Large Scale Directed Energy
The Path to Radical Transformation in Propulsion

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Abstract – Large scale directed energy offers the possibility of radical transformation in a variety of areas including the ability to achieve extremely high-speed propulsion for a wide variety of purposed including rapid high mass solar system missions and eventually relativistic flight that will enable the first interstellar missions. In addition, the same technology opens a wide mission space that allows a diverse range of options from long range beamed power to remote spacecraft and outposts to planetary defense to remote composition analysis and manipulation of asteroids among others. The key to being able to accomplish this is the ability to project large amounts of power over large distances. It is the projection of power over vast distances that enable this radical change. Unlike other forms of propulsion photonic propulsion has no upper limit not does it have any lower limit and thus allows scaling unlike any other propulsion technology. Photonics (the production and manipulations of photons) , like electronics is an exponentially expanding growth area driven by diverse economic interests that allows transformational advances in space exploration and capability. In order to begin to fully exploit this capability it is important to understand not only the possibilities enabled by it but also the technological challenges involved and to have a logical roadmap to exploit this option. This capability is both synergistic with conventional propulsion and offers a road to a future currently not possible with conventional capabilities.

Introduction - One of the dreams of humanity has been to travel to the stars. With the number of planets per stars being approximately unity based on the latest Kepler data and with even our nearest stellar neighbor, the Alpha Centauri system, having at least one confirmed exoplanet, the possibility of reaching interstellar targets is a dream we can came begin to seriously explore. However, the ability to travel to and explore the many nearby exoplanets requires a radical change in both propulsion systems and in spacecraft design. The ability to achieve the speeds required is becoming a possibility due to recent advances in directed energy systems that allow us to remove the propulsion system and its associated mass from the spacecraft. The transformations that will come from this approach allow a radical change in capability.

One question that is often pondered in space exploration is “why do we want to go there”? This is a valid question and should not be dismissed as simply “it is in the human spirit to explore”.

The question is more quantitatively proposed as “how close do we need to get to answer the questions we pose”? This at least can be quantified for a given question and set of assumptions.

For example, our atmosphere is quite opaque shortward of 330 nm and thus trying to conduct deep UV or X-Ray observations from the ground is not feasible. As a quantitative example let us suppose we bring a 10 cm diameter telescope to the nearest star to look, even if we do not land. What do we learn that a large space or ground based telescope will not “show us”? Suppose we take our 10 cm telescope to within 1 AU of the star or exo-planet. What size Earth (or near Earth) telescope would we need to be equivalent in resolution? This is simple to answer. It is simply the ratio of distances. The nearest star, Proxima Centauri, is about 250,000 AU (4.2 ly) and thus our 10 cm telescope at Proxima C is equal in angular resolution to a 0.1 x 250,000=25,000 m = 25 km telescope. In theory, we could build such a telescope. Indeed we will see that our system discussed

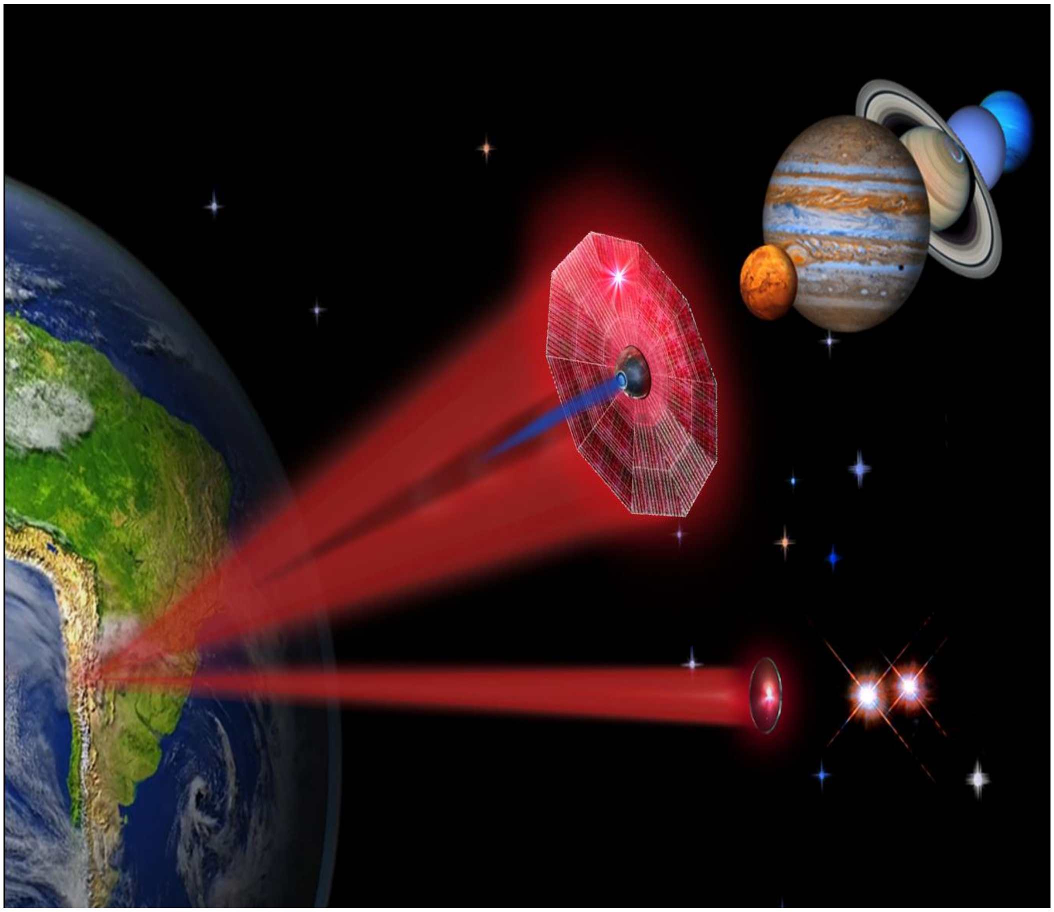


Figure 1 – Conceptual drawing of the overall system being used for both high speed high mass solar system mission via photonic power projection that is converted to electrical power to drive an ion engine (upper) while the lower shows the same system being used to project low mass relativistic missions.

below when used in the “receive mode” is actually a multi km “telescope” though not a general purpose one. Now , lets get to within 0.1 AU. The equivalent near Earth telescope , in terms of resolution, would be 250 km. A little harder to build. We can keep playing this game and come to the same conclusion, though on quantitative grounds, that IF we can “go there” we do learn a lot compared to “just remote sensing from the Earth or nearby”. In the end it will be a question of feasibility and "cost vs benefit" and what are the secondary “spinoffs” of the technology development required to “get there”.

