represent space escalators. These pinwheels have arms so long - more than two Mars radii - that acceleration poses no risk to passengers.

Much shorter pinwheels will work at the equator. If too short, their faster spin poses a risk to passengers. Acceleration at liftoff is simply the sum of the accelerations due to the tether’s orbital motion and its spin:³

$$(\text{Liftoff acceleration}) = (\text{Surface gravity}) r_p^3 / (r_o^3 - r_o^2 r_p) \quad (10)$$

This is plotted in Figure 8 for various pinwheel lengths, where it can be seen that the 3-gee safety limit is exceeded by any pinwheel whose arms are shorter than 307 km. The disadvantage of serving only the equator might be offset by the higher frequency of overflights per day (up to 11) and the larger number of ground terminals served (up to 22 equatorial sites spaced 970 km apart). With these advantages and their more manageable lengths, equatorial pinwheels are likely to emerge as alternatives to rockets much sooner than the high-latitude pinwheels

described earlier. This is fortuitous because it is near the equator where the first immigrants would be inclined to settle, given the Red Planet's comparatively frigid climate. By the time Mars becomes so crowded that newcomers seek elbow-room at higher latitudes, space tether technology may have advanced enough to build non-equatorial pinwheels to serve them.

CONCLUSIONS

The precautionary principle, originally formulated out of concern for human health and safety, instructs us to err on the side of caution when facing uncertainties with far-reaching consequences. By generalizing it to the health and safety of planetary biospheres, exobiologists stand a better chance of discovering their quarry. To the extent that the search for extraterrestrial life motivates the exploration and settlement of Mars, it is incumbent upon mission planners to heed the precautionary principle. The Mars Direct Plan's Earth Return Vehicle would inject environmentally significant amounts of water vapor into the Martian atmosphere. This would risk contaminating the surface locally, by hydration and other reactions with rocks and soil below the rocket plume. Pre-bacteria, if they exist on Mars, could be extremely fragile and altered or destroyed by the increase in relative humidity in their ecological niches. Larger scale Mars-Direct follow-on missions also using rocket propulsion for Earth-return could, over time, globally increase the relative humidity on Mars, and risk eradicating pre-bacteria before they are ever discovered.

These risks can be mitigated by developing non-propulsive methods of departing the Red Planet, and utilize them on Mars-Direct follow-on missions of exploration and settlement. Over the short term (decades), equatorial pinwheels could replace rockets. Imposing a 3-gee safety limit on acceleration would mandate pinwheel arm lengths of at least 300 km. Launching payloads without rockets from off-equatorial sites is more challenging, but several options could emerge over the long term (50 years). Pinwheels with arms 6800-9500 km long could serve launch terminals within 53° of the equator. Mass drivers could launch payloads to Mars escape velocity from any latitude, provided the local terrain permits a straight launch rail to be angled upward. The 3-gee safety limit would be exceeded by any rail shorter than 400 km, a constraint that leaves only a handful of sites qualified for passenger-rated launchers. Olympus Mons is the most promising such site. And finally, space elevators and escalators could join this list of non-propulsive alternatives to rockets over the very long term (centuries).

None of these rocket alternatives has received much support beyond conceptual design work. It is hoped that the precautionary principle, applied to hypothesized Martian life, will shine a spotlight on them and invigorate their development.

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Table 1. Atmospheres of Earth and Mars^{10,11}. Column air masses are shown for the constituent gases whose densities would be increased by hydrocarbon-burning rockets.

| | <u>Earth atmosphere</u> | <u>Mars atmosphere</u> |
|------------------------------------|---------------------------------------|------------------------------|
| Composition, % by volume [mass] | N ₂ 78.08 [75.52] | CO ₂ 95.3 [96.64] |
| | O ₂ 20.95 [23.14] | N ₂ 2.7 [1.74] |
| | Ar 0.93 [1.29] | Ar 1.6 [1.47] |
| | H ₂ O 0.1-2.8 [0.062-1.74] | O ₂ 0.13 [0.096] |
| | CO ₂ 0.034 [0.052] | CO 0.07 [0.045] |
| | H ₂ O 0.03 [0.012] | |
| Surface pressure | 1013. millibars (sea level) | 6.36 millibars (mean) |
| Mean molecular weight | 28.9644 | 43.4 |
| Surface gravity | 9.80665 m/sec ² (1 gee) | 3.71 m/sec ² |
| Column masses: Total | 10326. kg/m ² | 171. kg/m ² |
| Water vapor: | 6.4-180. kg/m ² | 0.021 kg/m ² |
| Carbon dioxide: | 5.4 kg/m ² | 165. kg/m ² |

