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Laser propulsion activity in South Africa

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R. Moorgawa^a, E. McKenzie^a and G. Turner^a

Three sets of laser propulsion experiments have been conducted in South Africa. The first, on the MLIS kilowatt CO₂ laser at Pelindaba, gave a surprisingly good result but could not be repeated after the laser chain was dismantled when South Africa's uranium isotope programme was closed. The second, conducted with a kilowatt CO₂ laser module, produced unexpectedly weak propulsion. We give reasons for the discrepancy between the two experiments. In the third experiment, hybrid solar and laser propulsion was tested: laser momentum coupling was enhanced as a result of generation of a dusty plasma by the concentrated solar energy.

Introduction

Space specialists in the northern hemisphere are becoming excited at the prospect of a considerable reduction in the cost of launch to low Earth orbit (LEO) by means of laser propulsion (LP) (see ref. 1). We argue here that developing nations also should assess the potential of a cheaper route to space, especially as LP has to involve one or several high, equatorial mountains. This is because it is necessary to transmit the laser beam from an altitude similar to that chosen for the world's greatest optical telescopes. Since laser propulsion does not offer the luxury of easy orbit modification as with chemical launches, the equator will become the preferred 'locus propellandi'. Industrially powerful nations such as Egypt and South Africa might do well to take an early interest in this equatorial laser propulsion venture, which should bring great economic benefits to the region.

The MLIS laser propulsion experiment

Just before the end of the South African uranium molecular laser isotope separation programme (MLIS) in 1997, two tentative propulsion experiments were conducted, one with the large UF₆ isotope-separation laser chain, the other with a 300-J, hydrogen fluoride (HF) system intended for military use.² Both these experiments would have been capable of growing into interesting full-scale laser propulsion projects, but both were interrupted by the shut-down of the MLIS plant at Pelindaba, west of Pretoria.

The only reasonably successful trial was a 'parasite' experiment involving the Atomic Energy Corporation's uranium separation CO₂ laser chain. The 5-element laser chain (Fig. 1a) could operate from 300 Hz to 600 Hz with a pulse length of 100 ns and an energy per pulse of approximately 1 J in the TEM₀₀ mode (the transverse mode of laser illumination that produces the least beam divergence and the highest focal intensity for a given beam width, otherwise known as a Gaussian mode). Figure 1b shows one of the laser amplifiers. The projectiles were made up of matching cones and cylinders and could be filled with a variety of 'fuels'. The best fuel turned out to be water ice mixed with Tipp-ex™, a commercial white fluid eraser used to correct paper

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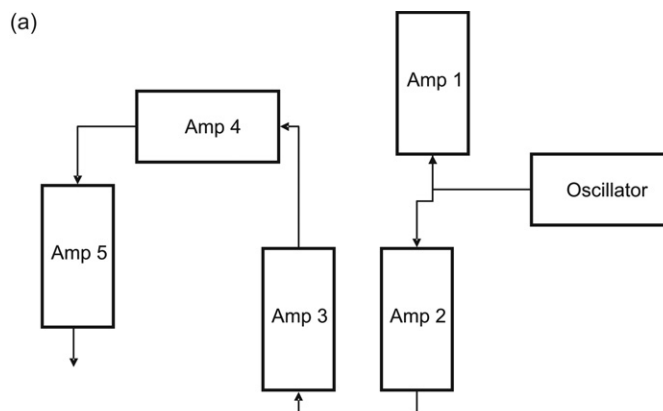


Fig. 1. Parasite LP experiment: (a) schematic layout of the kilowatt CO₂ laser chain developed at Pelindaba for the MLIS programme for isotope separation by laser. Amplifier 1 is a double-pass system, thus there are six amplification stages after the oscillator. (b) One laser in the Master Oscillator Power Amplifier (MOPA) chain (to give a sense of the size of the combined equipment), showing the gas circulating system with the laser head. Such an element can be configured to deliver 1 kW of average power and was used for the repeat CO₂ laser propulsion experiment.

documents, which dries to a solid on contact with air. At optimum repetition rate (300 Hz), the 1-g projectiles reportedly 'hit the roof' some 10 metres high. Unfortunately, no momentum coupling constants were available, nor was there any time to take measurements.