There is a profound difference in what we have been able to do in accelerating material via chemical means vs electromagnetic means. In order to achieve relativistic flight with propellants it is necessary to have a relativistic “propulsion exhaust”. It is useful to consider the energy release per unit mass as a metric for propellants. We can define an effective fractional energy release metric $\varepsilon=\Delta E/mc^2$ where ΔE is the energy released for a reactant mass m. This is an optimistic metric as it is assumes zero storage (confinement) and reaction chamber mass. With chemical energy per molecular bond of approximately 1 eV compared to the energy equivalent of the molecule itself of billions of eV this gives $\varepsilon<10^{-9}$ and thus the ability to use any chemical process that is carried on the spacecraft to achieve relativistic speeds is not feasible. In order to achieve relativistic flight with any form of “propellant” carried on-board we need energy release per unit mass of order unity. With any chemical process this is not possible and even with nuclear fission ($\varepsilon<10^{-4}$) and fusion ($\varepsilon<10^{-3}$) the ability to do this is extremely limited, even if the technology to do so was feasible. The only two choices with known physics are antimatter (annihilation) engines and standoff directed energy propulsion. Even ignoring the production costs for antimatter we are still faced with the large confinement and reaction masses needed for any realistic variant of matter annihilation engines. While nuclear fusion is often invoked as a possible solution to relativistic flight, a detailed analysis shows the relative low equivalent energy ($\varepsilon\sim10^{-2}$) combined with the extremely large secondary masses needed (storage and reaction) force any such system to become extremely large with modest performance. For nuclear fusion in particular it is instructive to consider the mass of highly optimized system such as thermonuclear weapons. The highest energy yield per unit mass is approximately 5 MT/Ton or an effective system energy release metric of $\varepsilon=\Delta E/mc^2 \sim 2\text{x}10^{16}$ J/(10^3 kg)c^2 $\sim 2\text{x}10^{-4}$. Looking at system such as Tokomak’s, the efficiency is vastly less than this though these are not optimized for mass efficiency. Annihilation engines then seem like a “logical” next step in analysis but all known confinement options (laser, magnetic bottles etc) also yield low effective overall system efficiencies due to the large additional masses required. Thus annihilation engines (even if we could produce and store the required antimatter) do not appear feasible currently.

Two modes of operation for Propulsion– Direct Drive Mode vs Indirect Drive Mode

The same basic technological underpinnings of the program, namely the ability to project power over vast distances can be used in two different modes. In the Direct Rive Mode (DDM) the propulsion is via photon momentum transfer while in the Indirect Drive Mode (IDM) the propulsion is done via converting the photon energy into electrical power on the spacecraft and using the electrical power to drive an ion engine. Both the DDM and IDM methods can use the same DELTA system. The DDM is simpler (only a reflector is needed at the spacecraft but due to the specific impulse I_{sp} of light being so high I_{sp} (photon) = c/g ~ $3\text{x}10^7$ s , this mode is generally used for relativistic missions or one where simplicity is required. In the IDM case the I_{sp} of the ion engine is set to optimize the mission requirements and is best used in high mass lower speed missions. As a simple “rule of thumb” a mission is “optimized” when the “engine I_{sp}” is roughly equal to the desired speed. Since the thrust per unit of power = $2/(g\ I_{sp})$, the high mass mission cases such as sending humans to Mars or large robotic spacecraft far into the solar system, the IDM case is a better choice which for relativistic missions the DDM mode is required. Ion engine mission cannot achieve relativistic speeds. We have had NASA programs for both DDM (Starlight) and IDM based missions. This is discussed in details in our many papers and in our technical book (The Path).

A Roadmap to the Future – One of the critical areas to understand is that photonic propulsion is radically different than any other form of propulsion. By its very nature it allows for a logical roadmap in both time frame and application space. This is a program that has no end and will only get more capable, more efficient, lower in cost and can address a wide variety of needs where "power projection" is applicable. While we are focused on "photonic propulsion" in this chapter, a better term to use for the entire approach we take is the ability to "project power" over vast distances. Our approach has always been to look at the long term goals while addressing the short term technological and economic realities of what is practical, affordable and meets a wide variety of needs along the way. While some, including ourselves, desires to achieve the dream of relativistic flight, there are many other needs that are addressed by the ability to send power over large distances. For some applications a "large distance" is a kilometer (for example our recent NASA LuSTR program whose goals are to beam power from the rim of a PSR (permanently shadowed region) over a distance of a km. While this may seem to be unrelated to relativistic flight, it utilizes many of the same technologies we apply to the long term goal of beamed power (or power projection) for relativistic missions in the future. Similarly, our NASA program in collaboration with JPL to explore the use of directed energy to power high performance ion engines (indirect drive) to enable rapid transit in our solar system with high mass missions including "Humans to Mars" is another example of being on a roadmap with a very wide range of applications that come naturally along the path to larger aspirations. We started development in 2009 and have now published over 70 papers and two books on both the long term goals of existing our solar system at relativistic speeds as well as the many applications that come

