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Article MP-4

Bootstrapping Space Communities with Micro Rovers and High Tensile Boot Laces (Tethers)

How to Start Building Cities and Factories Thoughout the Solar System, for What We Are Now Spending on Space.

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Since parts of this are already out of date, Please send me a note so I can inform you when major updates are made. Thanks. -Bruce, BMackenzie@draper.com

Based on a paper published in the Twelveth SSI Conference; May 1995

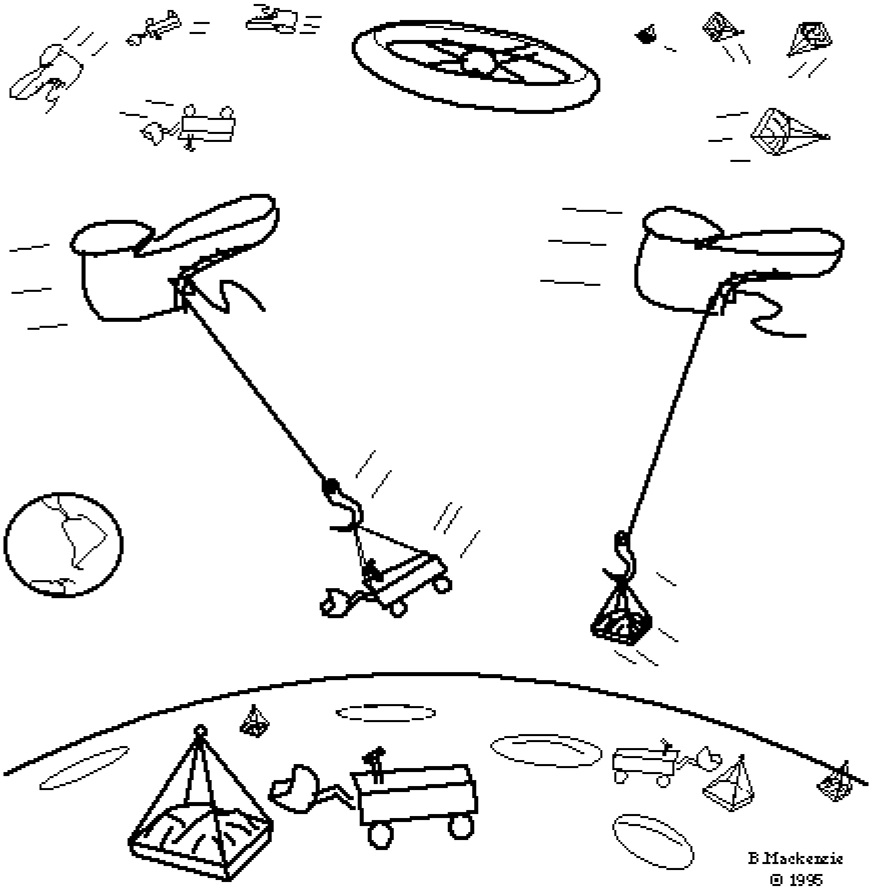

Fig. 1: A Cartoon: The tether (boot lace) and a ballast (boot) rotate clockwise together in Lunar orbit,

orbiting from left to right. A micro rover on left tether swings backwards in orbit and lets go when it has very low net velocity. It uses a small amount of rocket fuel to land softly. The rovers on Lunar surface load Lunar regolith into spacecraft. A Lunar-fuel rocket lifts regolith up to catch the tether at right. It swings around the ballast and is thrown toward upper-right to a refinery and factory (wheel). This regolith is raw material to produce more tethers, ballasts, and rovers which are sent back, upper left. Tether orbit is reboosted when it delivers this new equipment.

Abstract

"Bootstrapping" is the key to starting space settlement: Start with the least expensive manufacturing and transportation system which can increase its own capacity using materials already in space.

Other plans call for many tons of equipment on the Lunar surface to refine oxygen and other materials. The complexity of the equipment requires the presence of human technicians. The presence of people dictate a minimum size and reliability of the equipment. Most of the oxygen would be consumed as rocket fuel to resupply the base. It is not economically feasible to invest the many billions of dollars needed, for several years, before such a Lunar base starts to grow on its own.

In contrast, this proposal keeps complex refining equipment near Earth, where it is cheaper and safer to support people. Raw Lunar soil is brought to the refinery by reusable transportation systems using a minimum of expensive fuel. Material from asteroids could also be used. The system components are:

Tethers, rotating in orbit, catch raw materials coming from the Moon (Luna), recover their kinetic energy, and use that energy to throw additional mining equipment back to the Lunar surface. The tethers are fully reusable and do NOT consume propellants!

Miniature rovers are used instead of astronauts on the Lunar surface. They only need to sift Lunar regolith and load spacecraft. The mining base shrinks in mass (and cost) to a several 10 kilogram tele-operated rovers with a few hundred kilograms of stationary support equipment.

Regolith Rockets use preheated Lunar soil for reaction mass to lift off the surface. A liquid gas is vaporized by the heat of the particles, accelerating them out the rocket nozzle.

Electromagnetic Mass Driver (in later phases) launches miniature spacecraft carrying Lunar regolith into orbit, where they maneuver into a catcher.

This low cost transportation allows us to optimize the locations of manufacturing: Initial manufacturing is in LEO where machinery and workers are easier to support. Later, bulk materials such as oxygen, glass, and metals are refined in high orbit where solar energy is continuously available. Only simple "mining" takes place on Luna and asteroids.

The system grows by using Lunar or asteroid material to produce additional: fiberglass tethers; metals for spacecraft, rovers, and habitats; solar panels, slag for shielding, and oxygen. Growth may be self financing by selling fuel, power, satellite components, and transportation service. - All without the expense of sending people to the Lunar surface.

Bootstrapping this space transportation/manufacturing system breaks through an economic barrier and allows the settlement of space, the most significant migration in history.

System Architecture

Avoid Manned Lunar Base Some proposed systems assume significant refining of materials on the surface of Luna ("The" Moon). It would take a considerable mass of machinery to extract oxygen, or manufacture solar cells on the surface. Astronauts with their safety and support systems would probably be needed.