As to HF laser propulsion, only a rudimentary single-shot pendulum test was performed together with a propulsion demonstration with a small plastic target. The reason for reporting this is that HF LP or DF (deuterium fluoride) LP was the first type envisaged² but has never been developed even in the laboratory. The South African HF laser, presently in storage at Pelindaba, would be an exceptional tool for this research, since its single-shot energy surpasses that of most lasers.

The kilowatt laser propulsion 'repeat' experiment

Experiments conducted in 2001 were carried out with projectiles, optics and launch tubes (Fig. 2) similar to those used in the

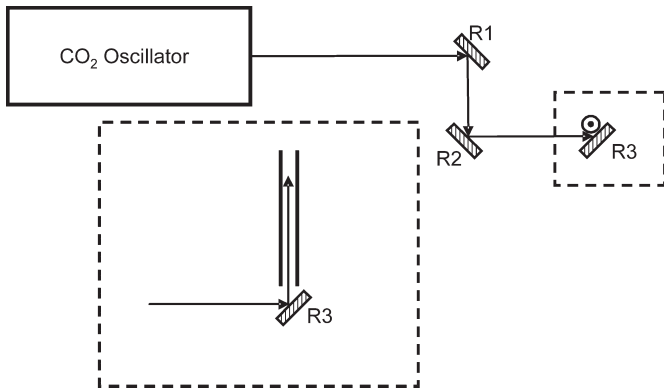


Fig. 2. Schematic illustration of the experimental layout for the South African laser propulsion repeat experiment. The dashed box (bottom left) shows the vertical aspect of the beam passing through the guiding pipe (which is also represented on the right-hand side of the figure). Data points were captured with a video-recorder and imaging system, then analysed as a function of time (from the video frame rate).

1996 experiments, but with a different laser system. The energy per pulse (1 J) was similar and the repetition rate could be varied from 100 Hz to 1200 Hz. To generate more quantitative results, the projectiles were accelerated by the laser beam inside guiding tubes of known length, and the resulting motion monitored after being ejected from the tube. Using basic theory of projectile motion, the momentum coupling constants could be determined quantitatively.

Theory

In this section we briefly cover the governing equations to obtain quantitative values for the momentum coupling constants in a laser propulsion experiment. The reader is referred to a more complete description of the theory of laser propulsion in ref. 1.

The equations governing the projectile motion inside and outside the launch pipe are, first, the momentum coupling equation

$$C_m \epsilon f = ma \tag{1}$$

(assuming no major change of mass m during the internal trajectory and where ϵ is the energy per pulse and f the repetition rate), and second, the ratio of the free ascension height h_2 to the length of the launch tube h_1 :

$$\frac{h_2}{h_1} = \frac{a}{g} = a^* \tag{2}$$

This ratio is proportional to the internal acceleration in units of g , which we refer to as a^* . This assumes that there is no interaction between the laser beam and the projectile after emergence from the launch tube. From these equations we can write the momentum coupling constant in terms of a measurable maximum height and the length of the launch tube as:

$$C_m = \frac{mgh_2}{\epsilon fh_1} = \frac{ma^*g}{\epsilon f} \tag{3}$$

Results

The attempt to reproduce the 1996 results (same energy, same repetition rate, same projectile) was frustrating. As before, the use of ‘no fuel’ (that is, bare aluminium), pure ice or even ‘black ice’ (ink-darkened) fuel failed to propel, although successful momentum coupling with these materials has been observed elsewhere. Surprisingly, the 1996 favourite fuel (frozen dissolved Tipp-ex™) also barely levitated the projectile, which failed to emerge from the copper launch tube. This was due to the poor beam quality and resulting low intensity on target. (Momentum coupling is extremely sensitive to this parameter.) Our best fuel in the 2001 experiment turned out to be black silicone rubber.