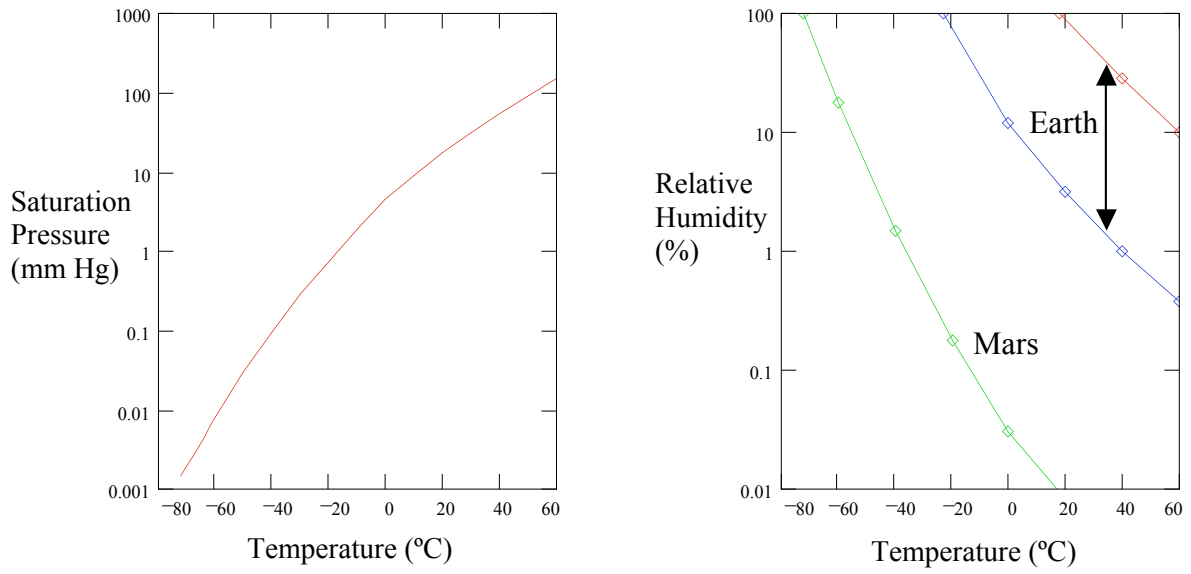


Figure 1. Relative humidity on Mars compared to the range of relative humidity occurring on Earth. Curves were derived from the total pressures and H₂O abundances in Table 1, using the saturation pressure of water vapor over condensed water shown at left.¹²

Table 2. Footprints of ERV launches (43,200 kg H₂O, 52,800 kg CO₂).

| <u>Exhaust product</u> | <u>Launch from Earth</u> | <u>Launch from Mars</u> |
|------------------------|--------------------------|--------------------------|
| H ₂ O | 241-6,750 m ² | 2,060,000 m ² |
| CO ₂ | 9,730 m ² | 319 m ² |

Table 3. Candidate sites for gun-type ERV launcher. Assumes uniform acceleration to escape velocity (5.03 km/sec) along a straight launch rail pointing eastward.

| | Olympus Mons (western slope) | Tharsis Montes (western slope) | Hellas Planitia (eastern slope) |
|---|---------------------------------|-----------------------------------|------------------------------------|
| Loading end location (lat, lon) | 18°N, 138°W | 3°S, 131°W | 40°S, 85°E |
| Length (L) | 210. km | 550. km | 500. km |
| Elevation range (H ₁ to H ₂) | 5 to 25 km | 5 to 9 km | -2 to +2 km |
| Mars rotation speed at site $v_r = v_{\text{equator}} \cos(\text{lat})$ | 229. m/sec | 240. m/sec | 184. m/sec |
| Velocity change required $\Delta v = 5030. \text{ m/s} - v_r$ | 4801. m/sec | 4790. m/sec | 4846. m/sec |
| Acceleration and time on rail $a = (\Delta v)^2 / 2 L$ $t = \Delta v / a$ | 5.60 gees 87. sec | 2.13 gees 229. sec | 2.39 gees 207. sec |