This is analogous to manufacturing steel and cars inside an iron mine. Instead, on Earth we transport the iron ore to steel mills located near good energy supplies, coal mines. Then we transport the steel to factories in cities where labor is available. Since the manufactured goods include coal railroad cars and coal mining equipment, this system grows, or "bootstraps" itself.

Optimize Locations: A space manufacturing architecture analogous to our steel industry is: Only collect material at the Lunar mine. Transport it to a refinery in high orbit where solar energy is more available. Then transport the refined materials to a factory in Low Earth Orbit (LEO) where it is easier to support workers and machinery.

Miniature Lunar Mine. Use the smallest and simplest equipment on the Lunar surface which is able collect material and load the spacecraft. This could be four tele-operated rovers with earth moving attachments, each about 10 kilograms. They can rely on a base-station with solar cells for power, communication relays to Earth, and a tent for thermal shelter at night. Avoid any complicated materials processing on the surface. For more details, see Phase 2, below.

Manufacturing in LEO. Since the manufacturing equipment may be temperamental and heavy, goods are initially produced in a space station in LEO, later in dedicated factories in LEO. The advantages are: It is cheaper to launch machinery, supplies, and people from Earth to LEO than anywhere else. Spare parts may be brought up quickly. Workers are protected from radiation by the Earth's magnetic field. They can get back to Earth quickly in an emergency. And, there is a market for these goods in LEO. See Phase 5, below.

Refining in High Orbit. Bulk materials such as oxygen, glass, steel, and aluminum should be refined in a high Earth orbit, anywhere between GEO and Lunar orbit. Solar energy is more available than in either LEO or the Lunar surface. There may be benefits from zero gravity, if not, part of the refinery can spin for artificial gravity. Transportation costs are low from high orbit to most anywhere, including interplanetary space. The refineries should be highly automated. Tele-operated robots would do simple repairs by swapping components. When human repair technicians are required, they would spend most of their time in workshops shielded with slag produced by the refinery itself. (For the lowest initial cost, the first refinery would be in LEO.) See Phase 6, below.

Transportation Systems: An efficient transportation system is required to move raw materials and finished products to where they are used. Chemical rockets are clearly inefficient, since they may burn more fuel than the payload they deliver. Although Lunar oxygen could be produced for rocket fuel, the initial oxygen plant would be very expensive to transport to the Lunar surface.

Here are some more efficient transport methods:

Rotating Tethers: Picture a massive object (a "ballast") in orbit and slowly rotating about its own center. A rope (tether) extending several kilometers from it and rotating with it would have a significant relative velocity at its tip. Spacecraft released from the tip could fly into much higher orbits. Craft coming in from those orbits could intercept the tether tip at a small relative velocity. If they hang on for a half revolution, and let go, they will fall into a much lower orbit. These tethers could be very massive, but, unlike rocket fuel, tethers are fully reusable. The same tether can catch and throw payloads repeatedly. See Phase 1.

Acting like a bucket-brigade, a series of three rotating tethers can throw mining equipment from low Earth orbit to the Lunar surface, and catch raw materials coming back. As a tether catches a craft coming down toward LEO, it recovers the excess kinetic energy and stores it as its own orbital momentum. That energy is later transferred to another craft when it is caught in LEO and thrown upward. By conserving and transferring the kinetic energy, no propellants are needed for two-way travel, except for minor obit adjustments to intercepting the tether. See Phase 3.

The Earth orbiting tethers should be kept well above the atmosphere. Due to orbital perturbations, the Lunar tether should be kept at a safe altitude and not allowed to touch down on the Lunar surface. Rockets or mass drivers are used for the ascent or descent to the surface.

Regolith Rocket: The most readily available rocket "fuel" on Luna is dirt (regolith particles), somehow thrown out the back of a rocket. To provide the energy needed, preheat the regolith with a solar collector before takeoff. The hot particles are fed into the rocket chamber. A small amount of any liquid gas is vaporized and then injected in behind the particles. The gas expands further due to the heat of the particles as it accelerates the particles out the rocket nozzle.

This regolith rocket is not very efficient, but it could get to a significant altitude and velocity in the low Lunar gravity. Most importantly, the fuel is readily available and "dirt cheap". See Phase 4.

Mass Driver: Perhaps the most efficient transportation off the Lunar surface would be to accelerate tiny spacecraft through a series of magnetic windings, known as an electromagnetic Mass Driver. No propellant is expended, only electrical energy from solar cells. Recent advances in miniature components, such as silicon based gyroscopes, would allow such a craft to survive the 1,000's g acceleration of the mass driver. The craft would solid state guidance system and miniature thrusters to rendezvous with a net dangling on the end of a tether. After delivering regolith to be refined, several of these mass-driver craft are returned to the Lunar surface using a rotating tether and regolith rocket. See Phase 6.

Summary of Implementation

To minimize the up-front costs, the system is implemented in the following phases, using the lightest and simplest components practical in each phase. More details for each phase are given later.

Phase 1. Commercial Tether Launch System:

A rotating tether assists small payloads to higher orbits (generating income).

1.a. Single tether delivers small communications satellites to medium orbits.

1.b. Two larger tethers delivers communications satellites to GEO (GTO). [TBD]

1.c. Catch and dispose of space junk (optional).

Phase 2. Establish Mini Lunar Base:

Establish a miniature robotic mining base, with small rovers, communication relay, and central power source. They are landed using a tether in Lunar orbit, which also transport scientific instruments to Lunar surface for more income.

2.a. Add third tether in Lunar orbit.

2.b. Scout rovers help choose site.

2.c. Land rovers and equipment.

Phase 3. Two Way Lunar Transportation:

Use tethers and small chemical rockets to return lunar soil for scientific and engineering studies (and to sell as souvenirs for income). This also reboosts the tethers, eliminating most use of propellant.

Phase 4. Regolith Rockets: Use regolith and any liquid gas as propellant for more frequent, larger deliveries of Lunar soil.

4.a. Dual fuel craft based in LEO, land with chemical fuel, ascend with regolith.

4.b. Regolith rockets based on Lunar surface grab payload from tether; ascend and descend with regolith.

Phase 5. Initial Space Manufacturing: Refine Lunar oxygen & fiberglass at a manned LEO space station (sell oxygen).