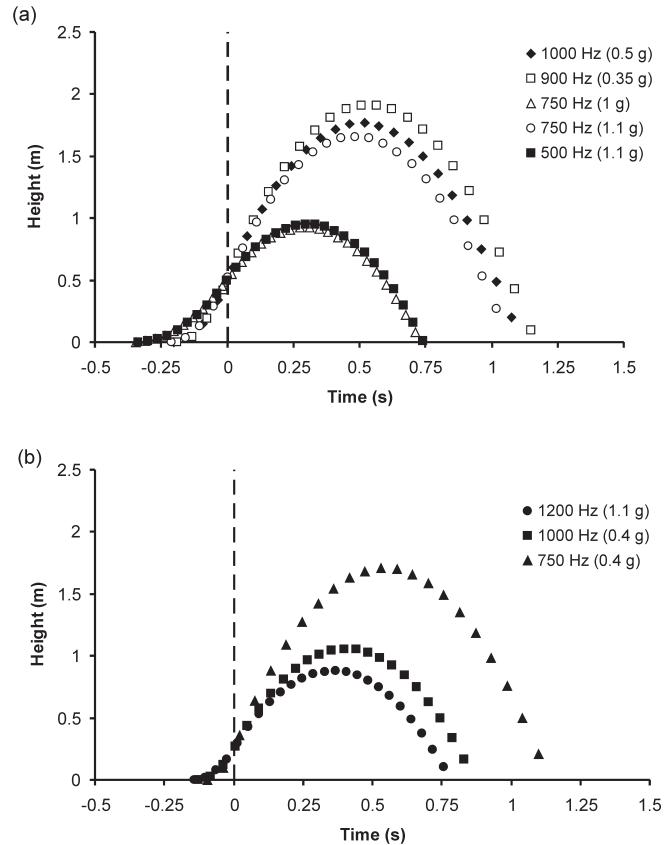


Fig. 3. (a) Results using the long (50 cm) launch tube. Coupling constants C_m vary greatly between data sets, from 14.6 $\mu\text{N/W}$ (900 Hz, 0.35 g) to 47.7 $\mu\text{N/W}$ (750 Hz, 1.1 g). (b) Short tube (25 cm) results. Coupling constants C_m vary greatly between data sets, from 16.6 $\mu\text{N/W}$ (1000 Hz, 0.4 g) to 35.7 $\mu\text{N/W}$ (750 Hz, 0.4 g).

The results shown in Fig. 3a are for different projectiles, but all loaded with that fuel.

What is not obvious from Fig. 3a is that the projectile’s behaviour was erratic: coupling constants C_m varied greatly, from 14.6 $\mu\text{N/W}$ (900 Hz, 0.35 g) to 47.7 $\mu\text{N/W}$ (750 Hz, 1.1 g) for the long tube.

Seemingly identical conditions did not always produce the same results. Only towards the end of our four days’ beam time did we understand the causes of this, as well as the fact that the previous best fuel gave such poor results. We were also able to understand why the highest repetition rate (1200 Hz) and power (1.2 kW) was never the optimum for the long tube experiments. This understanding came from using a glass pipe as well as relatively short pipes, as explained below.

Returning to the experiments, we now compare some typical 2001 results (Fig. 3a) with the 1996 experiment. We note first that for the 1996 projectile to have travelled 10 times further outside than inside the launch tube (as reported in ref. 2), requires an acceleration of $a^* = 10$. This implies C_m in the order of 300 $\mu\text{N/W}$ for a 300-Hz, 1-J pulse accelerating a 1-g projectile. This value seemed extraordinarily high and was in fact contradicted by our Durban pendulum experiments (see below). We can conclude only that because of the extraordinarily good quality and low divergence of the MLIS laser beam, the projectile would certainly have continued to accelerate, after leaving the launch tube (exactly as in all vertical propulsion experiments carried out in other laboratories with larger-diameter targets).

