

ORBITAL RING SYSTEMS AND JACOB'S LADDERS — II

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A method of transferring payloads into space without using rockets has been presented in Part I, in which massive rings encircle the globe in a low orbit supporting stationary 'sky-hooks,' from which cables hang down to any point on the Earth's surface. Vehicles can climb up these 'ladders' into orbit, or can accelerate along the rings. The structure and deployment of such Orbital Ring Systems is examined and their varied uses considered; several scenarios are considered and shown to be economically feasible and beneficial.

1. INTRODUCTION

Various authors have considered the possibility of dangling a centrifugally supported cable from geosynchronous orbit down to the Earth's surface. Such a 'Space Elevator' system suffers from the practical difficulty of manufacturing a cable capable of supporting thousands of kilometres of its own length; at present this cannot be done.

This paper examines the practicality of an alternative concept, illustrated in Fig. 1. In this concept a massive 'Orbital Ring' is placed in Low Earth Orbit (LEO); because it is in 'free-fall' everywhere (except where the 'skyhooks' deflect it) it does not need to bear large structural stresses. The 'skyhooks' ride upon Orbital Rings, supported electromagnetically, and hold station above specific points on the Earth's surface.

An 'Orbital Ring System' (ORS) has massive rings in a low orbit and skyhooks which are geostationary. Cables are suspended from the skyhooks down to the ground; these form the 'Jacob's Ladders.'

A Jacob's Ladder is much shorter than a cable geosynchronous orbit would be, and thus does not have to be made of so strong a material. It is within the reach of present-day technology.

In part I of this study [1] concentrated on the theoretical aspects of Orbital Ring Systems and Jacob's Ladders. The initial concept was generalised to include Eccentric Orbital Ring Systems (EORS) and Partial Orbital Ring Systems (PORS); it was shown that a large family of possible systems exists.

In Part II (this paper) I shall be concerned with aspects of engineering, logistics and safety; the theoretical foundation of Part I is assumed. I shall describe how Orbital Ring Systems could be built in the very near future and be used to transport large numbers of passengers and large amounts of cargo into space. I shall describe some of the potential applications and benefits of Orbital Ring Systems. And I shall make a tentative estimate of the costs of construction and use, and the economic returns that may be expected.

In Part III I shall examine some more of the possible applications, methods of use and various other aspects of Orbital Ring Systems to round off the complete work.

2. STRUCTURE OF ORBITAL RING SYSTEMS

2.1 Structure of Jacob's Ladders

There are several possible structures for Jacob's Ladders; the

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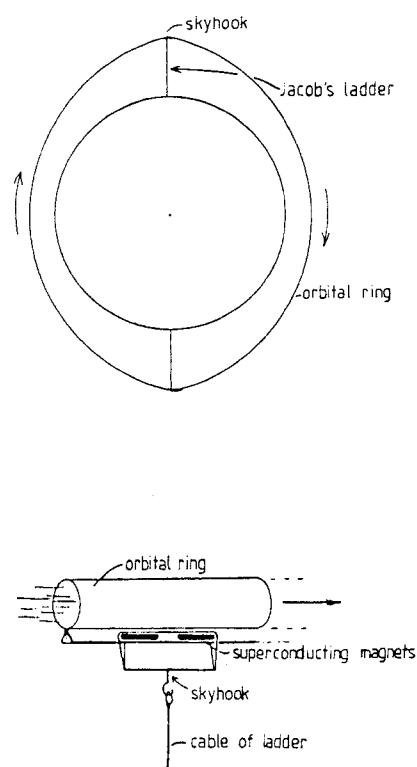


Fig. 1. The Orbital Ring Concept

simplest one has a solid core of cable clad in aluminium against which a linear induction motor can react. The apparent simplicity of this structure is offset by the problem of supplying power to vehicles climbing the ladder.

A mass-driver (see Ref. 5) is efficient at transferring energy into payloads and is probably the best choice for the ladder's drive mechanism. An axially symmetric 'inside-out' mass driver can be used to allow vehicles to ride on the outside of the ladder assembly as in Fig. 4 of Part I) whether the ladder itself is solid or hollow. A conventional mass-driver arrangement can be used to propel payload buckets up a hollow ladder assembly; it would also be possible to combine both forms in a single device, using small cargo buckets inside and large passenger or cargo vehicles on the outside.

It is apparent that external vehicles could be as large (within a given mass) as required; even small calibre systems would be well-suited to the carrying of passengers. The conventional form would be useful for streams of small cargo

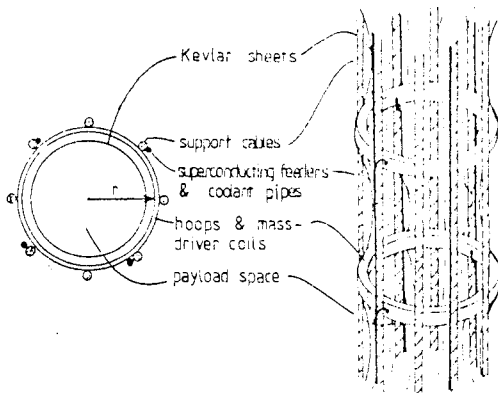


Fig. 2. Tubular Ladder Structure.

buckets, propelled at high accelerations; the inside of the tube would have to be evacuated of air to avoid shockwaves. Tubular ladders would have rigid hoops, carrying mass-driver coils and components, with "hourglass" shaped membranes between them (See Fig. 2, and Appendix 1, Part I). In each form of ladder assembly, the additional (non-cable) mass added can be thought of as a given thickness of steel on the outside; this extra mass should be small in comparison with the mass of the support cables.

Table 1 gives typical values for such ladders. It is apparent that high calibre tubular ladders for internal passenger vehicles would be very massive, suitable only for extremely high throughputs. Inside-out mass-drivers allow small calibres to be used, though care must be taken to minimise aerodynamic drag and noise (significant only for cargo vehicles using high accelerations).

TABLE 1. Structure and Properties of Jacob's Ladders

Property	Units	Hollow tubes with mass-drivers		Solid cable with jacket	
		Small bore	Large-bore	With Mass-driver	Without Mass-driver
Radius	m	0.1	3.0	0.05	0.05
Mean thickness of steel (1)	mm	0.2	3.0	0.2	0.2
Minimum thickness of steel hoops (1)	mm	2.0	90.	-	-
Thickness of support cables (2)	mm	10.	100.	(50.)	(50.)
Load, Fp	N	2×10^7	5×10^9	2×10^7	2×10^7
Fixed mass of accelerator (3)	kg	1×10^6	2×10^7	1×10^6	5×10^5
Net payload (including vehicle)	N	1×10^7	4.8×10^9	1×10^7	1.5×10^7
Maximum cargo mass (4)	kg	3×10^5	1.5×10^8	3×10^5	5×10^5
Cargo throughput	kgs^{-1}	300	1.5×10^5	300	500
Passenger capability	hr^{-1}	NONE	5×10^6	1×10^4	1.5×10^4
Power at full throughput (5)	GW	50	2.5×10^3	50	75
- with regeneration	GW	15	7.5×10^3	15	25

Notes:

- (1) These thicknesses apply at ground level where atmospheric pressure = 10^5 Nm^{-2} . They could be reduced at higher altitudes.
- (2) This is the ground level thickness; because of the increasing load this increases with height.
- (3) This estimate was obtained by using NASA SP-428 III. on mass drivers [5]. In the last column this is the mass of a 2 mm thick Aluminium sheath upon which a linear induction motor can react.
- (4) Vehicle (bucket) mass to cargo mass ratio obtained from NASA SP-428 III. It is somewhat arbitrary.
- (5) In the first line both vehicle and cargo are accelerated to escape velocity; in the second the cargo is released, the vehicle being decelerated and its energy recovered.

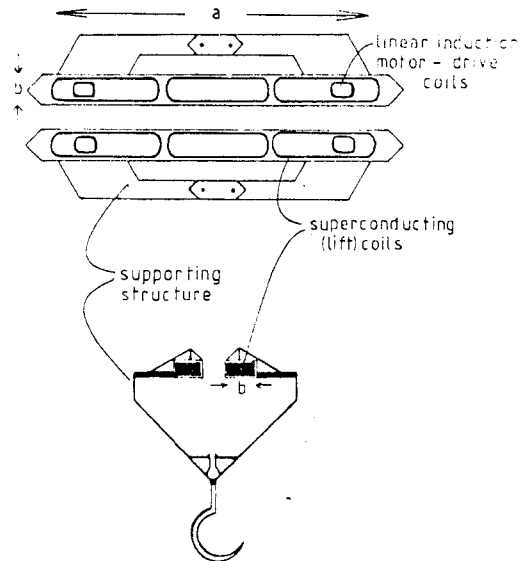


Fig. 3. Structure of Skyhooks.

2.2 Structure of Skyhooks and Orbital Rings

The skyhooks can obtain their lift by using superconducting coils to produce a persistent magnetic field, above a diamagnetic strip of aluminium (see Fig. 3, and Section 3.4-5, Part I). The "roadbed" for the skyhooks has been presented as a strip of aluminium Litz wire in a track underneath the ring, but it could also consist of a layer of superconductor with its coolant, insulation and so forth (precession forces can be applied via coils acting on these or other roadbeds in a similar way).