Phase 6. Boot-Strap Larger Manufacturing & Transportation Systems:

6.a. Use lunar fiberglass and slag to build advanced tether stations for out of plane launching. Assist larger commercial satellites to orbit (more income).

6.b. Enlarge Lunar mining base. Increase rate & size of returning payloads.

6.c. An electromagnetic mass driver on Lunar surface launches small special "high-g" spacecraft with regolith into low lunar orbit, catch in a net at end of tether.

6.d. Manufacture in LEO: structural components, solar cells, antennas, mirrors. Assemble satellites (to sell for more income).

6.e. Develop automated oxygen refinery. Move it to high orbit for better sunlight.

Phase 7. Break-Out:

To begin true settlement of space: manufacture components of habitats, greenhouses, and additional manufacturing plants. Use tethers to throw components to any location, including asteroids & Mars orbit. Assembled on site. This enables the most significant migration since Earth life began!

Financing: The initial system could be developed by either a consortium of companies or governments. It will be partially self-financed after phase 1 by selling transportation services. The commercial income sources are:

1. transportation of satellites from LEO to their desired altitude using tethers (phase 1, 6).

2. transportation of scientific instruments to Luna and interplanetary space (phase 2, 3).

3. selling Lunar soil for souvenirs and science (phase 3, 4).

4. selling Lunar oxygen to fuel spacecraft, breathing, drinking water (phase 5)

5. installing solar panels on spacecraft, and other components listed above (phase 5, 6).

6. building structural components of spacecraft and space stations (phase 6).

7. building space stations and Solar Power Satellites (SPS), tourism, communication, remote sensing, and eventually selling real estate in space habitats. (phase 7).

For maximum growth, we could temporarily forego any profit and use most of the manufactured goods to enlarge the manufacturing capacity.

Remember, this can be started and brought to a profitable stage without the expense of supporting people in a Lunar base.

Details of Phases of Boot Strap

Here are details for each phase to bootstrap the settlement of space using first tethers, then micro-rovers, then low-orbit manufacturing plants. Of course, development and testing must precede each phase, and the phases would overlap in time.

I have not tried to optimize this system. Most choices for mass and size of components are arbitrary. They were made to keep the cost down, but still be consistent with current technology. There are many possible 'trade-off' choices which a full system study should consider.

Phase 1.

Commercial Tether Launch System

The first and most important step is to lower the cost of space transportation. Reusable launchers may help lower launch costs to LEO, but we also need low cost transportation beyond LEO.

In Phase 1, we install and gain experience with a commercial inter-orbit transportation system based on rotating tethers. Both the income and transportation service from this phase are needed for later phases.

Why Tethers? Like rocket fuel, the mass (and thus cost) of a tether can be several times larger than the payload it launches, and it is proportional to the payload mass. Unlike propellant, a tether is completely reusable. Thus, a thin tether can launch many small payloads for less cost than the propellant that would be needed. Of course we must amortize the cost of the tethers over the number of craft they handle. See Appendix for the mass of tethers.

Why Rotate. Orbital tethers are subject to 'environmental damage', primarily risk of being cut by meteorites or orbital debris , degradation due to radiation and (at low altitudes) atomic oxygen. Many plans involve 'hanging tethers' pointing toward the Earth and stabilized by the gravity gradient. They must be hundreds or thousands of kilometers long, and very difficult to protect and repair. If allowed to rotate, they only need to be 5 to 40 km in length. Being shorter, rotating tethers are less likely to be hit be meteorites, and have less surface area needing protective coatings.

The best protection is to reel a tether in when not in use, with a meteorite shield around the spool. Note that it is difficult to reel in a hanging tether because its tension drops to zero toward the end, allowing it to tangle or hit the ballast. Pulling the tether part way in changes its tip velocity, allowing you to launch payloads into different orbits. Repair spacecraft can be caught and pulled in to repair the tether ballast.

First Tether: The upper stage of a rocket is fitted with a tether and related equipment as a secondary payload. After it is in orbit it releases its primary payload. Then the tether is deployed and started to spin by firing small thrusters at the tip. It is not reeled back in, thus avoiding some control problems. The spent upper stage serves as a passive counterweight, and should be as massive as possible.

Catching Sub-Orbital Rockets. Assume this tether system orbits at altitude of 370 km and orbital velocity of 7.7 km/sec. It rotates around the spent upper-stage at 1.75 rpm, with a length of 5 km and relative tip speed of 1.0 km/sec.

If the tether is made of 'Spectra 1000 polyethylene, with a safety factor of 3, it's mass will be 1.75 times the maximum mass of the payload.

A sub-orbital rocket accelerates to 6.7 km/sec, and releases its (small) payload. Both the payload and a 'catcher' on the end of the tether maneuver so that a hook on the payload catches a loop at the tether tip. The payload is swung through one-half revolution, and released. Its perigee is at 370 km and now 8.6 km/sec. Its new apogee is about 5000 km and 5 km/sec. Chemical rockets can be used to raise or circularize its orbit.

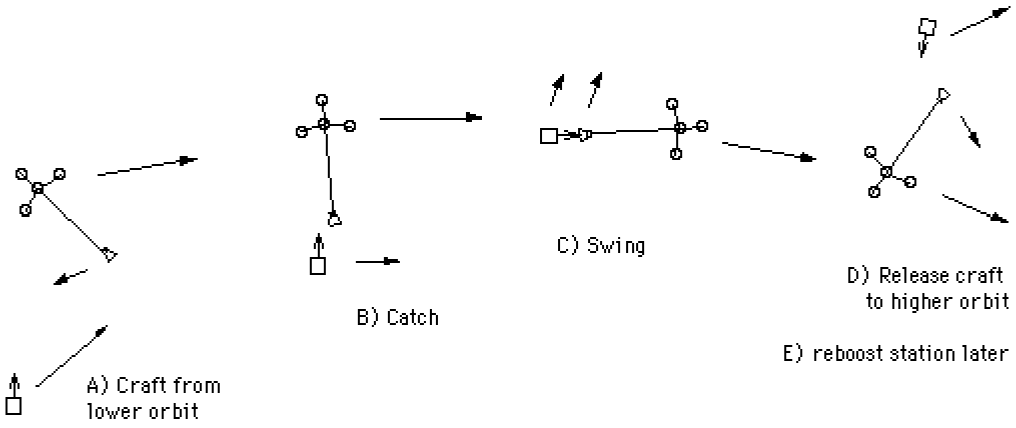

Fig. 2. Catch and Throw with Rotating Tether: Rotating tether and ballasts are in circular orbit from left to right. A) Spacecraft at apogee of lower orbit almost matches velocity of catcher on tether tip. B) Intercepts and hooks onto catcher. C) Rotate one-half revolution, transferring kinetic energy and momentum from ballasts to craft. D) Release spacecraft, now at perigee of a higher orbit. E) Reboost tether's orbit at leisure with electric thrusters or by catching another craft coming from higher orbit.