In contrast to this, no illumination from burning fuel was observed once the 2001 projectiles travelled above the launch tube. This was due to the beam no longer emerging from the tube. In even greater contrast, our best 2001 trajectories for the

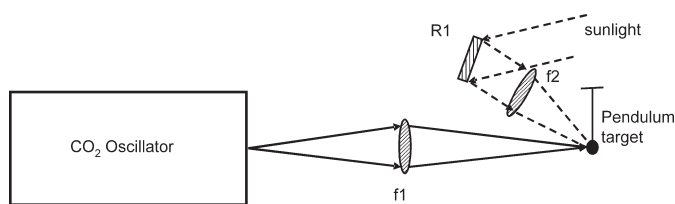


Fig. 4. Durban laser-driven pendulum experiment. Sunlight is collected using a solar tracking mirror (R1) and then focused using aspheric lenses (f2) onto the target.

50-cm launch tube corresponded to values of C_m below $50 \mu\text{N/W}$ (750 Hz, 1.1 g projectile) — a factor of 6 lower than the 1996 qualitative result.

As we explain below, this indicated that the ‘long tubes’ ($h_1 \geq 50$ cm) were not working properly; indeed, this was confirmed by replacing the long tube with a 25 cm ‘short tube’. The short tube gave nearly as good propulsion (see Fig. 3b) as the long with corresponding values of the momentum coupling constant C_m ranging from $16.6 \mu\text{N/W}$ (1000 Hz, 0.4 g) to $35.7 \mu\text{N/W}$ (750 Hz, 0.4 g). To verify our suspicions that premature breakdown was occurring — and although the long tubes did allow some observation of light emitted from the projectile via a few small holes — we repeated the long-tube experiment with a glass tube.

The difference between long and short tubes became obvious. In the long tube, the exhaust from the projectile immediately filled the tube with black smoke, causing premature breakdown about half-way up the tube. Moreover, the rapid coating of the walls after only a few shots meant that optical wave-guiding occurred only for a clean new tube.

To summarize, the causes of ineffective propulsion in the 2001 experiment were as follows: poor beam quality led to the necessity of focusing the beam at some point inside the tube. If the tube was clean (that is, for the first few shots), some wave-guiding may have occurred. The focusing caused premature breakdown below the projectile, especially when the focus was close to the base of the launch tube: the laser energy was transferred to the vapour in the tube rather than to the projectile.

Even if the focus was high in the pipe, premature breakdown occurred erratically lower down, especially at high repetition rates when the tube was full of dense absorbing ‘smoke’. The laser energy never seemed to reach the top of the very long (1 m) pipes. There are two conflicting requirements for optimum propulsion as observed in our experiments and as reported in recent Japanese work.⁴ The first requirement is optimum transmission of laser light by the fuel whereas the second is optimum absorption on the target. This explains why a high-quality beam needs a transparent vapour, even if the absorption on the target surface is lower (hence the best 1996 fuel was iced Tipp-ex™). A focused beam needs high surface absorption for a limited number of pulses, regardless of the fact that the beam may be extinguished once the projectile has left the focal region. The black

rubber fuel therefore became the best fuel in the second experiment due to its high surface absorption, as was observed in the Durban pendulum experiments reported below. Too high a repetition rate will fill the tube with dense absorbing vapour, regardless of beam quality, hence the need for a lower repetition rate optimum. A short tube (25 cm) worked nearly as well as a longer one, verifying all the above points.

We accept that these are very preliminary and somewhat incomplete results. However, they do represent the first quantitative laser propulsion experiments carried out in Africa and possibly in the southern hemisphere.