The main body of the ring can consist of industrial slag, lunar soil or the like; it need not be able to bear much tension, but it would be advantageous if the material can be extruded into a coarse fibreglass mat, which would have both strength and flexibility. This can be held in shape by a continuously woven sheath of steel cables. Such a ring can stretch readily for several per cent before the cables themselves are stressed, like a braided rope; this feature allows for small changes in specific length around the orbit.

3. A SCENARIO FOR ORS DEPLOYMENT

3.1 Baseline Assumptions

This scenario assumes that a mature Space Shuttle service will be available and that the construction of an ORS will take place alongside the initiation of a space manufacturing enterprise, as part of a programme to build space habitats and Solar Power Satellites (SPSs). The cost of the development of the shuttles, mass-drivers, lunar mining facilities and the Space Manufacturing Facility (SMF) are not considered here; only those aspects of the scenario described in Ref. 2. which would be altered significantly by ORS construction are treated in any detail.

I shall consider the scientific and economic benefits of an ORS in Section 6; for the moment I merely assume that there exists a requirement for a medium sized ORS (twin rings of 1 m diameter, $\rho = 2.5 \times 10^3 \text{ kg m}^{-3}$) and a number of ladders.

The unit of currency is the 1975 United States dollar (\$). It is used with S.I. prefixes (1 M\$ = 'one million dollars'. 1 G\$ = 10^9 \$ etc.). It may be noted that the 1975 US \$ is approximately the same as the 1982 £ sterling.

3.2 Earth-launched ORS

We consider an ORS composed of 1.6 m^2 of fused slag, with $1 \times 10^{-2} \text{ m}^2$ of steel and $2 \times 10^{-2} \text{ m}^2$ of aluminium across the two counter-rotating rings.

$$\text{Mass of slag in ORS} = 1.7 \times 10^{11} \text{ kg} \quad (1)$$

$$\text{Mass of steel in ORS} = 3.5 \times 10^9 \text{ kg} \quad (2)$$

$$\text{Mass of aluminium in ORS} = 2.4 \times 10^9 \text{ kg} \quad (3)$$

$$\text{Total mass of ORS} = 1.8 \times 10^{11} \text{ kg} \quad (4)$$

Now if this mass is to be launched from Earth, using the Shuttle Derived Heavy Lift Vehicle (SD/HLV) at $173 \text{ $ kg}^{-1}$ to orbit, the launch price will dominate the overall cost.

$$\text{Cost of Earth-launched ORS} = 31 \text{ T\$} \quad (5)$$

Since the GNP of the USA is only a few teradollars (T\$) this is not really practicable.

3.3 SMF-produced ORS

The SMF can produce slag at $0.21 \text{ $ kg}^{-1}$ and metals (iron and aluminium) at $7.05 \text{ $ kg}^{-1}$ [4] in suitable form and a useful orbit. Using Eqs. (1) - (3) we have

$$\text{Cost of SMF-produced ORS} = 77 \text{ G\$} \quad (6)$$

Now this, although quite expensive, is certainly practicable, since it is roughly equivalent to one Apollo programme. The SMF would need to be expanded considerably to cope

with so large a project (from $6 \times 10^8 \text{ kg yr}^{-1}$ to perhaps $10^{10} \text{ kg yr}^{-1}$); this would take time, but the prices per kilo would certainly drop with increased size of plant and due to the normal industrial 'learning curve' so the total cost might be less than the 77 G\$ of Eq. (6).

However, this is by no means the cheapest way to build an ORS.

3.4 Bootstrapped ORS

Consider a Jacob's Ladder working to capacity. Its cost will be dominated by the electricity bill; the energy cost to orbit is 9 kWhr/kg . If SPS electricity costs $5 \text{ m$/kWhr}$ locally [8] this implies that

$$\text{Cost to orbit by Jacob's Ladder} \approx 5 \text{ c\$ kg}^{-1} \quad (7)$$

At five cents a kilo very little will be added to the Earth purchase cost for delivery to LEO, except in the case of "zero-cost" materials like water, air or sand.

$$\text{Cost of slag in LEO by ladder} = 0.05 \text{ $ kg}^{-1} \quad (8)$$

$$\text{Cost of steel in LEO by ladder} = 0.25 \text{ $ kg}^{-1} \quad (9)$$

$$\text{Cost of aluminium in LEO by ladder} = 0.70 \text{ $ kg}^{-1} \quad (10)$$

Using steel and aluminium from the SMF (at $7.05 \text{ $ kg}^{-1}$) we can build a light-weight ORS as a cable of some 10 cm^2 cross-section and line density 4 kg m^{-1} . This can be made as a braided rope, allowing several per cent extension. It can carry 20 skyhooks evenly spaced with a payload of 10^8 N on each, with $\Delta H \approx 50 \text{ km}$ and $H \approx 300 \text{ km}$. Using Kevlar, each ladder can have a payload fraction of $1/5$ and thus a throughput of 300 kgs^{-1} .

$$\text{Mass of bootstrap ORS} = 1.8 \times 10^8 \text{ kg} \quad (11)$$

$$\text{Cost of bootstrap ORS} = 1.3 \times 10^9 \text{ \$} \quad (12)$$

This total mass is equivalent to two years' production of the SMF in these metals [7] and is chosen in order that the ORS shall be able to lift the mass of the full-size ORS in about a year.

$$\text{Time to lift mass of full-size ORS} = 3 \times 10^7 \text{ s} = 1 \text{ yr} \quad (13)$$

Combining Eqs. (1) - (3) with (8) - (10) we obtain

$$\text{Cost of slag in ORS at LEO} = 8.5 \times 10^9 \text{ \$} \quad (14)$$

$$\text{Cost of steel in ORS at LEO} = 8.8 \times 10^8 \text{ \$} \quad (15)$$

$$\text{Cost of aluminium in ORS at LEO} = 1.7 \times 10^9 \text{ \$} \quad (16)$$

$$\text{Cost of materials in ORS at LEO} = 1.1 \times 10^{10} \text{ \$} \quad (17)$$

Initially we use dummy weights on 19 skyhooks and set up a single Jacob's Ladder of the twentieth. The skyhooks and the ladder with its mass-driver components have to be flown up into LEO, since at this stage the SMF cannot produce niobium-tin superconductor or Kevlar cables.

$$\text{Mass of individual ladder} = 8 \times 10^6 \text{ kg} \quad (18)$$

$$\text{Mass of individual skyhook} = 1 \times 10^4 \text{ kg} \quad (19)$$

$$\text{Cost of ladder in LEO} = 1.4 \times 10^9 \text{ \$} \quad (20)$$

$$\text{Cost of 20 skyhooks in LEO} = 1.7 \times 10^6 \text{ \$} \quad (21)$$

TABLE 2. LORS for Initial Lunar Operations

Property	Value	Units
Mass of the Moon	7.35×10^{22}	kg
	0.0123	M_{\oplus}
Radius of the Moon	1740	km
Escape velocity	2.4	kms^{-1}
Surface gravity	1.62	ms^{-2}
Kevlar, Y/gm ρ	1350	km
	H = 300 km	
Mass of orbital ring (1)	5×10^{-2}	kgm^{-1}
	640	Mg
Breaking stress of ring (1)	1×10^5	N
No of skyhooks	20	-
Mass of skyhooks	250	kg
Weight per skyhook	2.5×10^4	N
ΔH	10	km
Mass of Kevlar ladder	3	Mg
Mass of Mass Driver (2)	a) 6	Mg
	b) 10	Mg
Ladder Payload	1.2×10^4	N
Muzzle velocity at 10 ms^{-2}	2.5×10^3	ms^{-1}
Throughput per ladder	1.5	kgs^{-1}
Power for full throughput	4.7	MW
Power loss per skyhook (3)	0.7	MW
Total power mass (4)	150	Mg
System mass (5)	1175	Mg

Notes:

- (1) Aluminium core with braided Kevlar strength filaments.
- (2) Mass-driver components a) supported by ladder b) on the lunar surface (excl. power mass),
- (3) Includes electromagnetic drag and cryogenics losses.
- (4) Power mass for 20 skyhooks and one functioning ladder, calculated at a specific mass of 8 kg/kW (NASA SP-428 II-2).
- (5) Includes LORS mass and 20 ladder systems, but includes only enough power mass to run one ladder at full throughput.

$$\text{Cost of 20 dummy weights} = 3.4 \times 10^7 \$ \quad (22)$$

The dummy weights are, of course, fused slag from the SMF at 21 c\$ kg⁻¹.

The remainder of the Kevlar ladders can be sent up the first at a rate of up to 300 kgs⁻¹; this could take as little as five days. Earth purchase cost for the ladders is taken to be a rather expensive 10 \$ kg⁻¹; this includes the mass-driver components.

$$\text{Cost of ladder in LEO by ladder} = 8 \times 10^7 \$ \quad (23)$$

$$\text{Cost of 19 ladders in LEO by ladder} = 1.5 \times 10^9 \$ \quad (24)$$

With all 20 ladders in place the mass of the full-sized ORS is lifted into space over the period of a year or so. when it is complete, the already existing ladders can be transferred to it and the original ring cannibalised or used elsewhere.