Fuel Efficiency: The tether system has transferred some of its orbital momentum to the payload it catches and throws. (Note its rotation rate has not decreased, only its orbital velocity). The orbital velocity is reduced by the payload's delta-velocity divided by the ratio of their masses. For phase 1, this lost momentum is made up by high Isp electric thrusters and solar cells attached to the ballast.

It is actually cheaper to reboost the tether with rockets, than to have accelerated the payload with rockets. The tether (and ballast) are much more massive than the payload, so it slows down very little. According to the 'rocket equation', fuel use grows exponentially with delta-velocity, but is only proportional to mass. Thus, it is inefficient to accelerate a payload's small mass at a high velocity, and more efficient to accelerate the tether's larger mass by a smaller velocity. This effectively eliminates the exponential term in the rocket equation.

In addition, these thrusters and power supply are effectively stationary (do not travel with the payload). They can be optimized for best specific impulse (Isp of several thousand seconds) at the expense of requiring larger power supplies. This Isp is about 10 times better specific impulse than chemical rockets. Also, release by a tether is an 'impulse thrust, which allows more efficient Hohmann transfers instead of the spiral orbits typical with electric propulsion.

Momentum Transfer: When a tether catches a craft coming from a higher orbit, its orbital velocity increases. It can act as a "momentum bank": receiving extra momentum from Earth-bound craft, and later returning that momentum to upward-bound craft.

The system would be most efficient with two-way traffic. This only happens in phase 1 when satellites are brought lower to be repaired, refueled, or deorbited. But, by phase 3, the tethers will recover the momentum of Lunar regolith coming down, and return that momentum to craft bound toward Luna. This will eliminate the use of propellant to reboost the tethers.

Surrogate Maneuvers: A tether may also modify its orbit by throwing payloads around the Moon or into the atmosphere and then catching them. I call these maneuvers "surrogate gravity assists" and "surrogate aero-braking" because the tether does not do the gravity assist or aerobrake maneuver itself, but has another (surrogate) craft do the maneuver for the tether.

Tether Components: Each "tether" is really an assembly of the following:

Tether: The tether itself is made up of multiple strands of polyethylene (or lunar fiberglass). They are separated by spreaders to minimize the chance that they are all cut by the same space debris object. Extra strands are added near the center of rotation to give the optimal taper.

Catcher: A 'sub-satellite' at the tip of the tether catches or releases the spacecraft. It dangles two flexible 10 meter 'fishing' poles with a cable between them, which the spacecraft will hook onto. It has sensors, reflectors, transponders, differential GPS, and other navigation aids to track the payload. A small winch can pay out tether if needed. Thrusters may be used for last-minute maneuvers to intercept a payload. Total mass is perhaps 20 to 40 kg. It could be based on the kinetic-kill vehicles currently being tested to intercept ballistic missile warheads. See Fig. 3.

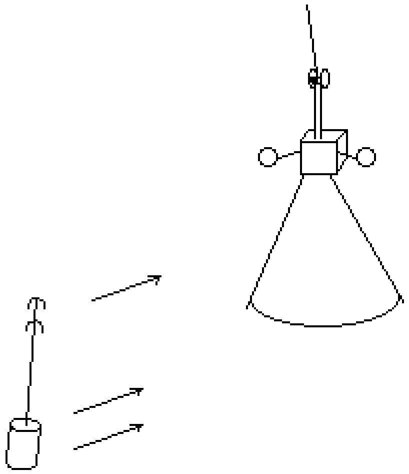

Fig. 3. Spacecraft (left) with pole and hooks maneuvering to intercept cable dangled below catcher (right) on tip of tether. Relative velocity is 1 to 100 m/sec.

Ballast: To maintain its orbit, the tether is anchored to, and rotates with, the most massive ballast practical. It has navigation sensors, communication relays, solar panels, winch, spare tethers, and electric thrusters. For extra mass, it may include spent rocket stages, discarded station supply vehicles, parts of shuttle external tanks, and any space junk. Later, Lunar rocks and slag left after refining Lunar materials are used for mass.

Winch and Repair: When not in use, the tether is rolled up on a reel for protection. As it is pulled in, it passes inspection stations. Any broken strands of tether are replaced by robotic arms located there.

Two Tether Bucket Brigade: As the velocity of a payload increases, the mass (and cost) of a tether to launch it increases faster than exponentially (see Appendix). Rather than use one massive tether to throw a payload GEO or beyond, it is cheaper to use a series of tethers in different orbits, and pass a payload from one to the next.

The catching and throwing should be done close to the Earth (perigee), because the payload's kinetic energy is proportional to the velocity-squared, which is greater at perigee. The ideal scheme would involve a series of tethers in elliptical orbits with there major axis aligned, unfortunately, their orbits would precess at different rates.

A good compromise is to have two tethers, one in a low, circular, equatorial orbit; and a second tether in an elliptical, equatorial orbit; as shown in Fig. 4. Being in equatorial orbits, their orbital planes will hardly precess. Precession of the upper tether's major axis does not matter, because the lower tether's orbit is circular. It can time the release of a payload so as to arrive near the upper tether's point of perigee.

With relative tip velocities of 1.5 km/sec., these two tethers can catch a payload from a suborbital rocket, and throw it to greater than escape velocity.

The sequence is labeled in Fig. 4:

1) suborbital launch to 6.2 km/sec,

2) catch tether in LEO, whose orbital velocity is 7.7 km/sec,

3) throw to higher elliptical orbit, perigee velocity 9.2

4) wait in elliptical parking orbit,

5) catch by upper tether, perigee velocity is 10.7 km/sec,

6) throw at 12.2 km/sec, (5.5 km/sec after Earth escape),

7) optional chemical thrust,

8) optional Lunar swing-by,

9) encounter any of 20 NEA asteroids.