Table 4. Atmospheric drag losses of payloads fired from candidate ERV launch sites. The last three rows are based on an ERV mass of 20 metric tonnes.

| | <u>Olympus Mons</u> | <u>Tharsis Montes</u> | <u>Hellas Planitia</u> |
|---|--|---|--|
| Muzzle elevation H_2 | 25 km | 9 km | 2 km |
| Launch angle (terrain slope E) $\tan(E) = (H_2 - H_1) / L$ | 5.44° | 0.42° | 0.46° |
| Air pressure at muzzle $P = (6.36 \text{ mb}) e^{-H_2 / 11.1 \text{ km}}$ | 0.669 mb | 2.83 mb | 5.31 mb |
| Air mass above muzzle $m_{\text{air}} = P / (3.71 \text{ m/sec}^2)$ | 18.0 kg/m ² | 76.3 kg/m ² | 143. kg/m ² |
| Air mass along flight path $m_{\text{AIR}} = m_{\text{air}} / \sin(E)$ normalized (m_{AIR}/M_P): | 190. kg/m ² 0.0095 /m ² | 10,400. kg/m ² 0.52 /m ² | 17,900. kg/m ² 0.895 /m ² |
| Velocity lost to air drag $v_{\text{LOST}} \approx \Delta v (m_{\text{AIR}}/M_P) C_D A$ | (22.8 /m-sec) $C_D A$ | (1245. /m-sec) $C_D A$ | (2169. /m-sec) $C_D A$ |
| Drag coefficient x area ($C_D A$) to keep $v_{\text{LOST}} \leq 100 \text{ m/sec}$ | $\leq 4.39 \text{ m}^2$ | $\leq 0.0803 \text{ m}^2$ | $\leq 0.0461 \text{ m}^2$ |

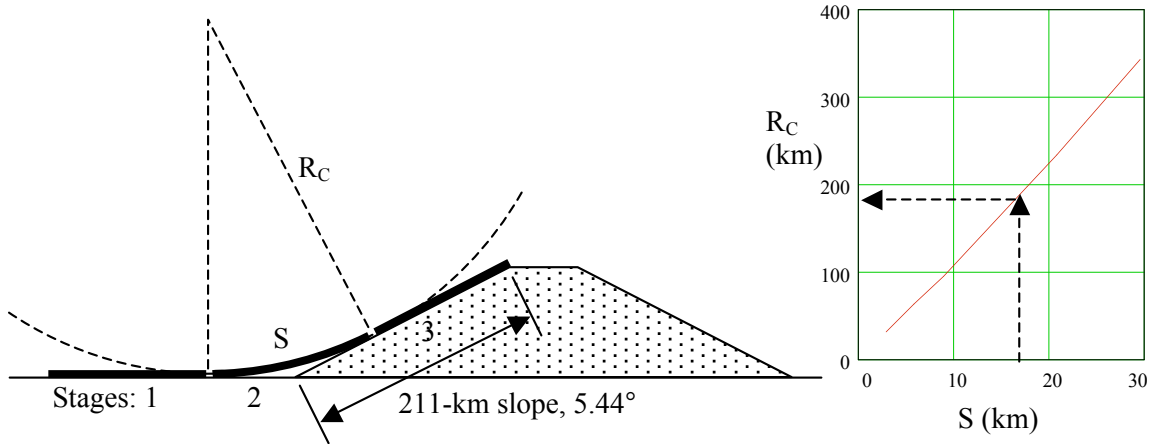


Figure 2. Olympus Mons ERV launch rail with curve (length S , radius of curvature R_C) to extend acceleration path. Vertical scale is exaggerated for clarity. Example (arrows) is described in text.