Thus, summing (12), (17), (20), (21), (22) and (24) we find that

$$\text{Cost of bootstrapped ORS} = 15 \text{ G\$} \quad (25)$$

This is considerably cheaper (and quicker than direct production by the SMF. But we can get it cheaper still.

3.5 Bootstrapped ORS with Lunar Orbital Ring System

So far I have only considered systems in orbit around the Earth. But we might as well build a Lunar Orbital Ring System (LORS) also. Because of the Moon's smaller size and lesser gravity, a ring in Low Lunar Orbit (LLO) will be much cheaper than one in LEO.

We can use a small LORS and ladder to replace the lunar launcher (a mass-driver system laid out horizontally on the surface). Table 2 gives some useful lunar constants and typical values for the early LORS. This system is chosen so that each ladder is well capable of handling 30,000 tonnes per year and the twenty ladders more than 60,000 tonnes per year (these are the basic SMF requirements [4]).

The following scenario follows the pattern of Ref. 4; most of the mass budgets and logistics described there will apply with only minor variations, up to the point at which a second LORS is built, the main difference being a slight saving in propellants when a minimal LORS is deployed straight straightaway.

After about a hundred Shuttle launches to set up the LEO station and to lift the equipment for lunar operations into orbit, a Mass-Driver Reaction Engine (MDRE) transfers the payloads to LLO. The first lunar crew then deploys the minimal LORS and attaches skyhooks and one ladder; a landing is made with minimum necessary equipment to set up the ladder ground station and catch the end of the ladder, after which the rest of the base equipment can be let down the ladder. This procedure will be repeated for the other 19 skyhooks over a period of about four years, allowing for the growth of the mining operations from an initial 30,000 tonne/yr to a total of 600,000 tonne/yr. Concurrently, the SMF is set up as in Ref. 3.

The next stage takes place in the fifth year of operations; this is the construction of a permanent LORS (25 kg m⁻¹) using metals and slag from the SMF. At the same time an ORS construction site is set up in Earth orbit; it receives steel and aluminium from the SMF and builds a lightweight (0.4 kg m⁻¹) ORS, which is deployed in LEO like the more massive bootstrap ring in Section 3.4. This ORS is used firstly to launch plant for expanding operations on the Moon and at the SMF and ORS construction site, and thereafter to launch the metals for the main ORS; which takes about a year.

Each lunar base in turn is expanded to the size of the single base in Ref. 4; each provides 1.4×10^6 tonne/yr of ore and 7.2×10^6 tonne/yr of tailings [7]. The tailings are sintered and sent to the ORS site; the ore goes to the SMF, where it can be stockpiled until the SMF can be expanded to use it.

Arriving at the ORS construction site, the soil is melted down into a coarse fibreglass mat, the metals into cables and beams; these are "extruded" from the factory as a fully fabricated ribbon of ORS. After about one and a half years, the completed ORS is brought down and deployed in LEO, with a total of 20 ladders (each capable of bearing 1000 tonne and lifting 300 kg s⁻¹) spaced around it.

The scenario can be compared with the original SMF/SPS scenario from Ref. 4. (which has been costed at 50-100 G\$). The mass budgets and costs are in fact very similar for the first few years, with a saving of around 250 tonne (and ~ 250 M\$) in Year 1 and an extra 3200 tonne brought from Earth by the end of Year 4 (at this stage the extra cost is about 500 M\$) when the lunar bases are working at 600,000 tonne/year. The process of LORS and boot-strap ORS construction in Year 5 costs an additional 1.4 G\$; then the expansion of operations in the next two years takes a further 800 M\$, with 400,000 tonne lifted from Earth by ladder (simultaneous expansion of the SMF to 2.8×10^7 tonne/year, though not strictly necessary, would take an extra 800 M\$). Finally, in Years 7-8 the construction of the main

ORS costs some 5G\$ (mainly purchase costs of the metals and ladders) and involves some 2×10^8 tonnes of material. This adds up to a total additional cost (over and above that of Ref. 4) of about 8.5 G\$.

At the completion of the programme there would be, not only the main ORS required, but also an LORS, lunar mining operations and an SMF of similar capacity. The SMF expansion is envisaged as taking place in conjunction with the construction of the first true Space Colony, a Stanford Torus with a population of $\sim 100,000$; and although this phase of SMF growth and space colonisation is not strictly a part of the ORS construction programme we shall leave it in:

$$\text{Cost of bootstrapped ORS with LORS} = 8.5 \text{ G\$} \quad (26)$$

3.6 PORS - Launched ORS

The disadvantage of the scenarios outlined above is that they require a considerable expenditure (50 - 100 G\$) on an SMF/SPS programme as a precondition. In the present political climate such funding does not seem very likely, so it is worth examining ways of minimising the total expenditure. In Section 3.4 a bootstrap ORS, made out of metal from the SMF, lifted the mass of the main ORS into orbit from Earth, for a cost of 15 G\$. By replacing the original small ORS by a small PORS set up on Earth the necessity for an SMF and lunar mining can be eliminated: all mass required in orbit can be sent up by ORS. Allowing 0.3 G\$ for the PORS and ground systems, and summing Eqs. (17), (23) and (24) we find that

$$\text{Cost of PORS-launched ORS} = 13 \text{ G\$} \quad (27)$$

The most uncertain factor in this cost estimate is probably the cost of electrical power (8.8 G\$ here at 5 m\$/kWhr); it is doubtful whether so low a cost can be expected in advance of major space industrialisation. However, dedicated large-scale baseline (i.e. constant) power generation on site can be provided for less than 10 m\$/kWhr, so the total cost should not exceed around 20 G\$ on this basis. Of course, it is quite possible to trade off cost against mass and capacity of the system.

4. A DESIGN FOR AN EARLY PORS

4.1 Design Features of the PORS

Let us consider the design and construction of a possible early PORS. For definiteness, consider a light PORS to be set up between Abemana and Canton Island in the Pacific (Fig. 4). Table 3 is a list of parameters chosen for the system.

The track of the PORS is about 4 arc minutes to the east of the great circle route at the ground stations, and about 1 km to the side at the peak; this is due to the Coriolis effect.

For the cable we use aluminium, braided like a Chinese finger and extensible. We choose a line density of 0.25 kg m^{-1} at ground level (greatest extent); that is, just over 1 cm diameter.

Allowing for stationary mass at one quarter of the cable mass we obtain the total force applied by the ground stations; this is πF_G , a factor $\pi/2$ higher than the net force on the ground stations, because the cable must be swung through a semicircle with the applied force always perpendicular to its motion. This force is produced by running the cable through a bed of superconducting magnets; induced current in the aluminium provide levitation, but also cause power dissipation.

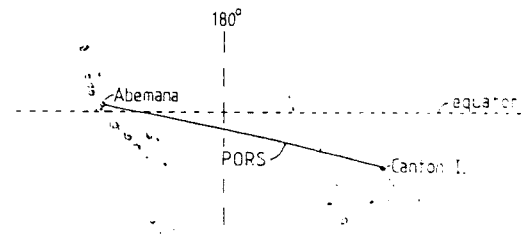


Fig. 4. Map of Location of proposed PORS.

TABLE 3. Parameters for a PORS.

	Symbol	Value	Unit
Abemana	Lat.	$0^\circ 20' \text{ N}$	
	Long.	$173^\circ 50' \text{ E}$	
Canton Island	Lat.	$2^\circ 50' \text{ S}$	
	Long.	$171^\circ 40' \text{ W}$	
Latitude difference	$\Delta \text{lat.}$	3.2	$^\circ$
Longitude difference	$\Delta \text{long.}$	14.5	$^\circ$
Angular separation	2α	0.259	rad
Great circle distance	$2\alpha R$	1653	km
Height at peak	H	385	km
Elevation angle	E	41.3	$^\circ$
	$V_p \mu^{1/2}$	3.78	km s^{-1}
Line density factor	μ^{-1}	1.25	
Speed at sea level	V_p	4.22	km s^{-1}
Line density	m_p	0.25	kg m^{-1}
Net force on station	F_G	8.9×10^6	N
Total force on stations	πF_G	2.8×10^7	N
Mass of cable	$M\mu$	1.1×10^6	kg
Total mass	M	1.4×10^6	kg
Stretch factor	V_p/V_S	1.41	

Following Section 3.4 of Part I we obtain the power loss per unit surface area of cable, radius r_c and conductivity σ where a is the acceleration produced:

$$p_A = (2/\pi) \rho a / \sigma \mu_0 \quad (28)$$

The power loss for a total force πF_G is

$$P_E = 4F_G / \sigma \mu_0 r_c \quad (29)$$

This power must be dissipated by radiation; if the cable, temperature T , is in a cavity of temperature T_0 it radiates

$$p_A = \sigma_{\text{STEFAN}} \epsilon (T^4 - T_0^4) \quad (30)$$

This must balance Eq. (28), in which the mean acceleration is $\pi F_G / M\mu$. For the conductivity of aluminium, we have

$$\sigma_{\text{Al}} \approx \sigma_{\text{Al}}(300\text{K}) \cdot (300/T) \quad (31)$$

Hence, the equilibrium temperature is given by

$$(2F_G/M_\mu) (\rho_{Al}/\sigma_{Al}(300K)) = \mu_0 \sigma_{STEFAN} \epsilon (300/T) (T^4 - T_0^4) \quad (32)$$