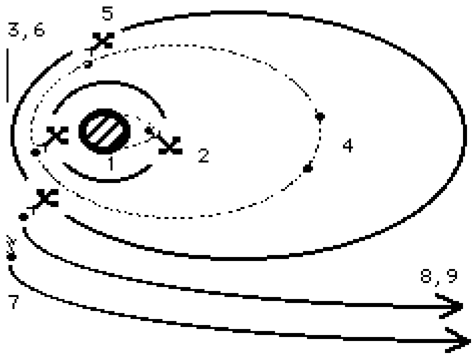

Fig. 4. Two Tether "Bucket Brigade" for suborbital to escape velocity transport.

There are two problems which need further consideration: The upper tether can only launch craft upward in the direction of its orbit's major axis, so they can only take a direct route to the moon when it is in that part of its orbit once a month. Also, it will be desirable later to develop a space station in the same orbital plane as the tethers, which is equatorial.

Collect Space Debris: Although not part of the bootstrap process, tethers could help reduce future space debris. The tether throws an orbital transfer vehicle to intercept and catch large space junk. It is then returned and caught by the tether. The junk is thrown backwards to deorbit it, or added to the tether ballast for extra mass and momentum storage.

Phase 2.

Miniature Lunar Base

A miniature, tele-operated Lunar base is established after the two tethers in Earth orbit are generating income and able to throw payloads toward Luna.

Lunar Tether Maneuvers: To inexpensively deliver equipment for this Lunar base, a third rotating tether is placed in Lunar orbit. It catches craft coming from Earth and decelerates them, dropping them at a modest velocity and altitude to descend to the surface. The following details are adapted from a proposal by Dani Eder.

The tether (including ballast) is launched into Earth orbit, and uses its own electric thrusters to climb to

Lunar orbit. Its altitude is 100 km, and orbital velocity is 1.6 km/sec. The tether tip has a relative velocity of 1.5 km/sec. The tether itself has a mass of at least 500 kg. The ballast has a mass of perhaps 2000 kg (larger is better), including an extra tether, extra catcher, solar panels, electric thrusters, and, of course, scientific instruments.

A small 100 kg craft is thrown by the other two tethers near Earth. It arrives with greater than Lunar escape velocity, about 3.2 km/sec. It grabs the tether tip on the far side of the moon, and hangs on until it is over the Lunar base. The craft lets go as the tether swings backwards. Its net forward velocity is less than 0.5 km/sec, although about 0.7 km/sec of deceleration is required from a chemical rocket to slow down, descend to the surface, and accurately land.

Propellant used to take this 100 kg craft from LEO to the Lunar surface could be as little as 20 kg (assuming an optimal series of tethers), but probably significantly more. However, the same mission would require 3500 kg of chemical fuel without tethers.

Some spacecraft are reusable and carry fuel for a return trip, but only deliver one 10 kg. rover. Equipment more massive than 10 kg. can still be transported by the tethers, but their landing rockets are abandoned on the surface.

The tether can also land scientific instruments at other points on the Lunar surface, providing additional income from government sponsors for transportation or sale of data.

Scout Rover: First to land would be a small rover to check out the potential site. It would be used to map the terrain, check the soil, choose safe landing areas, choose safe 'trails' for later rovers, and deploy navigation aids for accurate landing.

This scout rover could be based on "Grendel", a 2 kilogram, 6 leg walking robot. Grendel was successfully flown on and delivered by the Leap spacecraft, a follow-on to the Clementine mission. Unfortunately, it was an indoor test flight, which only delivered the non-space-rated Grendel to a simulated Lunar landscape. Slightly larger rovers are commercially available for only several thousand dollars.

Miniature Rovers: Most operations at the Lunar mine are performed by several small (10 kg) tele-operated rovers.

Their main function is 'earth' moving, just pick up Lunar regolith and load it into spacecraft. They might look like the rover in Figure 5, but with digging and scraping attachments. Traction is a problem in the low lunar gravity. So, they would attach a cable to an anchor, and winch themselves back toward the anchor while scraping up regolith. The same cable can supply the electric power needed.

Some rovers with robotic arms would also set up the major pieces of equipment. Four rovers could also pick up and carry a spacecraft if it landed in a bad location.

These rovers are simpler than exploratory rovers. They only travel in designated safe areas. They rely on navigation beacons, communication relay, a stationary power supply, and tent for shelter. The high-level control of the rovers is done by central computers, overseen by people on Earth.

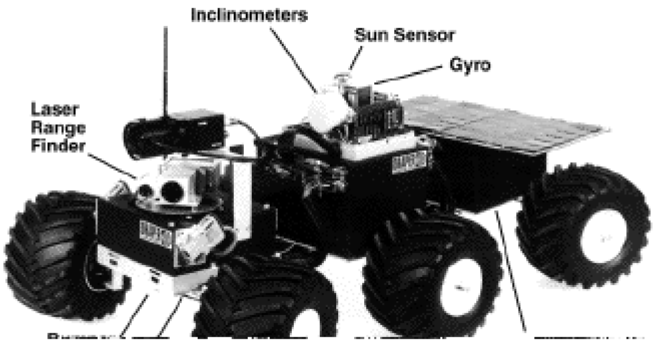

Fig. 5. "MITy-2" Prototype Micro Rover, about 10 kg and 50 cm long. (courtesy David Kang, Draper Lab.)

Mining Base Facilities: The central feature of the base is a shelter a few meters across. Rovers covere it with regolith for radiation protection and to even out the day/night temperature variations. The rover stay inside during the cold 14 day darkness (perhaps huddled around an RTG for warmth). See Fig. 6.

Most electronics are inside the shelter to lessen the radiation exposure. It includes the rover controllers; and communication links between Earth, rovers, and approaching spacecraft. For power, photocells are unrolled on the surface.