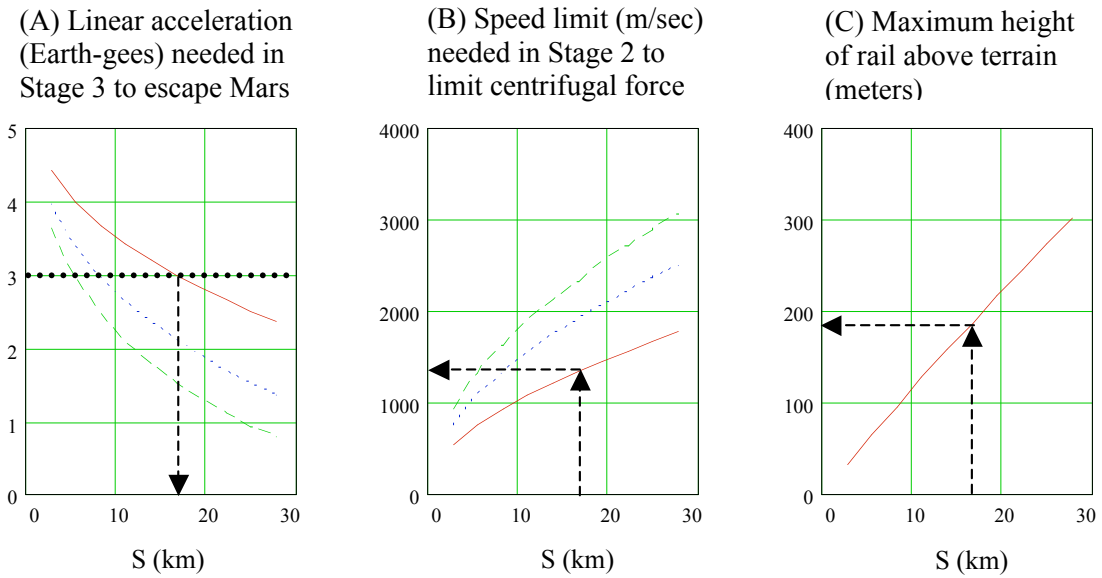


Figure 3. Parametrics of Olympus Mons launch rail with curved section of length S . Dotted line in (A) shows the safety limit for Stage 3 linear acceleration. Centrifugal acceleration in Stage 2 is also limited for passenger safety. Solid curves in (A) and (B) represent the nominal 1 gee limit. Curves for 2 gees (short dashes) and 3 gees (long dashes) assume riskier limits.

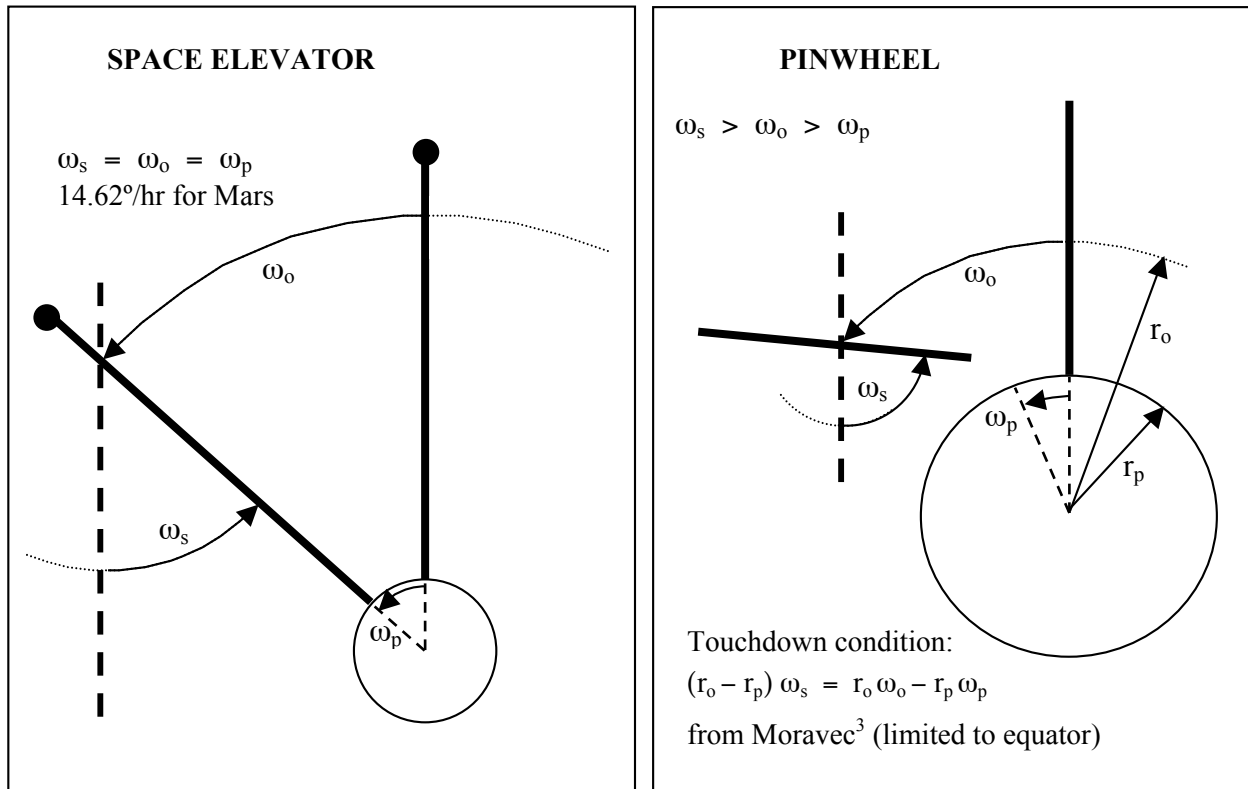
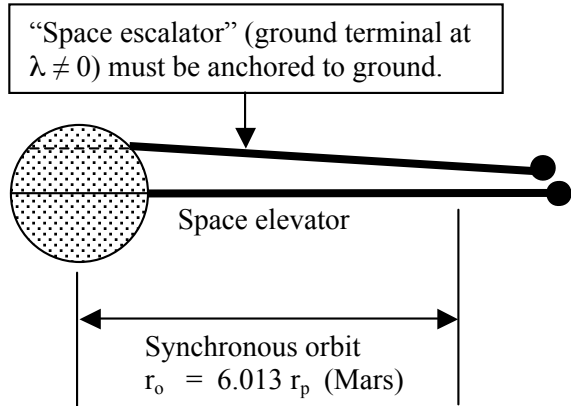