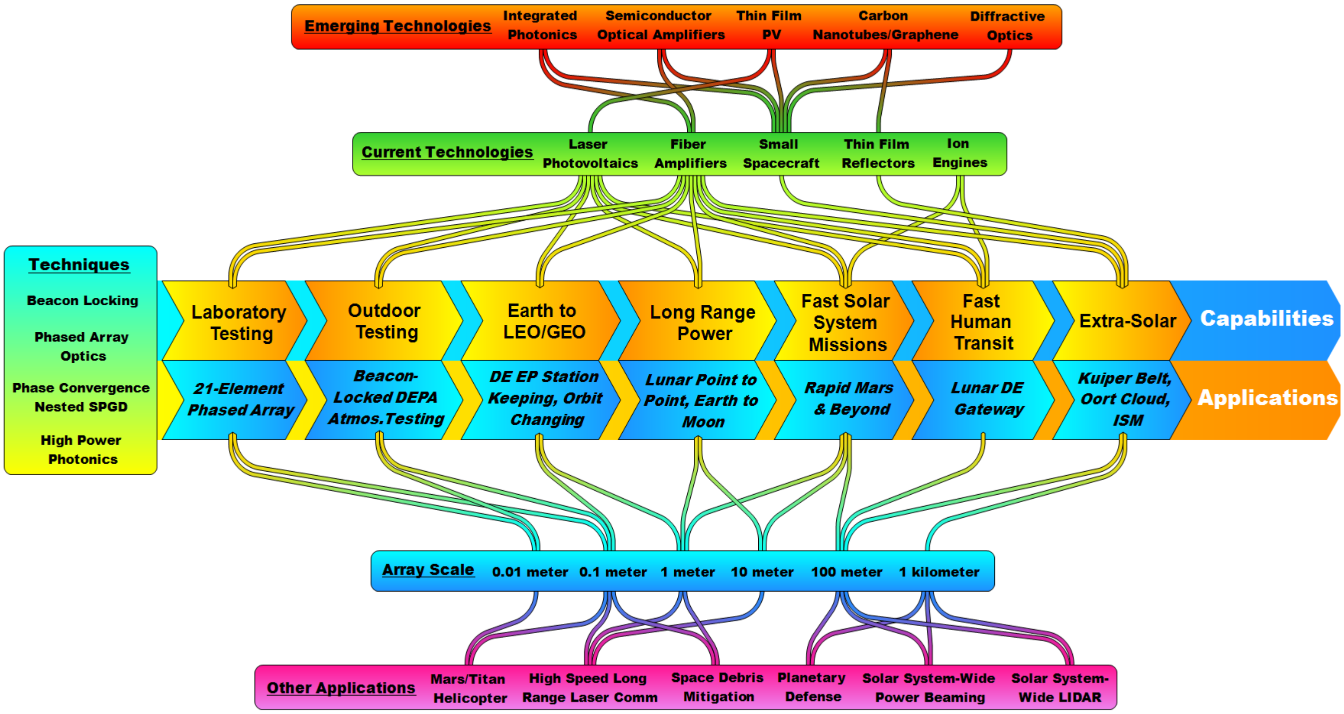


Figure 2 – Roadmap of long term strategy for both technology and application for photonic power projection.

from the more general ability to project power over vast distances. Trying to immediately achieve the long term goal without understanding the many application spaces enabled along the way and formulating a logical roadmap will lead to failure. It is not only a “good idea” to have a roadmap, it is absolutely critical to do so or the results will end in a pile of paper and nothing more. Give people what the need and they will help you achieve what you desire. The alternative is failure. Our program allows a logical roadmap forward as well as a large number of useful milestones along the way. It allows a realistic path forward on scales from very small size (10 cm for example) with low power (kw for example) for short ranges (km for example) all the way to km scale phased arrays with >100 GW power for solar system scale power projection thus enabling interstellar flight. Along the way from small to large comes a wide range of applications many of which have nothing to do with propulsion but all of which are related technologically. This logical “need driven” and “economically driven” roadmap is crucial to push forward.