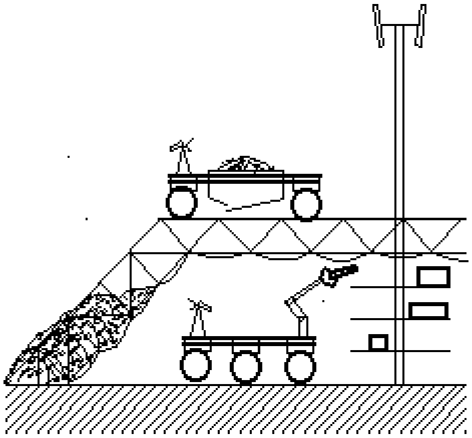

Fig. 6. Lunar shelter. Top rover is dumping regolith over truss for radiation shielding and thermal mass. Lower rover is installing additional electronics. Mast holds communication antenna.

Cost/Mass Estimate: It is time to estimate the project's cost, in terms of mass of deployed equipment. The following figures are very crude estimates based on a variety of informal sources, or just guesses.

The Lunar and Elliptical tethers are sized for 100 kg. payloads. The 1000 kg LEO tethers are sized for launching small 500 kg. commercial satellites. They could be lighter if only used to transport the smaller lunar craft.

The 10,000 kg. of extra mass on the LEO tether ballast is assumed to be discarded rocket stages, and thus not counted in the total 'cost'. These figures do not include prior test flights.

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Rovers, 5 @ 10 kg = 50 kg

Power, Electronics 6 @ 10 kg = 60 kg

Shelter + Antenna 1 @ 80 kg = 80 kg

Other / reserve 80 kg

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Sub-total on Lunar Surface ~270 kg

Landers (reusable) 10 @ 30 kg = 300 kg

Lunar Tether 500 kg +

Spare Tether 1 @ 500 kg +

Lunar Ballast 1000 kg = 2000 kg

Elliptical Tether 200 kg +

Spare Tethers 3 @ 200 kg +

Elliptical Ballast 1600 kg = 2400 kg

LEO Tether 1000 kg +

Spare Tethers 3 @ 1000 kg +

LEO Ballast 1000 = 5000 kg

LEO extra mass (junk*) (10,000 ) (10,000 *)

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Total in Space (w/o junk) ~10,000kg
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Phase 3.

Two Way Lunar Transport

A goal is to minimize the propellant (and thus cost) of operating the transportation system. Until this phase, the tethers must use their electric thrusters to reboost their orbits. This can be avoided if the tethers throw spacecraft in both directions.

Return Regolith Samples: As soon as the rovers are in place, the spacecraft which delivered them can start returning Lunar soil to Earth. The craft use their chemical rockets to lift off surface and accelerate to intercept the catcher of the Lunar tether. This requires much less fuel than reaching orbit. They are caught and thrown by each of the three tethers in turn: Lunar orbit, elliptical orbit, and LEO; until they either arrive at a LEO space station or return to Earth.

The regolith is used for scientific study, to test processing equipment planned for later phases, and to sell as souvenirs to help finance this project.

Avoid Tether Reboost: But, the real reason to return regolith is for two-way traffic. Each time a returning craft uses a tether it restores the momentum which an outbound craft borrowed from that tether. As long as the mass-flow is reasonably balanced, the tethers need not use their electric thrusters to maintain their orbits. Only a tiny amount of propellant is used for minor orbital adjustments and when the craft intercept a catcher.

Mass Flow Estimate: Here are crude estimates of the mass of spacecraft, propellant, and payloads. It assumes several reusable chemically powered craft are based at a LEO space station. There are 5 round trip flights each Lunar month. Each flight delivers one 10 kg. rover or other equipment, and returns with perhaps 67 kg. of regolith, using about 50 kg. of propellant for the round trip. (Note, these figures are not accurate enough to compute a ratio of regolith to propellant.)

There is a problem: the outbound and inbound mass flow as measured at the tethers is not balanced: Total outbound mass affecting the tethers is (88 x 5 flights) 440 kg/month; while total inbound mass is (100 x 5) 500 kg/month. So the Earth orbiting tethers will be boosted to higher and higher orbits. To "deboost" the tethers, it is necessary to add additional out-bound flights, averaging 60 kg. per month. These could be scientific payloads to various Lunar sites. (After waiting years between launch opportunities, I am sure the scientific community would love the challenge of supplying an instrument package every month.) [TBD, can control eccentricity by careful choice of location and timing of the other landings.]

[[Disclaimer: preliminary mass estimates. Used data from different sources, not confirmed.]]

```
Leaving LEO Station kg/flight kg/month

--------------- --------- ------

Craft, dry mass 25

Payload (new rover) 10 x 5 flights = 50

Propellant carried 53 x 5 = 265

Mass on tether, outbound 88 x 5 = 440

Propellant for tether int'cpt 3

Propellant for descent 18

Propellant remaining 32

Mass at landing 80

One-way Craft + fuel: 60 x 1 flight = 60
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```
Total Mass flow, outbound (440 + 60 =) 500

Leaving Lunar Surface kg/flight kg/month

--------------- -------- ------

Craft, dry 25

Payload (regolith) 67 x 5 flights = 340

Propellant at launch 32

Total Mass on takeoff 124

Propellant for ascent 24

Mass on tether, inbound 100 x 5 = 500

Propellant, tether intercept 4

Propellant, reserve (4)

Mass on return to LEO 96
```

Cost Effectiveness: This Lunar regolith will not be a cost effective source of materials since the amount of regolith payload delivered to LEO is about equal to the propellant used for Lunar landing & takeoff. However, the regolith is valuable for experiments and souvenirs. The critical use of regolith is to balance the mass flow, while we build up the Lunar mining base by 50 kg per month, plus additional scientific payloads. Also, public attention will be focused on the use of extra terrestrial materials and it will be taken seriously by the funding agencies and investors.

If the estimate from phase 2 of 10 tons of tethers plus ballasts is anywhere near accurate, it means we can begin the Bootstrap process of using space resources with a single large launch; or, more likely, a few small launch vehicles plus some secondary payloads. At $20,000/kg [TBD ?], the launch costs would be 200 million dollars. For comparison, this is only ___% of the ____ [TBD ?] tons which are launched into orbit each year.

Phase 4.

Regolith Rockets

To further reduce the use of propellants from Earth, the Lunar soil can be used in a "regolith rocket". None have been tested yet, so this phase could be skipped if they do not work as predicted.