The aluminium cable can easily be given a high emissivity coating, so we may put $\epsilon = 1$. Using values from Table 4 we obtain

$$T^3 - T_0^4/T = 5.8 \times 10^7 (K^3) \quad (33)$$

Using a conservatively high value for the cavity temperature ($T_0 = 300K$) we find

$$T = 425 K \quad (34)$$

This is a steady state temperature; in reality the heat is dissipated at the moment the cable passes through the ground stations and is radiated over the rest of the path. There will be a temperature jump at these two points of dissipation:

$$\Delta T = 2F_G(T/300)/(m_p/V_p \mu_0 C_{Al} r_c \sigma_{Al}(300k)) \quad (35)$$

where $C_{Al} = 908 J kg^{-1} K^{-1}$ is the specific heat capacity of aluminium. Substituting from Table 3 and Eq. (34) we find

$$\Delta T = 108 K \quad (36)$$

Thus the temperature immediately after passing the ground station will be about 480 K; this will fall to 370 K just before entering the other ground station. The overall temperature is quite high, but a long way below the melting temperature of aluminium (933 K). The temperature cycling is also quite a large effect, but fortunately the cable is not called upon to sustain tension and the period of the cycle is quite long ($M\mu/2m_p V_p \approx 530$ seconds), so thermal fatigue should not be a serious problem.

Using Eq. (30) we find that the total power dissipation is

$$P_E = 2.1 \times 10^8 W \quad (37)$$

We note that the total energy (KE + PE) stored in the system is

$$E = 9.8 \times 10^{12} J \quad (38)$$

The power loss (and thus the cost of the power plant) is rather high, so some attention should be given to the various possible ways of reducing it, with a view to minimising the overall cost. However, a mature system based on this PORS would launch perhaps $100 kg s^{-1}$ and require about 3 GW; the power losses due to dissipation would then amount to less than 10% of the total power.

One possible cable structure is shown in Fig. 5. For the balloon material we use a Kevlar-49 fabric of areal density $0.06 kg m^{-2}$ and tensile strength $4 \times 10^4 Nm^{-1}$ [10]. Using ten segments to make a tube of overall diameter 10 cm, with the straight portions at the conjunction of the segments 1 cm long for an internal diameter of about 2.9 cm we can calculate the total length of balloon material used around the tube; this is

$$L_B \approx 0.87 \text{ metre} \quad (39)$$

and corresponds to a line density for the balloon material of

$$M_B \approx 0.052 kg m^{-1} \quad (40)$$

The effective line density takes account of the air mass excluded from the evacuated tube and contained in the

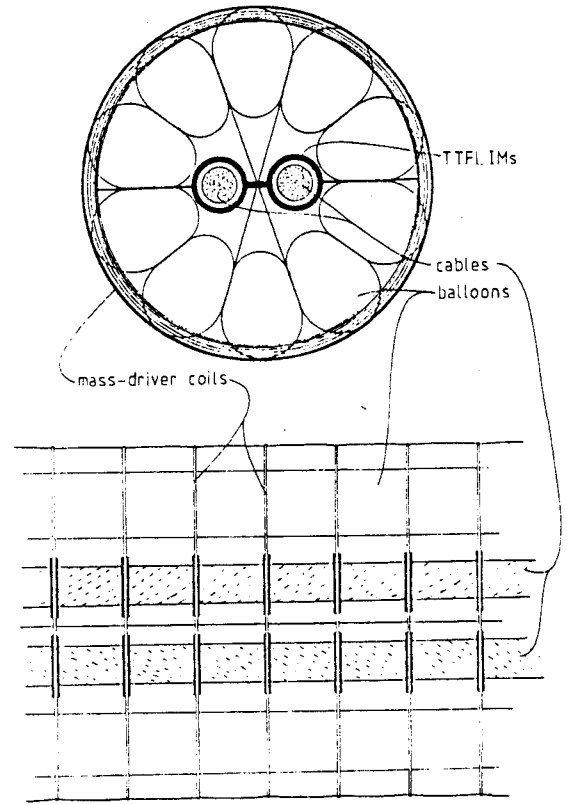


Fig. 5. Proposed PORS Structure.

pressurised balloons. At sea level (using air at STP) this is

$$M_T \approx 0.073 kg m^{-1} \quad (41)$$

The balloons are pressurised to 4.3 times the external pressure to be able to withstand it against an internal pressure of zero. The balloons also provide a longitudinal strength of about $4 \times 10^4 N$.

The remainder of the stationary mass ($0.073 kg m^{-1}$) is divided among the TTFLIM (Tubular Transverse-Flux Linear Induction Motor) and mass-driver components. The mass-driver should be capable of driving 30 tonnes at three gravities to orbit, in order to match Shuttle capabilities (we shall examine the practicability of this later).

At the ground stations there are superconducting coils and linear induction motors, as well as cryogenic equipment with a capability $\sim 250 W$ at 4 K; there will also be a need for control equipment, computers, power plant and so forth.

Payload vehicles can be carried along the PORS on sleds (which can also be used for repairs to the cable assembly); the sleds consist of superconducting coils mounted upon a titanium or composite frame and can be linked together into long trains for carrying heavy loads (Fig. 6). Vehicle payloads can be attached to sleds at one of the ground stations and accelerated up the PORS; upon reaching orbital velocity they can be released and the sleds decelerate down the other arm of the PORS, to accumulate at the opposite ground station. From time to time the sleds can be sent back again.

The sleds can be made in two parts, which bolt together from opposite sides of the cable, each part having half coils spaced an odd number of half-wavelengths apart (Fig. 6), which together make up coils of alternating sense. Because the acceleration of the sleds is low (3g as compared to 1000g for an MDRE) their mass will be very much less than the payload mass.

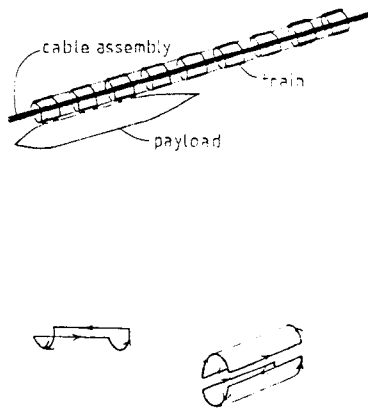


Fig. 6. Sled Train for use on PORS.

4.2 Deployment of PORS and Cost Estimate

As in Section 3, we shall work in 1975 US dollars. We start with the cable assembly, assuming a specific cost of 1 \$ kg⁻¹ for the aluminium cable, and 33 \$ kg⁻¹ for the balloon material and for the mass-driver and TTFLIM components. Since Kevlar cables are now about 15 \$ kg⁻¹ and are coming down in price, this is probably pessimistic for the balloon, and is unlikely to be greatly exceeded for the mass-driver system, even if much of the mass is in power semiconductors. We have,

$$\text{Cost of aluminium cable} \approx 1.1 \text{ M\$} \quad (42)$$

$$\text{Cost of balloons} \approx 3.8 \text{ M\$} \quad (43)$$

$$\text{Cost of mass-driver and TTFLIMs} \approx 5.3 \text{ M\$} \quad (44)$$

At the ground stations the cryogenic equipment is likely to cost $\lesssim 1 \text{ M\$}$ (since units of about 1 W capability can be purchased for less than 5000 \$). For computing equipment, to calculate orbits and control the induction motors and mass-driver, etc., we can allow for two mainframes, and a selection of minicomputers and peripherals (this seems excessive, but a reasonable amount of computing power is never enough). We have, then,

$$\text{Cost of cryogenics and coils} \approx 5 \text{ M\$} \quad (45)$$

$$\text{Cost of computers, etc.} \approx 3 \text{ M\$} \quad (46)$$

A work-force of ~ 100 people on site might be typical for a project of this nature; they will need workshops, offices, living accommodation, as well as equipment, books stationery, etc. Over a period of ~ 4 years for development and deployment we have, roughly,

$$\text{Cost of buildings and equipment} \approx 2 \text{ M\$} \quad (47)$$

$$\text{Cost of salaries and travel} \approx 4 \text{ M\$} \quad (48)$$

The deployment of the PORS cable assembly must also be considered. One method that might be used is to obtain the initial lift by means of balloons: the balloons would be distributed smoothly along the PORS with the cable assembly supported in between two "lobes."

When the central portion of the assembly is high in the atmosphere the cables can be spun up by the ground station TTFLIMs; the weight on the balloons would decrease and

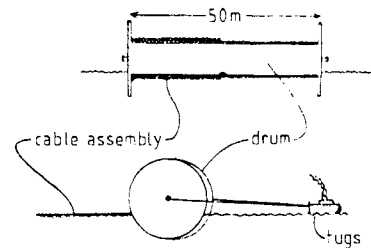


Fig. 7. PORS Deployment from Drum.

they would rise further. As the middle section rises out of the atmosphere the balloons can be pulled back down, leaving the PORS free. The balloons and the hydrogen used to inflate them can be stored for reuse (and the PORS could be let down again by reversing the procedure).