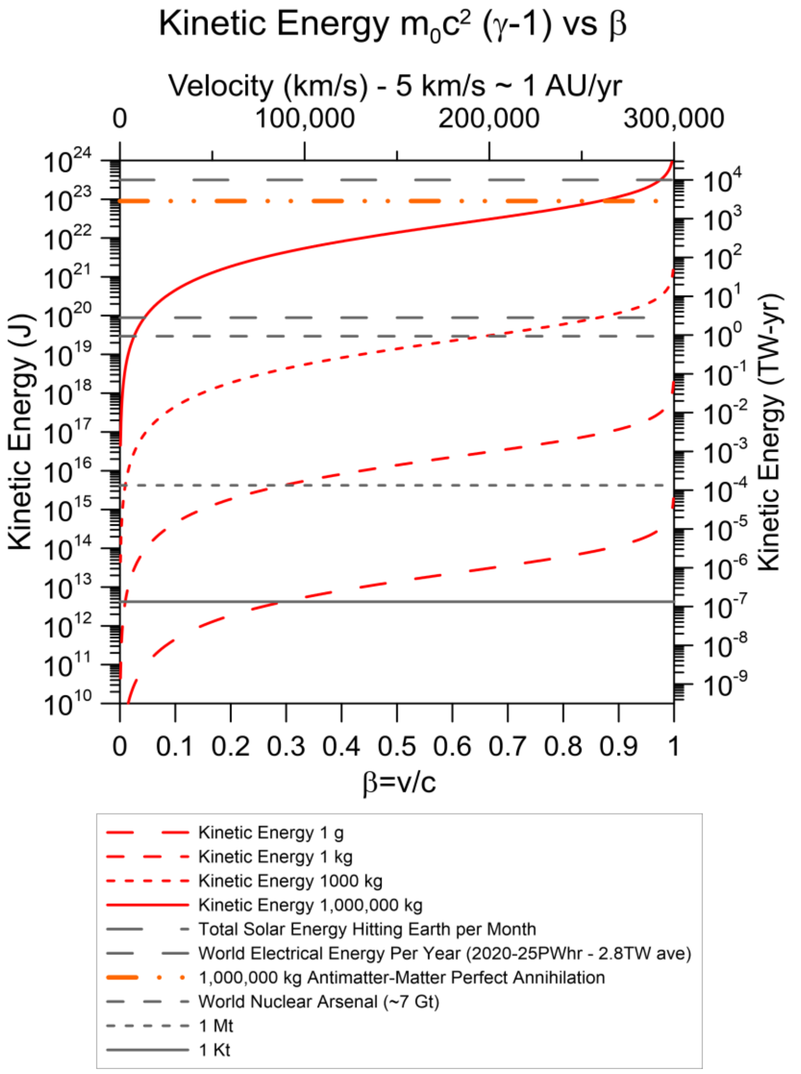


Figure 3 – Spacecraft kinetic energy of missions from 1g to 1000 metric tons. Note the enormity of the kinetic energy. While photonic power has high propulsion efficiency at high speeds, the numbers are still daunting for high mass relativistic missions such as human capable programs. Note comparison to annual world energy

Directed Energy Approaches – DDM - a completely different approach to propulsion is to “leave the propulsion system at home” using photons from a source not on the spacecraft. In this approach no propellant is carried and the propulsion is achieved by direct transfer of the photon momentum to the spacecraft via reflection. This is an old concept and is the basis for solar sails as one example. While solar sails cannot achieve relativistic flight and thus are not useful for interstellar flight, laser driven sails can. The difficulty in using a laser driven system is the ability to produce a directed energy system that is sufficiently powerful and is sufficiently collimated both of which are required. This is shown schematically in Figure 1.

This difference in speeds achieved is dramatically illustrated if we compare the beta (v/c) and gamma factors achieved (Figure 3). We clearly have the ability to produce highly relativistic systems but only at the particle level. Practical systems need to be macroscopic as we do not currently have the technological means to self-assemble relativistic particle into macroscopic systems. Electromagnetic acceleration is only limited by the speed of light while chemical systems are limited to the energy of chemical processes which are typically of order 1 eV per bond or molecule. To reach relativistic speeds we would need GeV per bond equivalent or about a billion times larger than chemical interactions.

We propose electromagnetic acceleration to achieve relativistic speeds for macroscopic objects though not using conventional accelerators but using light to directly couple to macroscopic objects. This is simply using a very intense light source to accelerate matter. It has the additional advantage of leaving the propulsion source behind to greatly reduce the spacecraft mass. Of course, this has the disadvantage of reducing or eliminating (depending on the system design) maneuverability once accelerated. For many systems this is not acceptable so hybrid systems are proposed as well as pure photon driven systems.

While photon drive is not a new concept, what is new is that directed energy photonic technology has recently progressed to the point where it is now possible to begin seriously consider the construction of systems to accelerate macroscopic systems to relativistic speeds. Reaching relativistic speeds with macroscopic systems would be a watershed moment for humanity in our path to the stars.

Recent changes in directed energy, combined with miniaturized probes allows a path to relativistic flight that was not possible previously. **These technologies also allows for a completely modular and scalable technology without "dead ends"** [7,8]. This will allow us to take the step to interstellar exploration allowing us to reach nearby stars in a human lifetime. This is discussed in a series of papers from our group which also discuss the numerous additional capabilities that arise from this technology [9,10].

Phased Array Laser - The key to this program is the ability to build a sufficiently powerful laser driver with a large enough effective aperture to allow the beam to stay on the spacecraft long enough to propel it to high speed. For relativistic flight (>0.1 c) development of ultra-low mass probes is also needed. Recent developments now make both of these possible. The photon driver is a laser phased array which eliminates the need to develop one extremely large laser and replaces it with a large number of modest laser amplifiers in a MOPA (Master Oscillator Power Amplifier) configuration with a baseline of Yb amplifiers operating at 1064 nm. The system is inherently phase locked as it is fed by one seed laser. Maintaining phase integrity is one of the key challenges. This approach is analogous to building a super computer from a large number of modest processors. This approach also eliminates the conventional optics and replaces it with a phased array of small low cost optical elements. As an example, on the eventual upper end, a full scale system (50-100 GW) will propel a gram scale wafer scale spacecraft with a **meter class reflector** (laser sail) to about c/4 in a **few minutes of laser illumination allowing hundreds of launches per day or 10^5 missions per year**. Such a system would reach the distance to **Mars (1 AU) in 30 minutes, pass Voyager I in less than 3 days, pass 1,000 AU in 12 days and reach Alpha Centauri in about 20 years.** The same system can also **propel a 100 kg payload to about 1% c and a 10,000 kg payload to more than 1,000 km/s**. The system is scalable to any level of power and array size where the tradeoff is between the spacecraft mass and speed. The system is modular with identical sub elements allowing for a logical build phase with critical and immediately useful milestones along the path to building increasingly capable systems. The is no upper limit to the power of the system which allows for for the investment in the core technology development to be amortized over One of the advantages of this approach is that once the laser driver is constructed it can be used on a wide variety of missions from large mass interplanetary using beamed power to high performance ion engines to low mass interstellar probes with all missions essentially using the same core technology and in many cases the same laser array. This allows an enormous cost savings in the long runs as this opens an essentially unlimited mission space. A range range of applications is discussed in details in our more than 50 technical papers.