Regolith Rockets Engines: The reaction mass for these engines is "fluidized regolith", the finest regolith particles suspended in a gas so they act as a fluid. Energy is provided by preheating the particles. The particles are fed the rocket 'combustion' chamber, along with a small quantity of liquid hydrogen. As the gas vaporizes, it expands and accelerates the particle out the nozzle. Lunar oxygen or other liquefied gases could be also be used.

Their Isp is predicted to be 70 to 220 seconds, depending on the regolith temperature and amount of gas used. To avoid the possibility of sintering the regolith in the fuel tank, its temperature should be kept below 1000 deg. K, Isp would be less than 100 seconds. The mixing ration is greater than 50:1; that is, the amount of gas needed is less than 2% of the mass of the regolith. So it would be reasonable to bring the gas from Earth at first.

Tethers and regolith rockets complement each other nicely: Regolith rockets would be inefficient for launch into lunar orbit. But, they can achieve half orbital speed with a significant payload. A modest orbiting tether can catch a payload at half orbital velocity. But, a tether to pick up payloads directly from the surface would be much more massive, and its orbit must close to the surface and therefore unstable.

Here are two possible uses of regolith rockets:

Dual Fuel Spacecraft. It uses liquid oxygen and a chemical fuel for the final descent to the Lunar surface, bringing equipment plus a small reserve of oxygen. At the mining base, it is loaded with hot regolith particles. It takes off using its regolith rocket engine and the reserve of liquid oxygen. It catches the end of the Lunar orbiting tether. The series of tethers throws it back to the LEO station, with the tank still half full of regolith as the 'payload'. It is serviced and refueled in LEO. Had it missed the first tether, it has just enough regolith to achieve Lunar orbit, where it waits for later rescue.

Surface Based Regolith Rocket: The rocket is based at the Lunar base fueled with regolith and Lunar oxygen. It flies up perhaps 100 km and with slight horizontal velocity. There it catches a payload from the tip of the rotating Lunar tether, and returns to the base. Routine servicing must be done on the Lunar surface. For a major overhaul, it is light enough to use the tethers for transport to LEO, but with no payload.

Regolith Processing. Additional equipment is needed on the Lunar surface to load the regolith rockets. The rovers dump raw regolith through screens to separate gravel. (The gravel is then spread on the spacecraft landing areas so they will not blow dust around.)

The finest regolith is separated further in 'float zone' tanks, by pumping a gas up through it. The particles smaller than 10 to 20 micrometers (10% to 20% of the total mass) float to the top and are pumped out for use as propellant. These "fluidized particles" are pumped through a solar furnace to heat it to at least 1000 deg. K, and then into the rocket's regolith tank. The surplus gas from the top of the tank is piped back to carry more regolith.

If hydrogen gas is used in the solar furnace, some will bind with oxygen from the regolith. It comes off as water which can be electrolyzed to recover the hydrogen and produce oxygen.

Phase 5.

Initial Space Manufacturing

There is now a steady supply of regolith arriving at a LEO space station. It is used to produce oxygen and simple materials, such as fiberglass and aluminum. The oxygen is sold as rocket fuel. Regolith is also used in greenhouses to grow food, or at least in plant growth experiments. Equipment for more advanced refining and manufacturing is tested.

This phase may be very labor intensive, trying out machinery which has never been used in space. This is the reason we brought the regolith to low Earth orbit, where people are more protected from radiation, and transportation from Earth is less expensive.

The actual processing methods are not the subject of this paper, and are well covered in other papers at these SSI conferences.

Phase 6.

Boot-Strap Transportation

The system begins to grow itself by producing machinery which enlarges its own manufacturing and transportation capabilities. The materials produced are:

Glass: Fiberglass for stronger tethers to increase the maximum payload which can be returned from Luna. Glass mirrors for solar furnaces. Glass windows for habits.

Oxygen: for breathing, water and food growth allows more people to work in space (with hydrogen brought from Earth).

Solar panels: to produce electric power

Metals: aluminum and steel to make fuel tanks, trusses, radio antennas, other large spacecraft components, and manufacturing equipment.

Slag: the leftover material, for shielding worker's habitats, and as ballasts for tethers.

Automated Refinery: Automated refineries for simple materials such as oxygen and metal are build in LEO. Then moved to high orbit to be in continuous sunlight and nearer the raw materials.

Upgrade the Lunar Base: Larger rovers are assembled, with the chassis, wheels, and solar cells made from lunar materials. Spacecraft are assembled from fuel tanks, frames, legs made from Lunar materials.

Mass Driver: Place an electro-magnetic mass driver on Lunar surface to launch material. Small space craft can be developed to carry regolith and withstand the acceleration of a mass driver. They would be quite similar to the guided artillery shells being developed. These have micro-machined silicon gyroscopes, and a global-positioning-system (GPS) receiver. After launch from the mass driver into a low lunar orbit, they maneuver into a net at end of tether. They are assembled together, and thrown to other tethers in high earth orbit. (Regolith or chemical rockets are still used to return the mass-driver craft to the surface to be refilled and launched.)

Advanced Tether Station: In this phase Lunar materials can be used to construct a type of rotating space stations with attached tethers (designed by myself). They have the medical benefit of artificial gravity, the habitats also serve as ballasts for the tethers, and the tethers can throw craft into inclined orbits, thus avoiding plane change maneuvers.

At least 3 habitat modules are suspended from and rotate around a central axial truss. The habitats store most of the angular momentum and also act as lever arms for fast deployment of tethers. The habitat arms are hinged in such a way that the entire craft is self-balancing. See Fig. 7.

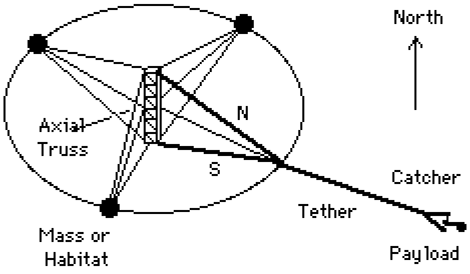

Fig. 7. The truss along the axis has cables to swing tethers out of plane of rotation, enabling launch or capture out of the orbital plane.

A "Small" version of this station rotates at 1.75 rpm and has living modules at 110 and 290 meter radius (3/8 and 1 gravity). Cargo-only craft use tethers 5 to 8 km in length, providing a delta-V of 1.0 to 1.5 km/sec.