To obtain enough lift to take the cable assembly to a high altitude we let the balloons have about the same mass as the PORS (0.63 kg m⁻¹): this is sufficient to provide as much as 500 m³ m⁻¹ of lifting volume. For hydrogen-filled balloons a line density of 1.25 kg m⁻¹ can be lifted by 1.04 m³ m⁻¹ at sea level (at STP) using 0.093 kg m⁻¹ of hydrogen. We have

$$\text{Mass of hydrogen} = 2.1 \times 10^5 \text{ kg} \quad (49)$$

$$\text{Cost of hydrogen} = 0.1 \text{ M\$} \quad (50)$$

$$\text{Mass of balloons} = 1.4 \times 10^6 \text{ kg} \quad (51)$$

$$\text{Cost of balloons} = 2 \text{ M\$} \quad (52)$$

The balloon size and mass can probably be reduced considerably, since the volume provided is very large compared to the volume needed at sea level.

Before the PORS can be lifted into the air the cable assembly and balloons must be laid out on the water between the ground stations. If the balloon and cable are coiled together on a large drum (Fig. 7), which can be towed by tugs, the drum will roll along the water paying out the cable behind. The drum would be large, but of very simple construction. If the tugs steam at 10 ms⁻¹ (about 20 knots) the cable-laying will take about two days, during which time shipping must be kept clear of the cable. If necessary, small sections could be lifted by helicopter to allow ships to pass underneath. The route would have to be patrolled, probably by about a dozen seaplanes, perhaps with a patrol boat also. Allowing 50 \$ hr⁻¹ for the hire of each aeroplane (wet) this would cost around 2×10^4 \$; including the use of the tugs and other vessels we might have

$$\text{Cost of laying cable} \approx 0.1 \text{ M\$} \quad (53)$$

$$\text{Cost of cable drum} \approx 0.1 \text{ M\$} \quad (54)$$

As soon as the balloons are inflated the cable should be spun up to speed as fast as the power plant will allow. This is because the cable-balloon combination can be blown about by the wind while it remains in the atmosphere; since the drag force on the balloons can exceed the overall weight the assembly must be allowed to drift. Therefore speed in deployment and moderately calm weather are required. Using the power plants mentioned below the time taken to deploy the PORS completely is 24 hours (allowance has been made for power loss during deployment).

An overall 120 MW generating capacity at each station leaves enough power to launch 1 kg s⁻¹ into space after

making up the power dissipation. We could use on-site nuclear power plants at around 200 \$ kW⁻¹ and 50 \$ kW⁻¹ or fossil fuel plant at around 120 \$ kW⁻¹ and 100 \$ kW⁻¹ yr⁻¹ [11] giving

$$\text{Cost of Nuclear power plant} \approx 48 \text{ M\$} + 12 \text{ M\$ yr}^{-1} \quad (55)$$

$$\text{Cost of fossil power plant} \approx 36 \text{ M\$} + 24 \text{ M\$ yr}^{-1} \quad (56)$$

Because the South Sea Islands are so out of the way, and far from a cheap supply of coal, and because nuclear power is cheaper in the long run, the nuclear option is probably the better. However, the funding for either option, allowing for one year's operation, would be about the same.

$$\text{Cost of power plant} \approx 60 \text{ M\$} \quad (57)$$

In recent years the costs of building a power plant has increased; for nuclear power plants, legal costs now dominate the capital costs. For political (rather than technological) reasons, Eq. (57) may be a considerable underestimate.

We now turn to the sleds and payload vehicles that will ride on the PORS. The vehicles themselves could vary from simple payload fairings for satellites and spacecraft (costing a few thousand dollars or less) to man-rated vehicles with re-entry capability (like a simplified version of the Shuttle Orbiter). A hypersonic glider, with hypergolic propellants for orbital manoeuvres, and payload similar to the Shuttle, but without the need for the SSMEs or related equipment, could probably be developed for around 50 M\$ [12].

However, for the development and early operational stages of the PORS a rather simple vehicle should suffice, perhaps with a modified jet or rocket plane for experimental manned flights. For this purpose we put

$$\text{Cost of vehicles, \&c.} \approx 2.4 \text{ M\$} \quad (58)$$

$$\text{Cost of sleds, \&c.} \approx 0.1 \text{ M\$} \quad (59)$$

Summing the appropriate equations we obtain the estimate:

$$\text{Total cost of PORS} \approx 90 \text{ M\$} \quad (60)$$

This sort of amount could soon be paid back, even at present traffic levels. For example, undercutting the Space Shuttle service by a factor ~ 10 would give some 30 tonnes/week at 100 \$ kg⁻¹; this adds up to 150 M\$ in a year, enough to pay back the development cost with interest. Such a PORS could also be used as a heavy lift system at much higher traffic levels; it could, for example, launch the materials for an Earth-circling ORS.

4.3 The PORS Mass-Driver

The PORS mass-driver will differ from the lunar launcher or MDRE of Ref. 2 in several ways. Firstly, it will obtain its power from the moving cables of the PORS *via* TTFLIMs. Since the cables are fast moving the TTFLIMs will operate at frequencies of around 500 kHz and should provide in excess of 50 kW kg⁻¹ average, with peak specific powers very much greater. The TTFLIMs count as the 'power mass' (which is actually on the ground) and may also be able to replace the capacitors, whose energy storing function can be taken over by the PORS mass-streams.

Secondly, the PORS mass-driver must be capable of accelerating not only small buckets but also large and massive payloads (30 tonnes) to orbit. The accelerations required are about 3g (not 1000g) and the launch frequencies $\sim 10^{-3}$ Hz

(rather than ~ 10 Hz). Can the design cope with these changes while remaining within the allocated mass?

Now a given mass-driver coil, with a given current, will produce a certain force on a passing superconducting coil and transfer a certain amount of energy at a rate of proportional to the velocity; these things do not depend upon the acceleration induced, nor upon the mass attached to the bucket coil, so a mass-driver will still be able to work at low accelerations (provided that the system is stretched out accordingly).

There is a limit to the force which can be applied to a single bucket or sled coil: if the mass-driver radius is r_{md} then

$$F_{\text{max}} \approx (B_{\text{max}}^2/2\mu_0) (\pi r_{\text{md}}^2) \quad (61)$$

For Nb₃Sn superconductor and the 10 cm diameter PORS this limit is $\sim 10^5$ N, so a payload of 30 tonnes, driven at 30 ms⁻¹, would need at least ten coils on its sled.

A more important limit is on the power transfer per coil. Let the specific power and line density of the SCRs be p_{SCR} and m_{SCR} respectively, then the maximum power transferred per unit length is

$$(p)_{\text{max}} = p_{\text{SCR}} m_{\text{SCR}} \quad (62)$$

Thus, for a payload M_p , of velocity V , being driven at acceleration a_p , the minimum length of sled that can be used is

$$(L_S)_{\text{min}} = M_p a_p V / p_{\text{SCR}} m_{\text{SCR}} \quad (63)$$

Using, as an average value, $m_{\text{SCR}} = 0.025$ kg m⁻¹ and $\langle V \rangle = 4$ km s⁻¹, with a payload of 30 tonnes at three gravities of acceleration, for $p_{\text{SCR}} = 2 \times 10^8$ W kg⁻¹, we obtain

$$(L_S)_{\text{min}} \approx 700 \text{ m} \quad (64)$$

Since a sled of this length will pass by in about a sixth of a second the surge current ratings of the SCRs can be used. A typical cheap (< 1 \$) plastic-package device manufactured by Texas Instruments (TIC 226) has a standoff voltage of ± 800 V, can slew at 500 V μ s⁻¹ without loss of gate control, and has a maximum continuous RMS current of 5A; but over 10 cycles at 60 Hz (i.e. $\frac{1}{6}$ sec) the RMS current can be increased to 40A. It has a specific power of about 3×10^7 W kg⁻¹ in these conditions and is fast enough to switch the coils of this PORS even at escape velocity. Higher power devices of similar mass exist and a change to a more expensive packaging with little increase in mass allows considerably higher voltages (~ 10 kV) to be used, so the quoted value p_{SCR} (2×10^8 W kg⁻¹) should not be hard to reach or exceed.

Note that the duty factor of this mass-driver is low: even at 100 kg s⁻¹ throughput there is at least 5 minutes between launches of 30 tonne payloads, corresponding to a duty factor of $\sim 5 \times 10^{-2}$. This contrasts sharply with the case of lunar launchers and MDREs [2], for which continuous current ratings must be used.

Although 700 m would be a considerable length for a single vehicle, it is by no means excessive for a train of sleds. We can calculate the mass of tension members for the sled-train quite simply: the average distance through which the acceleration forces act is $L_S/2$, so the mass is

$$M_t = (M_p a_p) (L_S/2) (\rho/Y) \quad (65)$$

Using the values assumed above

$$(M_t/M_p) \approx \begin{array}{ll} 4.5 \times 10^{-3} & \text{Kevlar cable} \\ \text{for} & \\ 2.9 \times 10^{-2} & \text{Titanium wire} \end{array} \quad (66)$$

In both cases it is apparent that very much longer trains could be used if necessary. Titanium wire is useful here because of its high strength at cryogenic temperatures and its low thermal conductivity ($23 \text{ Wm}^{-1} \text{ K}^{-1}$); it can be used to strengthen the superconducting coils and tie them together and to the framework of the sled. Titanium can be used for the frame and internal ties of sleds perhaps ten metres in length; and Kevlar cables used to carry the increasing tension along the line of sleds, with extra strands (say, $4 \times 1 \text{ mm}$ diameter) joining the cable at each sled, to a total mass of about 300 kg over 1 km.