Ablation-driven pendulum experiments

Ablation, or photon-deflected, pendulum experiments are now standard procedure.^{5,6} During the period of intense research into laser technology at Pelindaba, apart from the uranium separation and military laser programmes, there was also an active industrial CO₂ commercial venture undertaken by the Optical Energy Systems group. Some dozen ‘marking lasers’ were built for the soft drinks and sugarcane industries. These lasers are now part of the considerable laser and optics assets of the National Laser Centre at the CSIR in Pretoria. One such laser has been loaned to the University of KwaZulu-Natal, where it serves for engineering student demonstrations and experiments. Our aim is to use this laser to measure the momentum coupling constant C_m for various fuels, at various intensities in air and under vacuum. This study has only just begun (Table 1) but, as can be seen, burning rubber has the highest C_m for our conditions, followed by wet Tipp-ex™. We assume that in the 1996 Pelindaba experiment, the irradiation level and duration would have been sufficient to melt all the ice of the frozen Tipp-ex™. Likewise, we assume that in the 2001 propulsion experiment, ‘burning rubber’ is the correct description of the fuel: a bright flame was often seen bursting from the base of the projectile as it emerged from the launch tube, but not beyond this point. Table 1 indicates that the burning, or solar-illuminated, targets exhibited considerably higher momentum coupling. We believe that this phenomenon could be used to increase the efficiency of laser propulsion by supplying large amounts of solar power (as explained in more detail below).

Hybrid solar and laser propulsion

Mankind has long been concerned with using the Sun’s rays. What we propose here is a long-term study of whether solar energy could be effectively used to boost laser propulsion.⁷ The earliest proposal⁸ for solar-boosted LP was made by Jordin T. Kare, the editor and organizer of the first-ever conference on LP, at Los Alamos National Laboratory, New Mexico, in 1987.

A first strong reason for this study is that, although the Sun is a poor quality optical source (10 mrad divergence), compared with any laser, its energy is almost limitless. Several solar power stations have been built in the US and Japan. The most famous is probably that in the French Pyrenees at Odeillo (Font-Romeu),

Table 1. Momentum coupling constants C_m (in $\mu\text{N/W}$) for various lasers and for materials in air.

Laser type	Material							
	Thermal paper (e.g. fax paper)			White paper	Rubber		Wet Tippex™	Various plastics
	Back	Front	Burning		Cold	Burning		
TEA CO ₂ ($\lambda = 10.6 \mu\text{m}$)	20	40	60	20	10	60	35	0
Nd:YAG ($\lambda = 1064/532 \text{ nm}$)	0	0	0	0	$\epsilon/0$	0	$\epsilon/10$	ϵ

ϵ indicates small but immeasurable movement. All average pulse intensities were approximately 50 MW/cm^2 .

where focal region temperatures of 4000°C and industrial powers in the megawatt range have been reached.⁹ A second reason is that 'lift off' through the atmosphere of a heavier-than-air spacecraft laden with laser 'fuel' may not be the most imaginative way to solve the enormous energy requirements this initial mass places on the laser. Solar energy balloons have been around for decades: why not modify the technology for propulsion into near space?

A third reason is that, although in the ideal world of perfectly functioning adaptive optics, low-level extra radiation would serve no purpose compared to the cost of providing it, in the real world of atmospheric absorption by, for instance, aerosol layers, intensity on target may fall below optimum. The double-pulse (one for evaporation, one for propulsion) proposal⁵ is one way to optimize the coupling. Present-day pulsed lasers simply are not capable; what is needed is a means of dissipating aerosol layers and of steadily evaporating layers of target material prior to illumination. This could be accomplished by a long, low-intensity laser pre-pulse or by a continuous wave (CW) laser or by the Sun.

A further reason is that part of the on-board solar concentrator could be reversed in space to gather direct sunlight with its high UV content to power an on-board laser for low fuel cost, high exhaust velocity corrections.

The broad principle of solar-assisted laser propulsion is two-fold. First, focused solar energy is used to evaporate the target material, thereby saving the pulsed laser from having to deliver the latent heats of melting and vaporization and the small rise in temperature required. Second, the layer of vapour serves to shield the target and absorbs the high quality pulsed laser light to give a high exhaust velocity, exactly as with the double-pulse scheme.