Figure 4. Skyhook concepts. The synchronous skyhook (left), first described by Tsiolkovski¹⁷, corotates with its planet. The non-synchronous skyhook (right), first described by Artsutanov¹⁸, must spin to cancel its orbital velocity at touchdown.

Far Future: Space elevator, a special case of 1-armed pinwheel such that $\omega_s = \omega_o = \omega_p$ ($=14.62^\circ/\text{hr}$ for Mars).



Far Far Future: Constellation of space elevators, escalators, cross-threads: literally a World Wide Web. Dashed line is synchronous orbit.

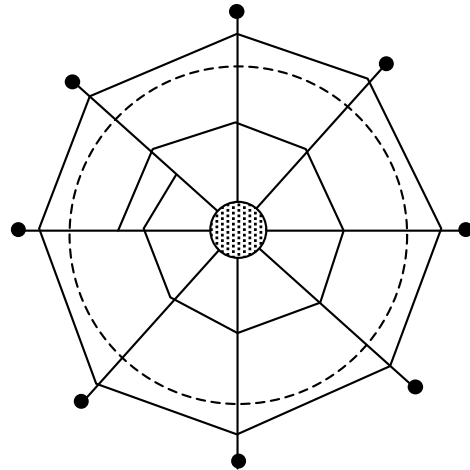


Figure 5. Skyhooks of the unforeseeable future. Large blobs past stationary orbit are counterweights whose centrifugal force holds up the space elevators.

Access to ground terminals at nonzero latitude λ :

- ♣ Requires orbital inclination $i=\lambda$
- ♣ Limits touchdowns to 2 per orbit, at latitudes $\pm\lambda$ where tether tip can descend vertically.

Number of pinwheel arms N:

- ♣ N = any number if $\lambda = 0$.
- ♣ N = 1 (asymmetric pinwheel) or 2 (symmetric pinwheel) if $\lambda \neq 0$.

Definitions:

T_{TD} = time between successive touchdowns at ground terminal.

T_{PASS} = time between successive overflights of ground terminal meridian.

J = number of complete orbital revolutions per day.

K = number of complete pinwheel revolutions per orbital period.

Spin constraint on non-equatorial ($\lambda \neq 0$) pinwheel:

- ♣ If pinwheel has one arm, K=1 or K=2 is allowed.
- ♣ If pinwheel has two arms, only K=1 is allowed.