Now the R&D costs of the mass-driver have actually been included under various headings above, for example, in the salaries of the research staff and in their equipment and facilities. It is felt that the total is consistent with the estimate of Ref. 2. Nevertheless, to be on the safe side one might be wise to add an extra 10 M\$ to the mass-driver R&D, bringing the overall cost of the ORS to the round figure of 100 M\$. Obviously there is a considerable uncertainty in these cost estimates, but I have tried to use fairly pessimistic figures at doubtful points. Clearly the power consumption and power plant is the most important and uncertain factor.

5. SAFETY CONSIDERATIONS

5.1 Risk Identification

As for any large edifice we must consider what risks are entailed in building an ORS. We need to identify the possible modes of failure, and examine the consequences of any such failures. We should also look for ways of making the system safer and minimising the risks.

In general, sub-systems should be designed to be inherently reliable and to have adequate redundancy. It is best if they are 'fail-safe' or at least limit the extent and effect of failure.

Nevertheless, some risks will always remain: no material construction is ever absolutely safe. It is worth considering, not only what limited accidents are at all likely to happen, but also what is the worst that can happen.

The following sections deal with the question of ORS safety. They show that danger due to natural causes (meteoroids, etc.) is slight, that skyhook failure can be avoided by multiple redundancy, and that the orbital rings are inherently 'fail-safe.'

5.2 Skyhook Failure

Skyhooks are the most likely source of trouble in the Orbital Ring System, because we rely upon their superconducting magnets' functioning all the time. This applies equally to the true skyhooks (which bear loads) and to those designed to apply precessing forces between the rings ('riders').

Sudden changes in the magnetic field around the lift coils could cause a breakdown of the superconductor; the windings are therefore protected by eddy-current shields. The coils are also strengthened and braced to withstand the magnetic stresses; structural steel and high-strength composites can be used for this.

Cryogenic failure could lead to the loss of superconductivity in the lift coils. This must be avoided. Heat leaks are minimised by using multi-layer vacuum flask insulation; the

silver-coated copper of these flasks doubles as the eddy-current shield. The heat-pumps are designed to have no moving parts and high reliability; they are generously rated for a high heat-sink temperature of 300 K. Furthermore, if refrigeration is lost, there is enough liquid helium in the cryostat reservoirs to last for 24 hours or more before evaporating.

The power supply to the cryogenic system and to the skyhooks' electronics must be reliable and largely self-contained. Throughout the day solar power can be used; at night power can be sent up the ladders or extracted from the orbital rings, but the helium reservoir will in any case last through the hours of darkness. Solettas could be used to provide night-time illumination.

Redundancy in the lift coils is employed to enhance reliability; a number of independent systems operate continuously. Because the available lift to weight ratio is so high there is little weight penalty invoked for high levels of redundancy. A typical skyhook could contain several hundred separate lift units; even if less than half of them are working the load will not exceed the design specifications of the coils. There is comprehensive fault monitoring so that malfunctioning units can be repaired or replaced easily and quickly.

Finally, critical loads (e.g./ space platforms or hotels carrying many people) can be supported by several independent skyhooks, any one which is capable of carrying the full weight.

5.3 Collapse of a Jacob's Ladder

The collapse of a Jacob's Ladder need not be a very serious accident. If its skyhook drops off the ORS then the ladder will fall vertically; it will hit the ground in a neat pile along a well defined track.

There are two effects to be considered here: the Coriolis effect causes the ladder to fall on an eastward track several kilometres long (Part I Ap. 2) while the ladder collapses into coils contained within a radius of a few tens of metres. Thus a guard band a hundred metres across and two kilometres long ($H = 300 \text{ km}$) is sufficient allowance for ladder collapse and for safety from objects falling off the ladder or skyhook. This path will be modified if the ladder is sloping or curved, but the corresponding track is easily calculated.

The base of the ladder is thus situated in an area of unpopulated or sparsely populated territory several kilometres in radius, with the guard band marked out within it. The loading bays, passenger facilities, approach roads and so forth are dug underground; a few metres of rock are ample protection against a falling ladder.

So the only people at risk due to a possible collapse of the ladder are those that actually travel on it. This is in contrast to road transport, for example, where it is often bystanders that are most at risk.

Most payloads will consist of cargo; less than 1% of the system throughput is likely to be in passenger vehicles, so that a ladder collapse would usually cause no casualties. However, large passenger vehicles might carry up to a thousand people, who could be killed if a ladder failed. Although the magnitude of such a disaster is on a par with conventional airliner crashes, the risk is likely to be a good deal less. The risk could be reduced further in several ways.

Redundancy in the ladder could prevent the catastrophic fall of passenger vehicles: if the ladder is divided into two smaller cables, each perhaps on separate skyhooks, the failure of only one (as by meteoroidal rupture) is not so disastrous. A passenger vehicle, which will have less than half the weight of the limiting payload, can still use the remaining half of the ladder for support. Obviously there are many ways in which this principle of redundancy may be applied.

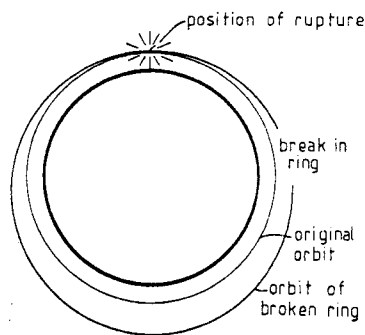


Fig. 8. Path of a ruptured ORS.

It is not only the collapse of a ladder which could lead to the crash of a passenger vehicle. It is possible that a vehicle might accidentally drop off the ladder, particularly at the skyhook end during transfer to the orbital rings, or might fall off the ORS itself. A safety measure of use in all such accidents would involve designing the vehicles to be able to land safely on their own.

There seem to be three basic ways of accomplishing this. The most straightforward allows the vehicle to parachute to Earth; this is a standard method of bringing spacecraft down safely. The vehicle could be powered and use rockets of air-breathing engines (jets) for a controlled landing; but this method may impose a severe weight penalty. Perhaps the most elegant method is the one employed by the Shuttle Orbiter: an aerodynamically shaped vehicle is able to guide to an unpowered landing. A simple landing strip can run from the base of the ladder, out along the guard base and several kilometres beyond it.

5.4 Rupture of an Orbital Ring

If an orbital ring is snapped (perhaps by collision with a meteor, although the time-scale for such a collision is 10^7 years or more – see Section 5.5) the skyhooks will probably drop off the end. Two things concern us; the fate of the skyhooks and the fate of the orbital rings.

The skyhooks can still be held by the counter-rotating ring but the sudden increase in weight is likely to snap that ring also unless great care is taken. Because the precession forces will be lost it seems improbable that the ladders could remain intact, so it may be best to jettison half of the load on each skyhook in order that the load on the intact ring remain unaltered. This could be achieved by allowing the lower section of the ladders to fall to the ground. This is a somewhat costly and unsatisfactory solution but at least it limits the damage to only half of the ORS and the skyhooks themselves survive undamaged. Fortunately, if the suggestions of the last two paragraphs of Section 5.3 are followed, it will not be costly in human lives.

It is only natural to ask if the ruptured orbital ring will fall to the ground, and whether that would cause a great disaster. However, it must be realised that the weight on the skyhooks has been holding the ring down; released, it has more than enough energy to maintain its orbit. It will move into a higher orbit than before (Fig. 8). In other words, a broken orbital ring will not fall down; it will *fall up*.

Even if the broken ring were then to be left entirely alone it would take thousands of years for its orbit to decay. There is thus ample time for the two ends to be brought together again and for the PORS to be reformed.

It has been pointed out that the failure of one ring could cause the other to be overstressed, so although this could be avoided it remains a possible failure mode. Moreover, it is quite reasonable to suppose that an accident could result in both rings being severed simultaneously. The loss of both orbital rings causes all of the skyhooks and their loads to fall on the ground.

When both rings break each one falls upwards into an elliptical orbit. Skyhooks of various kinds can be used to exert a small measure of control during the break-up, sufficient to put the rings into non-intersecting orbits. No further damage will occur to the rings and the ORS is readily reformed. Again, there are not likely to be any casualties if the precautions of Section 5.3, etc. are followed.

Now consider what happens if the twin orbital rings cannot be prevented from colliding. On first sight it seems as if the rings might become entangled and then fall down. However, this is not possible for energetic reasons. Three numbers are relevant here.

The specific kinetic energy of the orbital rings is 30 MJ kg^{-1} . The maximum potential energy that the rings can absorb in tensile strain is about 0.05 MJ kg^{-1} . The amount of heat needed to vaporise the rings is approximately 5 MJ kg^{-1} .

It follows that the rings cannot lose their kinetic energy by becoming tangled together: if one could bring a small section of a ring to a halt the rest would immediately tear apart from it and would continue along its orbit with scarcely any loss of energy. Only where portions of the rings meet “head on” can they lose their orbital velocity; but the kinetic energy goes into heat and the portions are vaporised instantly. Any odd droplets or ring fragments, which may survive such a collision and fall towards the atmosphere, will of necessity be small and retain most of their orbital velocity; they will burn up harmlessly like meteors.