We now make a proposal to demonstrate the potential of a solar-assisted, lighter-than-air launch. The basis for the proposal is the creation of an ultra-cheap, ultra-large mirror. This would be created by excavating a 3-km-diameter paraboloid less than 20 m deep, coat it with wet clay followed by a thin layer of aluminium foil. Such an equatorial mirror would focus approximately 6000 MW into a focal region 300 m in diameter at a height of 30 km. The intensity would rise to around 100 kW/m².

There have been several proposals for balloon-aided launches in which a balloon lifts the spacecraft to an altitude of some 30 km prior to acceleration. Here we envisage a lighter-than-air hydrogen-filled craft rising to a height of some 20 km, when it starts to interact with the beam of concentrated solar power. The craft is configured to concentrate the solar flux by a further factor of 10 and the diameter of the funnel to just over 20 m (not large by hot air balloon standards). Some $P_T = 30$ MW of power is thus concentrated onto a target area of about 2-m diameter. Assume now that, say, half this power (P_k) is converted into kinetic energy of exhaust gases from a surface temperature typical of solar furnaces of some 3000°C (the rest goes into latent heats, radiation and other losses). There is then a choice of exhaust gases. For a light gas (such as hydrogen or helium), typically $v_E = 10^4$ m/s; for a heavy gas (such as CO₂) or water vapour, typically $v_E = 10^3$ m/s. For a heavy gas we then have

$$P_k = 15 \text{ MW} = \frac{1}{2} \dot{m} v_E^2,$$

where \dot{m} is the rate at which 'fuel' is burnt ('fuel' being a generic term for gas, liquid or ablated solid or a mixture of these). We can then use the result obtained for \dot{m} to find the lifting force F_k :

$$F_k = \dot{m} v_E = 30 \text{ kN}.$$

If the craft has a mass of 500 kg and carries 1000 kg of fuel, then using the rocket equation we find that it rises with an accelera-

tion a varying from 1 g to 5 g , reaching twice the speed of sound (at ground level). The total height reached is 30 km above the point ($h_0 = 25$ km) at which the solar power became available. In all this we have been deliberately pessimistic about the available power in order to be optimistic about such things as aerodynamic drag and Rayleigh range (the distance at which the beam cross-sectional area has doubled from its minimum value).

We also assume that a special 'ablation motor' can be invented and developed — a sort of hybrid between a rocket, a gas burner and a laser ablation system (such a motor has already been designed by Kare⁸). Pressurized gas or liquid would be blown through the heated and ablating surface of a block of appropriate material. Once the gas and the solar heating are exhausted, the same block — possibly with slightly different composition — would continue to ablate under the irradiation of the laser alone.

The mirror surface would need to be aligned to perhaps one-tenth of the Sun's divergence. This requires the surface height to be precise to within a few millimetres. Discussion with civil engineers confirms that this is not impossible, but difficult. First, a standard earth-moving machine hollows out the profiled hole to an accuracy of a few centimetres after laying a solid base with conventional road-building techniques aided by a central surveying tower. Then, a modified machine travelling along a spiral path improves the accuracy to less than 1 cm. This is then followed by a machine designed either to lay an extremely smooth concrete surface or (for a less permanent installation) a clay surface which is baked as the machine moves along. The surface-laying machine is followed by another specialized vehicle carrying a large drum of aluminium reflecting foil.

A possible problem with the proposed use of very large mirrors is their effect on the micro-climate. It is well known that fires generate convection clouds. The effect of a large mirror producing a multi-gigawatt CW beam, even if not vertical, is uncertain at this stage.

We intend coupling our Durban atmospheric transmission studies with the principle of hybrid solar-laser propulsion. Even an apparently clear atmosphere can distort a laser beam in a variety of well-known ways. The second connection with atmospheric physics is that we believe that tropospheric and stratospheric events will become crucial to the routines of laser launching just as maritime weather is paramount to shipping. As one example, we cite the effect of atmospheric aerosol layers. Such seasonal layers were detected by the Durban atmospheric LIDAR and also reported in the LP context at High Power Laser Ablation (HPLA) III, as well as by observers at the Laboratoire de Physique de l'Atmosphère at Reunion Island.⁹⁻¹²

Hybrid laser experiments have been conducted in a variety of high power/energy laser experiments, involving beat wave electron accelerators, rainbow and ignitor fusion, particle acceleration and double-pulse laser propulsion schemes. Hybrid solar-laser propulsion is a natural extension of these ideas.