The small relativistic interstellar missions are flyby missions as no current technology allows for sufficient deceleration except for another laser array at the target, which is not feasible for the interstellar case. On the larger mass end a 1 metric ton spacecraft could be sent to Mars in about 11 days with a peak speed at midpoint of about 320 km/s and assuming either a second laser array at Mars or a retro reflector system to reflect back the laser light from the Earth/ lunar based system that is then used to slow down the spacecraft. A 10 metric ton spacecraft would take about one month with a peak speed at midpoint of about 100 km/s and a 100 metric ton spacecraft would take about 4 months and reach a peak speed at midpoint of about 32 km/s. On the lower mass end a 100 kg payload reaches Mars in 3.5 days with a peak speed of 1000 km/s, a 10 kg payload reaches Mars in one day with a peak speed of 3000 km/s and a 1 kg payload reaches Mars in about 8 hours with a peak speed of about 10,000 km/s. Each of these systems (to Mars) would require a spacecraft reflector that is only about 15 -20 meters in diameter and can be made of existing materials as the flux is modest for large payloads. Note that the reflector size to Mars is smaller than that used for maximum speed as Mars is relatively "close". For exploring the outer solar system an example would be a 100 kg spacecraft with a 1 km reflector that reaches a speed of 2400 km/s at 26 AU in 37 days and achieves a limiting speed of 3400 km/s (1.1% c). Such a system (100 kg) reaches the solar gravity lens focus (~ 550 AU) in less than 1 year. **These systems are vastly faster than any currently imagined conventional propulsion system including ion engines, solar sails, e-sails etc.**

Modularity and Scalability – The laser array for propulsion or for any type of long-range power projection is called a Directed Energy Launch technology Array (DELTA) and is completely modular and

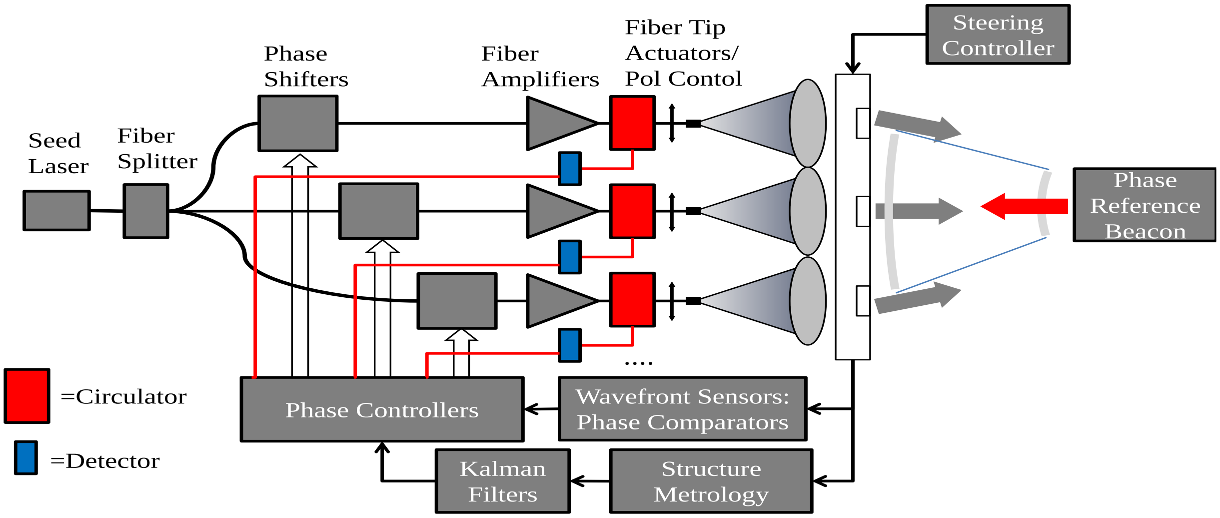


Figure 4 – System topology used for our program. It is known as a MOPA (Master Oscillator Power Amplifier) topology and is analogous to a Fourier transform where both phase and amplitude can be controlled. A beacon for phase locking is required within the isoplanatic patch for ground-based systems and even for space based systems a beacon is still required. In our system the beacon is a coherent multi-wavelength laser. Multiple beacons can be employed as well as a comb wavelength beacon. Target plane phase locking to beam form properly is one of the challenges of this program.

scalable and lends itself to mass production as all the elements are identical. There are very large economies of scale in such a system in addition to the exponential growth. The system has no expendables, is completely solid state and can run continuously for years on end. Industrial fiber lasers have MTBF in excess of 50,000 hrs. The revolution in solid state lighting including up-coming laser lighting will only further increase the performance and lower cost. The "wall plug" efficiency is currently greater than 40% The same basic system can also be used as a phased array telescope for the receive side in the laser communications as well as for future kilometer scale telescopes for specialized applications such as spectroscopy of exoplanet atmospheres and high redshift cosmology studies.

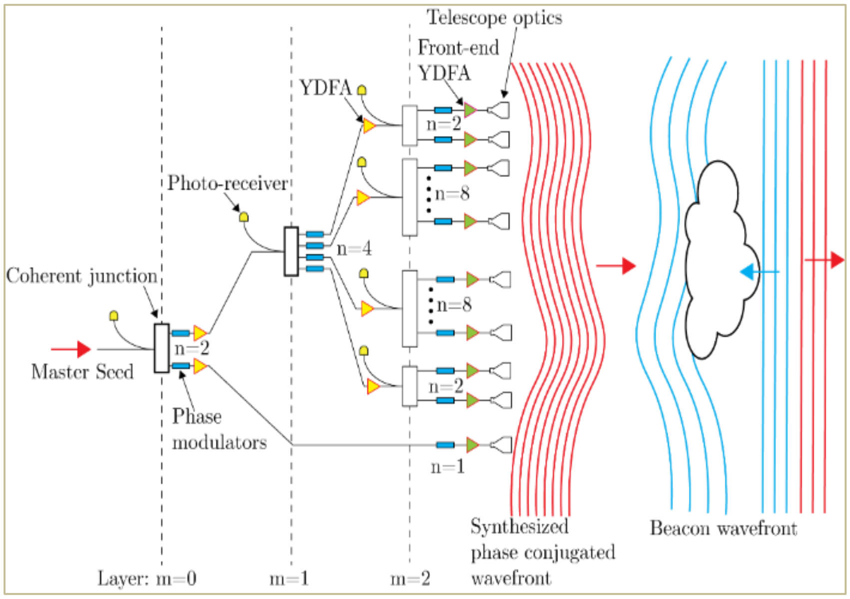


Figure 5 – Beam synthesis strategy for target plane phase control we use to overcome multiple sources of phase perturbations including atmospheric (if ground based) as well as a structural (microphonic). We use a complex nest tree algorithm for beam formation with the multi-color beacon as a part of the feedback loop.