So the picture of rings becoming tangled together and falling earthwards is not a tenable one. Instead we can imagine lengths of ring moving towards each other on intersecting paths; a sudden flare of vapour marks the point of collision and the severed sections of stream on their orbits. From time to time another brief encounter may chop them into smaller pieces; but none of the pieces falls to the ground.

Since the orbits of the rings are altered only slightly by the collisions the pieces can be collected again without much difficulty (although the job might be tedious if the rings have been cut into many sections). With the addition of some short lengths to replace the vaporised material the ORS can be reconstructed.

5.5 Rupture of Ladders by Meteoroids

Meteoroidal damage to ladders is of two kinds; very small particles gradually erode the surface of cables and larger particles can rupture them. Let us explore the possibility of catastrophic failure of the ladder.

In a multi-filament cable or wire under tension meteoroids bore out a hole of their own size: we use the concept of minimum damaging particle size [13] for meteoroidal rupture.

Let the particle diameter be d_p and let the wire diameter be d_w . The wire is stressed to a fraction f_σ of its rated breaking stress; its redundancy is therefore $(1-f_\sigma)$, which is the fraction of the cross-sectional area of the wire which can be removed before the breaking stress is reached.

Figure 9 shows how a meteoroid could penetrate the wire and produce such a cut. We have

$$(1-f_\sigma) = (2\alpha + \sin 2\alpha)/\pi \quad (67)$$

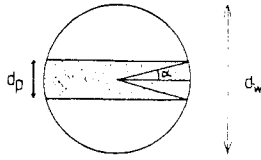


Fig. 9. Meteoroidal Damage to Cables.

For rupture by the meteoroid we need

$$d_p = d_w \sin \alpha \quad (68)$$

Now for a Kevlar ladder, of height 300 km and payload fraction 1/5, has a safety margin of 40%. That is to say that 30% of the cable's cross-sectional area can be cut away before it snaps. Substituting this value in (67) and (68) we find

$$d_p/d_w = 0.24 \quad (69)$$

From several references [13, 14] we obtain the following estimate of the meteoroid particle flux, where d_p is the minimum particle in metres and N_t is the flux in particles per square metre per year

$$N_t = 3.6 \times 10^{-14} d_p^{-2.639} \quad (70)$$

Let the cable diameter at ground level be d_0 . For $H = 300$ km and $p = 1/5$ (see Section 2.1 of Part I) we have

$$d_w = d_0 \exp(2.68 \times 10^{-6} h) \quad (71)$$

Consider the damaging particle flux at height h .

$$dN = N_t(d_p) \cdot d_w \xi \cdot dh \quad (72)$$

where ξ is the body shielding factor of the Earth, here $\xi \approx 0.5$.

Substituting in (72) from (69) and (70) for an exponentially tapered ladder yields

$$\frac{dN}{dh} = 3.2 \times 10^{-12} d_0^{-2.639} \exp(-7.07 \times 10^{-6} h) \quad (73)$$

We integrate this from 100 km to 300 km. The reason we do not go down to ground level is that these meteoroid particles will burn up in the atmosphere below about 100 km. The atmosphere thus protects the thinnest part of the ladder.

$$\therefore N = 1.7 \times 10^{-7} d_0^{-2.639} \quad (74)$$

From Table 1 we take the case where $d_0 = 0.1$ m ($F_p = 2 \times 10^7$ N) giving

$$\tau_N = 14\,000 \text{ years} \quad (75)$$

This is a satisfactory length of time which can nevertheless be increased significantly. For hollow or tubular ladders we find that

$$d_p/d_w = 0.41 \quad (76)$$

This increases lifetimes for the same diameter by a factor of 7. For a hollow mass-driver (which could also be used as an inside-out mass-driver) of radius 10 cm and $F_p = 2 \times 10^7$ N we obtain

$$\tau_N = 150\,000 \text{ years} \quad (77)$$

It is obvious that the hollow form is much less vulnerable to rupture by meteoroids; but both forms have a long lifetime and the danger of catastrophic rupture will be slight.

The principle of redundancy can be used to reduce the risk even further. For example, if the payload fraction is decreased to 1/6 and the solid cable is divided into three well-separated cables thus \therefore , there will be a damaging hit 13 times more often; but since only one of the strands is broken the overall breaking stress is not reached and the ladder remains in place. Two strands must be broken if the ladder is to fall; with a separation of 10 metre, say, this will happen only once in $\sim 600,000$ years. More cables mean even longer timescales for coincidental rupture.

Thin metal wires are threaded through strands of the cable so that meteoroidal rupture can be detected by the breaking of electrical connections; the location and severity of the rupture can be known within milliseconds, allowing repair work to be carried out or emergency action to be taken.

Meteoroidal erosion is caused principally by very small particles (< 1 mm diameter). The total meteoroid flux is $\sim 2 \times 10^{-16}$ kg m $^{-2}$ s $^{-1}$ with specific energies of 2×10^8 J kg $^{-1}$ (both derived from Ref. 14).

$$\therefore \text{Rate of deposition of energy} \sim 4 \times 10^{-8} \text{ Wm}^{-2} \quad (78)$$

Now the cable material is vaporised by about 4 MJ kg $^{-1}$

$$\therefore \text{Rate of erosion of material} \sim 1 \times 10^{-14} \text{ kg m}^{-2} \text{ s}^{-1} \quad (79)$$

Dividing by the density and putting into convenient units we have

$$\text{Speed of erosion by meteoroids} \sim 10^{-7} \text{ mm yr}^{-1} \quad (80)$$

This bulk erosion is obviously negligible.

5.6 Protection of an ORS Against Sudden Changes of Load

If the load on a skyhook drops off the orbital rings will not be able to follow their original paths. Because the force bending them back towards the next skyhook is no longer being applied they will "overshoot" and miss the subsequent skyhooks and then tear apart. The loss of a single skyhook and its load could therefore cause the breakup of the entire ORS; this effect is reduced by the internal tension forces within the individual rings (the rings have some tensile strength) and this may be enough to prevent the orbital rings from breaking by smoothing out the transition.

In general, however, protection will be needed. If the counter-rotating rings are constrained to follow the same path then, whatever happens in the middle, the orbital rings will always find the next skyhook. The release of a skyhook load would produce a bulge and kink moving upwards and outwards from the centre; but the rings would still reach succeeding skyhooks.

Riders on the orbital rings, probably using the same road-bends as the skyhooks, are used to keep the rings together. They have superconducting magnets like those of skyhooks, arranged so that they give no lift normally but resist any vertical displacement. The coupling between the sections of the rider on either ring is spring-loaded and damped. The riders hold station at intervals along the ORS; with as close a spacing as is required to protect the ORS from sudden changes of load. There are more near a heavy skyhook than elsewhere.

The riders operate independently of the skyhooks and of each other. They aid in the distribution of stresses when a

vehicle is accelerating along the ORS and can also apply precession forces between the rings.

A further technique which is available uses dummy loads, which normally ride around with the orbital rings but which can be decelerated and dumped on to skyhooks to replace a fallen-off load.

5.7 Overall Estimate of Safety

If the whole ORS could simply fall to the ground we should expect this to cause approximately 700 casualties (planetary population times fraction of Earth hit by falling ORS). However, we have already seen that the only parts of the system that can fall down are the skyhooks and the ladders; these have their own guard zones, in which falling debris can do no harm.

It is hard to conceive of any accident – or any form of sabotage – which could allow more than a few small bits of the ORS to strike the ground. To reiterate, the orbital rings are inherently 'fail-safe.'

Thus only those people actually making use of the ORS need be at risk, and with reasonable precautions they can survive even very serious accidents. In other words, an ORS is safer than a conventional airliner network, both for users and for the general public.

6. USES AND BENEFITS OF ORBITAL RING SYSTEMS

6.1 Transport Involving Orbital Ring System

Horizontal movement of vehicles along an ORS is important in putting cargoes and passengers into orbit. Vehicles could acquire horizontal momentum by climbing long curved ladders, although the logistics and safety aspects of this method might pose some problems. There is also the method of acceleration along a ladderless PORs.

The following procedure could be used for a "conventional" ORS: a vehicle climbs a (nearly vertical) ladder and stops at the skyhook, where it is swung up on to the orbital rings; there, it accelerates horizontally, using linear induction motors reacting against special roadbeds or the metal sheathing of the rings. Different vehicles could of course be used for the two stages.

An important point here is that the vehicle does not have to supply any of the energy for its acceleration: this comes from the counter-rotating rings. Thus the major problem for linear induction motors – how to get power to the moving vehicle – does not arise.