Laser propulsion in South Africa

Several experimental and theoretical papers on LP involving South African authors have appeared in laser journals and in conference proceedings during the last decade; it would not be difficult to generate a local body of appropriate expertise. The subject meshes especially well with atmospheric LIDAR studies as well as with that of dusty plasmas, both well-established local research disciplines. LIDAR and atmospheric meteorology has never yet been applied to assess the risks of mission abortion for laser-propelled satellites. Dusty plasma studies are relevant to laser-target interaction. On the experimental front, we note that the National Laser Centre has an unemployed stock of indus-

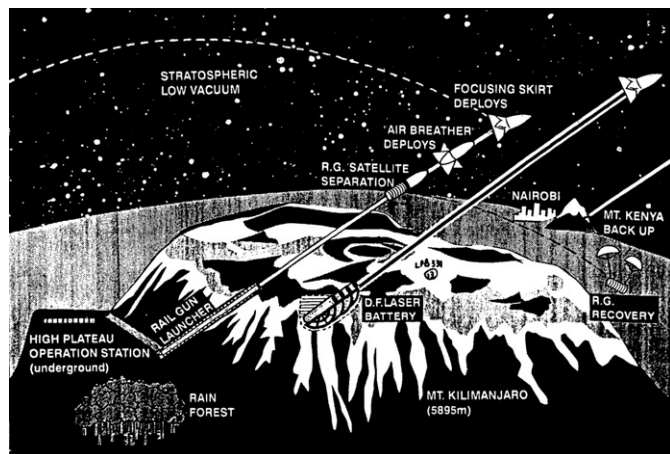


Fig. 5. Space-port Kilimanjaro (after ref. 13). The sketch shows a hybrid propulsion solution incorporating a laser system, and has the benefit of near-equatorial location and high altitude. Graphic: Jo Orsmond.

trial-size lasers: copper vapour, CO₂ and HF. Even if the former CO₂ Master Oscillator Power Amplifier (MOPA) laser chain cannot be partially revived, it would not be difficult to re-energize the HF laser. We suggest that a modest HF laser propulsion research programme could be combined with theoretical studies of the quantum mechanics of chemical lasers, atmospheric phenomena and laser propulsion. In the event of the grandiose scheme of 'Space Port Kilimanjaro' (Fig. 5), envisaged by various authors becoming a reality, South African scientists, engineers and financiers would benefit. Kilimanjaro is regarded by some¹³ as the prime location for laser propulsion: it lies within a few degrees of the equator; it is further from the centre of the Earth than Everest and it is easily accessible and has a more favourable climate than other candidates such as glacier-covered Chimborazo in Ecuador. Nor, being truly dormant, does it suffer from the volcanic instability of the Indonesian, Malaysian, or South American mountain ranges.

At virtually no cost to South Africa, a modest experimental and theoretical study of laser propulsion has been accomplished. Given the rapid growth in the international LP programmes, it is certain that South Africa will be excluded from these developments, unless a real commitment to this new laser discipline is made. In addition, given the fact that central Africa, with its high equatorial mountains, may become a centre of LP activity, it would be wise to maintain at least a 'watching brief' during the next stages of this work.

Conclusion

Preliminary laser propulsion experiments in the southern hemisphere have been reported for the first time here. Results indicate that good beam quality (near TEM₀₀ mode) is a necessary requirement when delivering the laser beam to the target. The momentum coupling constants for various materials and for three laser systems have been calculated from experimental data, and it has been shown that the momentum coupling constants increase when the target absorber is at a raised temperature. From this we speculate that hybrid solar and laser propulsion systems would result in enhanced momentum coupling constants, which could lead to improved efficacy in relation to laser-only propulsion solutions.

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