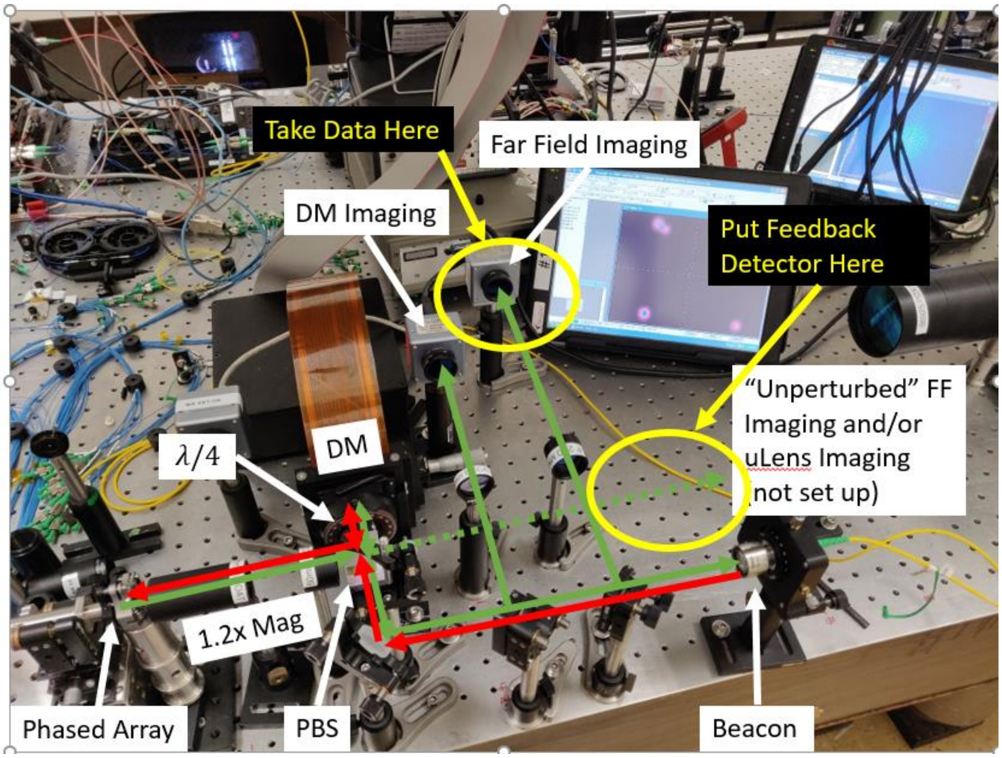


Figure 6 – Laboratory demonstration of full system phase locking topology including the injection of atmospheric and microphonic perturbations via a deformable mirror.

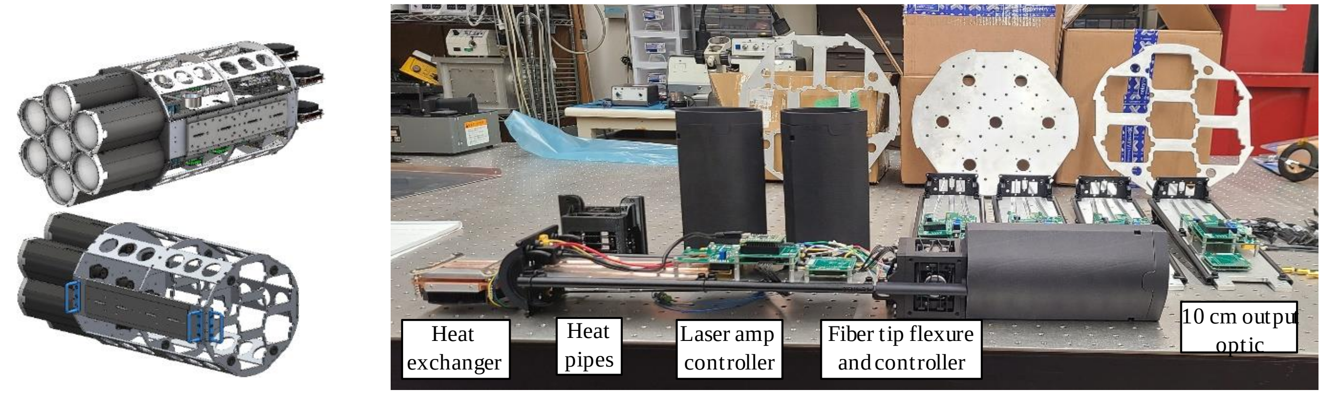


Figure 7 – Some of the current array designs and hardware we are building for deployment of small systems using the full system topology. In the long run photonic integration will yield more compact (in one dimension) , lower cost and lower mass systems but the overall 2D aperture is still physics limited not technology limited (for a given wavelength). Our systems are already >40% efficient in terms of photon power output/ electrical power input. The largest changes will occur in cost reduction. The array sub-element optics shown are 10cm (final lens) in diameter and are designed for ground based systems. The sub-element diameter (10cm) is the maximum allowed given typical atmospheric turbulence (seeing) from high altitude (4-5 km) ground based astronomical quality sites when used at 1 micron wavelength (our current wavelength is 1.064 microns). This diameter is based on our simulations of the atmosphere. The diameter can be smaller than this but larger than this requires high order AO for every sub element which greatly complicates our system topology. Each sub-element includes first order tip/tilt active control. An alternative we have explored is to make each sub-element optic smaller than about 3 cm eliminating the need for tip/tilt but requiring about 10x more sub-elements. This is spart of our long-term technology roadmap. For space based deployment of the DELTA (lunar for example) where there are no atmospheric corrections for be made, the sub-element aperture can be larger than 10 cm. Again, this is part of our long-term technological roadmap.