A Large station rotating at 0.25 rpm would have living modules on cables at 5.4 km radius (3/8 gravity). Extending tethers 38 km provides a delta-V of 1.0 km/sec with less than 3 g acceleration, acceptable for passengers. Catching a 2-person, 5000 kg craft at 1 km/sec could be done with a graphite tether massing 8300 kg (1.66x payload). Fig. 8.

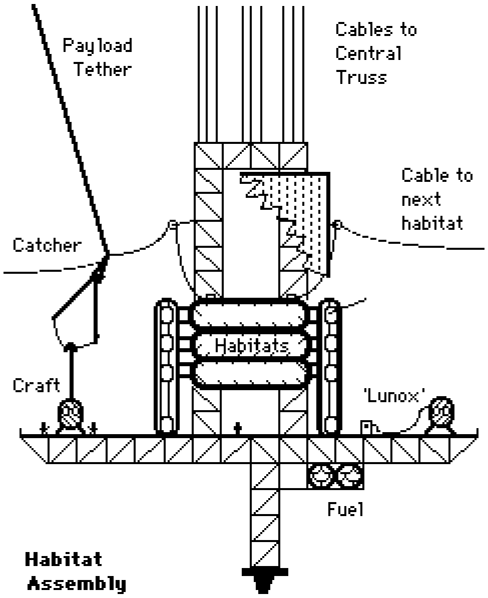

Fig. 8. Large habitat and satellite servicing module for advanced tether station, one of 3 in previous figure.

Phase 7.

Break-Out

As more people work and live in orbit, a space economy will develop. There will be multiple Lunar and Asteroid mines, multiple factories, and a network of tether stations throwing shipments back and forth between them.

This network of tether stations may have an interesting effect on space commerce. A tether has a strict upper limit for the mass of payload. Assume a maximum of 5000 kg to allow for a two-person craft 30% heavier than a Gemini spacecraft. Eventually, many spacecraft would be that size. There would be a strong economic incentive to keep all shipments below this 5000 kg limit, and little economic incentive to build tethers stronger than 5000 kg. (Just as many trucks are the maximum height, and few highway bridges are much higher than the standard truck.)

However, shipments within this limit would be inexpensive. A factory could produce pre-fabricated components of a space habitat. Tethers could deliver the components most anywhere inside the asteroid belt. But, the pieces of the habitat must be assembled on-site. And, some mass should be sent back to balance the momentum lost by the tethers.

As the people in space become less dependent on Earth, settlement may shift to asteroids where materials are plentiful, and the asteroid's low gravity allow for this inexpensive transportation. All of humanity would benefit: It relieves some industrial and social pressure on the Earth. We gain experience managing a variety of ecosystems (the lessons can be applied to Earth). Civilization could now survive most any global catastrophe. And, it broadens the horizons of our children.

Conclusion

This outlines an in-expensive way civilization can begin to "Break-Out" of the Earth's gravity well:

First establish a small, but reusable transportation system for raw materials. It consists of miniature space craft and rovers to transport Lunar regolith. Long rotating tethers in various orbits throw and catch the spacecraft, recovering momentum from them to avoid using propellant.

Second, use those materials in low Earth orbit to manufacture components to enlarge the systems; thus "bootstrapping" to better transportation and manufacturing systems.

Continue enlarging the system, including building habitats and later whole communities for the people involved. Eventually, a network of space communities can use tethers to throw vehicles back and forth, at very low cost, much like railroads do on Earth.

Appendix: Tether Strength.

The figure and table below show the required mass of commercially available tether materials compared to the mass of the payload plus catching mechanism. A safety factor of 3 is assumed to account for defects, wear, broken strands, and peace of mind. Any protective coatings and spreaders are NOT accounted for. Fig. 9.

Fiberglass produced from Lunar or asteroid material is included, with a safety factor of 4. Since it can be produced in the complete absence of water, it may be stronger than terrestrial fiberglass, which is about as strong as stainless steel for its mass. Manufacturing fiberglass in space may be much cheaper than transporting tether material from Earth. Due to its higher density, it should be used for the inner, thick portion of each tether.

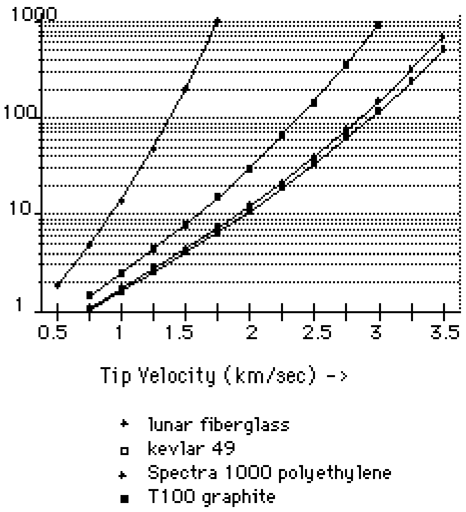

Fig. 9. Ratio of Tether Mass to Mass of Payload as a function of tether tip (payload) velocity.

`Material: Fiber Kevlar S1000 T1000`

`glass 49 Poly. Graphite`

`max. stress`

`(GPa): 2.8 3.62 3.45 6.9`

`safety`

`factor: 4 3 3 3`

`working`

`stress: 0.7 1.2 1.15 2.3`

`density`

`(g/cm3): 2.5 1.45 0.97 1.83`

`mass ratios for:`

`0.5 km/sec: 1.85 0.80 0.64 0.62`

`1.0 km/sec: 14.1 2.51 1.75 1.66`

`1.5 km/sec: 197 7.96 4.46 4.11`

The ratio of the mass of a tether to its maximum payload is given by the following formula:

tether_mass / payload_mass = square_root(pi * density / 2 * working_stress) * delta_V * e ^ ((density * (delta_V ^ 2)) / (2 * working_stress))

Working_stress is the maximum stress divided by the safety factor, e is 2.718..., and "^" means raise to a power. Notice that the velocity of the payload, delta_V, is a factor and is also squared in the exponent of 'e', so the tether mass increases faster than exponential as the payload velocity increases.

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-Thanks, Bruce Mackenzie, BMackenzie@draper.com