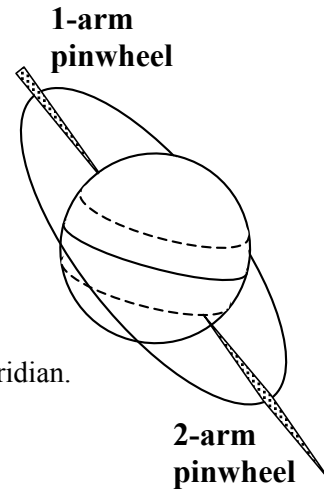


Figure 6. Skyhooks of the foreseeable future. Tether tip descends to ground terminal, where arriving/departing payloads are removed/attached. Tether tip rises again into space. Motion appears vertical to the ground terminal crew at the moment of touchdown.

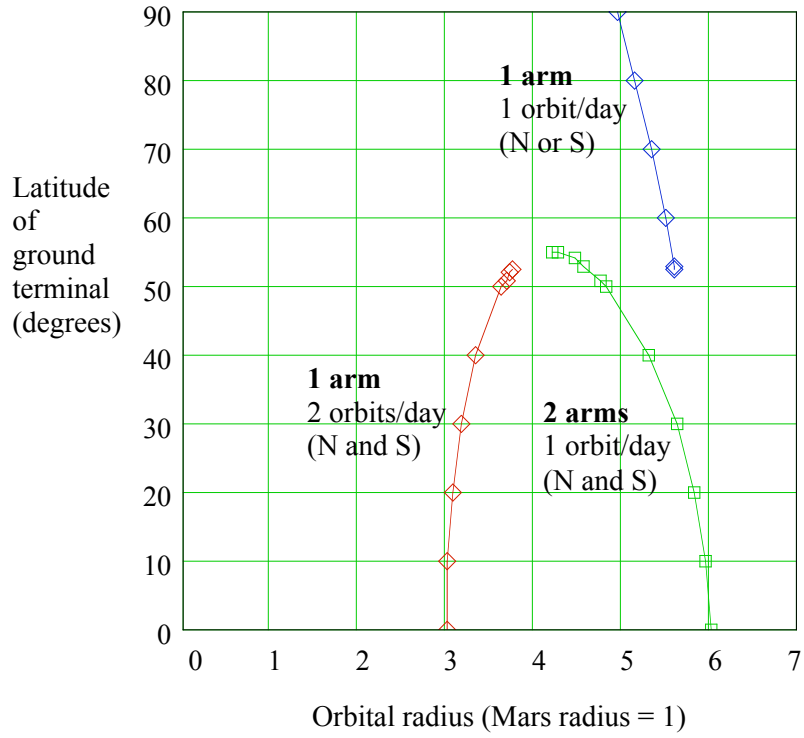


Figure 7. Orbital radii of non-equatorial pinwheels. Ground terminal latitudes north and south must equal the pinwheel's orbital inclination, so one pinwheel can serve at most two latitudes.

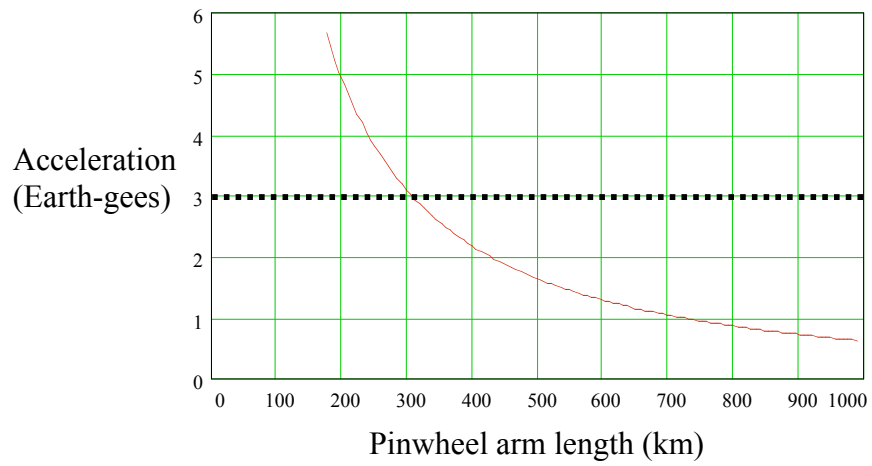


Figure 8. Acceleration of pinwheel payloads upon liftoff from the Martian equator. Dotted line marks acceleration safety limit.