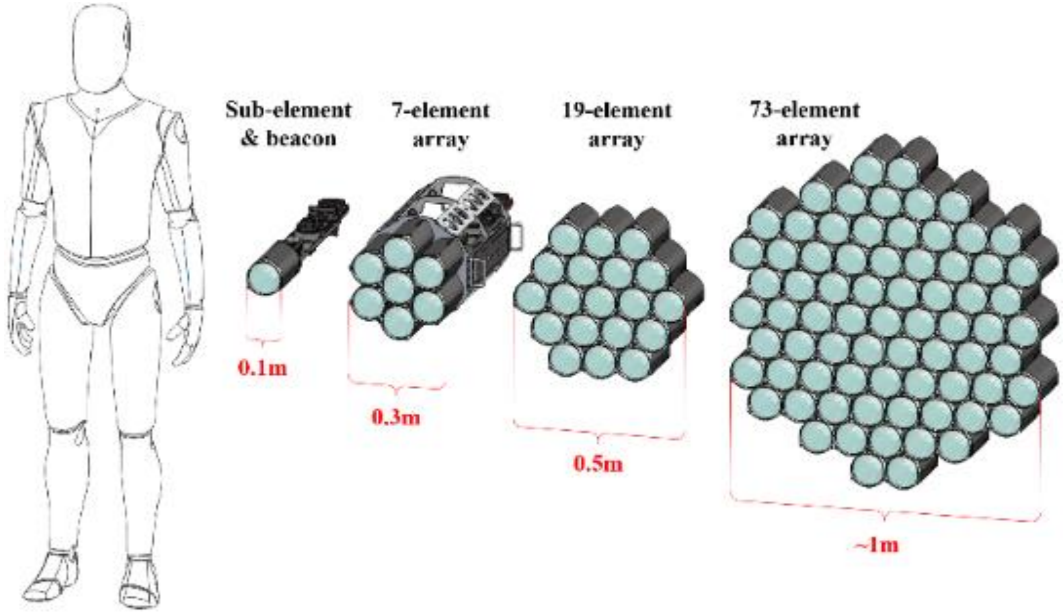


Figure 8 – Current array evolution in production in our lab. For reference a 1m aperture array projects a 1 m radius spot at 1000km distance sufficient for LEO assets. Hence, even small apertures become useful for space applications. All of the sub-elements are identical allowing for mass production and economy of scale.

Low Mass DDM cases – Along the roadmap to relativistic missions, the early cases of low mass missions become a critical testing ground. While the DELTA technology is basically the same for all cases (whether DDM or IDM), the long term goals of relativistic flight can be tested with increased capability by “starting small” and working our way up the ladder. We show the results for two low mass cases of 1g (wafer scale) and 1 kg (Cubesat) with DELTA sizes from 1-10^4 m and DELTA fluxes of 1,10 and 100 kw/m^2 (all quite modest) and reflector thicknesses of 0.1 and 1 micron thick. All of this is discussed in detail in our technical papers.