Let the vehicle, mass m , thrust against the rings with forces F_1 and F_2 and move with velocity V , acceleration a . The orbital velocity of the rings is V_0 . Now, by NSL

$$ma = F_1 + F_2 \quad (81)$$

The work done by the vehicle is

$$P = F_1 (V_0 + V) - F_2 (V_0 - V) \quad (82)$$

If no net work is done

$$F_1/F_2 = (1-V/V_0)/(1+V/V_0) \quad (83)$$

If the acceleration is held constant F_1 & F_2 each vary with velocity

$$F_1 = \frac{1}{2}ma (1-V/V_0) \quad (84)$$

$$F_2 = \frac{1}{2}ma (1+V/V_0) \quad (85)$$

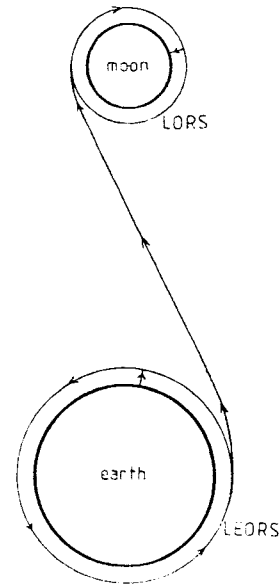


Fig. 10. Earth-Moon Transport *via* Orbital Ring System.

Because $F_1 \neq F_2$ there is also a coupling acting on the vehicle; an opposing couple can be applied using transverse forces if the vehicle rides on the tracks above the rings, rather than the skyhooks do below.

With this arrangement the maximum speed is limited by the acceleration that the passengers or cargo can take, the vehicle having to be held down on to the ORS above orbital velocity. If the angular acceleration is not allowed to exceed 10 ms^{-2} the vehicle can reach a little over escape velocity (the hyperbolic velocity, $V_\infty \approx 2.5 \text{ km s}^{-1}$ for $H = 300 \text{ km}$). As greater "gee-forces" are permitted, V_∞ increases (for example 15 ms^{-2} yields $V_\infty \approx 6 \text{ km s}^{-1}$).

As an example of the usefulness of an ORS for transport (apart from its obvious function in launchings payloads to LEO) consider the simple Earth-Moon transport system in Fig. 10: a vehicle climbs upon a ladder from Earth and is spun up to 11 km s^{-1} along the ORS in LEO; released at the appropriate point on its orbit it falls freely towards the Moon, where it meets the LORS at a tangent, is captured and decelerated, before descending a ladder to the lunar surface. No propellant is used (apart from very small amounts for mid-course corrections) and at no time does the acceleration exceed 11 ms^{-1} , yet the whole journey takes only one and a half days.

This 'slingshot' method of launch can also be used for interplanetary missions. Ballistic ellipses to any planet or asteroid can easily be achieved; an ORS in polar orbit can dispatch payloads in any direction over the course of a day.

The energy supplied to the payload from the rings can easily be replenished *via* the skyhooks, or *via* Power Transfer Systems (PTS) from other rings: but more care is required in balancing the angular momentum, either by releasing the payloads with zero average angular momentum or by supplying it to the ORS by the ladders. A skyhook can be driven sideways, so that the sloping ladder exerts a couple of the same order of magnitude as that produced by the acceleration of payloads.

Payloads can be sent off in either direction or, in a precessing system, can have the angular momentum vector-averaging to zero, even if they are all sent off the same way round the rings.

A vehicle can be launched into any orbit in the plane of

the ORS for which the radius of the ring's orbit is either perigee or apogee; and it can be released with any velocity tangential to the ORS (so there is even greater flexibility with an EORS). In precessing systems the orbital plane changes throughout the day, introducing an extra degree of freedom. It is also possible to inject payloads into higher orbits which can be circularised on rendezvous with an SMF or Space Colony. It will be apparent that the examples which have been chosen are only a small sub-set out of numerous possibilities.

It is obviously important to arrange the movement of vehicles along the ORS so as to avoid collisions. It may well be practicable to allow vehicles to overtake and cross, perhaps by having several lanes or tracks.

6.2 Economic Benefits of Orbital Ring Systems

From the work above (particularly Section 3) it will already be obvious that an ORS would be very useful for lifting payloads into space, the cost of orbit being $\sim 5 \text{ c}\$ \text{ kg}^{-1}$. Its nearest competitor would perhaps be the Single Stage to Orbit (SSTO) vehicle, with a similar development cost ($\sim 10 \text{ G}\$$) and a cost to orbit of $\sim 15 \text{ }\$ \text{ kg}^{-1}$.

If we were to charge, say, $1 \text{ }\$ \text{ kg}^{-1}$ initially then investment of $\sim 10 \text{ G}\$$ could be paid back (including interest) in a little as three weeks at full throughput; or the charges brought down to $\sim 0.1 \text{ }\$ \text{ kg}^{-1}$ within a year.

Of course, this depends upon finding customers enough to make good use of the ORS; this in turn depends upon the use that is made of space industry and the extent of space colonisation. These things are bound together and will grow together; certainly they can be very profitable indeed.

Solar power satellites can provide a rapid return on investments and great economic benefits to the world. The original SMF scenario [4] was intended to produce 2.4 SPSs a year, each supplying 10 GW to Earth; using the expanded SMF, supplied with ore by LORS from the Moon, this can be scaled up to 1000 GW capacity per annum. In only a decade (by Year 19) as much as 10^{13} W (the total world energy demand in 1980) could be brought on-line. This rate could almost be doubled if full use is made of the main ORS for this purpose. Even if the SPS electricity is sold at the low price of $1 \text{ c}\$/\text{kWhr}$ this could provide benefits of around $50 \text{ }\$/\text{kWhr}$ up to $\sim 500 \text{ G}\$ \text{ yr}^{-1}$. This is a lot (cf. Gross World Product of about $5 \text{ T}\$ \text{ yr}^{-1}$).

Although a 10^5 population Stanford Torus could support all the construction workers needed in making these SPSs it would be better to have a broader-base and self-sufficient colony in which they can live. A colony of about a million people would make a useful start. This would need some $3 \times 10^{10} \text{ kg}$ brought from Earth and 10^{11} kg (mostly shielding) from the Moon, which would tie up the ORS for two months, the LORS for six.

Colonies could be built as an adjunct to space industrialisation, but they could also be built for their own sake, as real estate, and sold to would-be colonists - just as new towns are founded today. The cost of such a colony (see Ref. 2, especially Ref. 3, and the above discussion) is likely to be about $10,000 \text{ }\$$ per person (for 10 m^2 'ground area,' or 2000 m^3 per person) plus $200 \text{ }\$$ for each extra square metre. If a typical colonist were to pay $\sim 25,000 \text{ }\$$ outright for his new home then the "builders" could make a profit of $\sim 10,000 \text{ }\$/\text{person}$. Re-investment could help fund mortgages and development of the colonies. Over the course of a working lifetime each person would be able to contribute as much as $10^5 \text{ }\$$ to habitat construction, and then retire to really spacious colonies with $500 \text{ m}^2/\text{person}$ or more.

Since the ORS and LORS, working together, could found colonies for up to 3×10^6 people per year the revenues from this source could amount to $30 \text{ G}\$ \text{ yr}^{-1}$. This is not so

lucrative (in the short term) as SPS manufacture, but is still well worth while.

One advantage of space colonisation by ladder is that the emigrants can take most of their personal property with them (perhaps a tonne or so per person, at a cost of a few hundred dollars), making colonisation that much simpler and cheaper). Another advantage is that visits to and from Earth would be frequent and inexpensive.

Tourism is an obvious possibility, with return tickets to orbit being sold for perhaps $100 \text{ }\$$ (they could become much cheaper). The ORS could even be used for transport across the globe (come up one ladder, go down another). This would be faster than conventional aeroplanes, but would use very little fuel.

The many other uses of ORS, mentioned throughout this paper and to be mentioned in Part III, all have their own appropriate economic benefits and it is not hard to think of others.

7. SUMMARY AND CONCLUSIONS

A space transport system should be fast, cheap and safe. Orbital Ring Systems could be at the heart of such a system, which might replace the second generation Space Shuttles; these, the Heavy Lift Launch Vehicles (HLLV) and Single Stage to Orbit (SSTO) vehicles, are expected to have launch costs of several tens of dollars per kilogram (e.g. Ref. 15). Payloads could be launched very much more cheaply from an ORS, perhaps for as little as $5 \text{ c}\$ \text{ kg}^{-1}$.

In Part I of this study I examined the theoretical principles of Orbital Ring Systems (of many types) and Jacob's Ladders. In this paper (Part II) I have examined aspects of their construction, deployment and use. My aim has been not simply to provide these concepts as scientific curiosities, but as useful starting points for technological realisation; this is why I have devoted so much space to particular scenarios for ORS deployment, and why I am considering the use of Orbital Ring Systems in so much detail.

I conclude that Jacob's Ladders and Orbital Ring Systems are firmly based upon well-known physical and engineering principles, and that no exotic technology is needed for their construction; it would appear that they could be built today. It seems that if an ORS is built as part of a general plan for the exploitation of space it will cost surprisingly little, yet provide great benefits.

I recognise, of course, that much detailed work remains to be done (on stability, oscillations and stresses, orbital elements and perturbations, on the logistics of construction, deployment and use, and so forth), and would recommend that an early feasibility study be carried out.

In Part III I shall consider some further uses of Orbital Ring Systems, in the generation and transfer of power (both solar and gravitational), in the provision of fixed platforms in space, and in the most far-out applications imaginable; how to conquer the Universe with ORS.

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In Part I of this paper (*JBIS*, **35**, 475-497 (1982)), part of Section 3, pages 482 and 483, was inadvertently transposed during final preparation for printing.

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