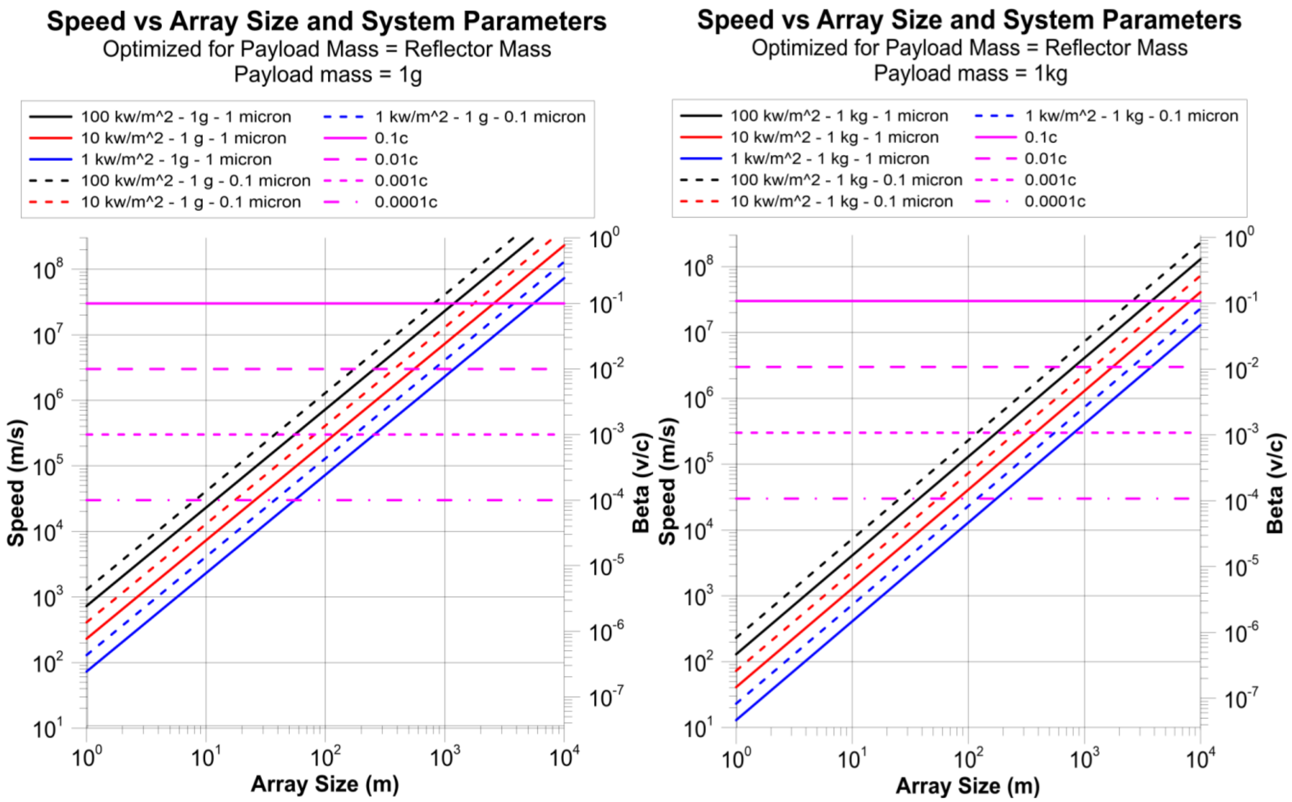


Figure 9 – Left: Speed vs array size and flux for a 1g wafer scale spacecraft. Right: Same but for a 1kg spacecraft. Both are for direct photon momentum transfer mode (DDM).

Avatar Example – Human Missions including Landing - Facts are Inconvenient Truths – As an "extreme" example of a future potential mission, namely a human mission to the mythical planet Pandora orbiting Alpha Centauri A (4.37 ly away). We were asked to analyze this case for a documentary on the future of relativistic missions. We were asked to achieve a flight time from Earth to Pandora of 7 years and achieve a maximum speed of 0.7c. We asked about mission mass, how are you going to land etc. These were somewhat inconvenient questions but we did our best. The script called for a laser driven sail mission as the primary propulsion for the ISV Venture Star spacecraft with an additional "antimatter annihilation" engine and for "fun" a fusion engine. Everything but a kitchen sink engine. Our main question was (as above) "how are you going to stop". There was not a good answer so we discussion possible use of an "antimatter" engine to slow down and stop but we explained this was highly problematic given the mass of "antimatter" needed (see below). Since they had not assigned a bare spacecraft (not including reflector) mission mass, we made up one based on the number of people they wanted to transport ~ 200) and decided on a 1000 mt (10^6 kg) spacecraft mass not including any antimatter nor fusion system since they were not defined sufficiently. This would likely be a significant underestimate of the bare spacecraft mass (5 mt/person) but we chose this to give a concrete example. This is a classic example of a mission design lacking specifics but given the future nature of the program, this is to be expected. **Our online relativistic mission calculator allows you do rapid photonic mission calculations based on our published analytic calculations.**

https://www.deepspace.ucsb.edu/projects/starlight
https://www.deepspace.ucsb.edu/wp-content/uploads/2023/05/Relativistic-Laser-Propulsion-Classical-1D-Standalone.html

Stopping is useful – For a crewed mission, such as in the movie Avatar, stopping is highly recommended. The problem with stopping a relativistic mission travelling at 0.7c is formidable as shown below. This is where some reality of the system energetics needs to be pondered. One options is to send a second phased array (DELTA) to the destination but that begs the question of "how do you do that". For long term targets it might be possible to "bootstrap" a long term fast mission by send the necessary photonic infrastructure, which is essentially the same as the launch side infrastructure but do so via slow passage to prepare for fast passage. In the solar system for fast Earth to Mars mission using only direct drive this is viable but for interstellar this would be extremely daunting.

We show the Avatar solution below but note the extremely large energetics needed and IF one were to propose an antimatter annihilation engine then the mass of the antimatter/ matter needed exceeds the mass of the primary (human caring) spacecraft even assuming no radiation shielding.

The bottom line is that human interstellar missions using DE propulsion or antimatter propulsion are incredibly daunting. Hypothetical fusion engines are vastly worse given the low efficiently of fusion processes (<1% energy released compared to rest mass).

Avatar – ISV Venture Star analysis

- **Requirement – 0.7c with 7 time to target including slowing to orbital entry speed**

- **No Engine = No Mission**
- **Unless we discover new Physics we are pushed into a corner for relativistic flight**
- Some numbers to think about: 1 kg@ 0.3c ~ 1 MT (3x modern ICBM thermonuclear weapon)
- **Sci Fi fans – Avatar 0.7c – 200 people + 25 crew – est ~ 1000 ton ship, 7 yr to Pandora**
  - ISV Venture Star is the Avatar spacecraft…. Math is optional and annoying!
  - **Laser driven (primary) with anti-matter and fusion additions – read our papers**
  - **KE at 0.7c=8.6 MT/kg → 8.6 tera Ton** (compare to KT extinction ~ 50 TT) – planet killer
  - We ran a rough laser propulsion design analysis for the hypothetical mission
  - 100km array (prefer lunar or space based), **10 PW**, 36 km diam sail (1μ thick)
  - 10 PW ~ 0.11 kg/s matter annihilation →3.3 Mkg/yr of matter-antimatter annihilation, 2.5 MT/s!
  - **10 PW ~ 1000x world electrical production – cover entire Moon in solar panels – 13 PW incident**
  - **Think about it… 3300 tons/yr of matter-antimatter annihilation > 1000 ton spacecraft inert mass**
  - IF you want to use an annihilation engine instead of DE (acc/de-cel) you will be in serious trouble
  - →You want (prefer) a laser infrastructure to slow down as well … chicken and egg problem
  - 0.66c limiting speed – 1.5yr accel ($2L_0$) , 3.4g, 6.7 yr to Pandora (α Cent A)
    - *Option with thinner reflector: 0.80c with 0.1μ thick sail*
    - 10 MW/m^2 flux on sail, 172K eq temperature (don't need exotic sail) 99% ref, 0.1% absorption
    - **Rel soln - 17% launch eff (KE/ph energy at L_0 (0.56c@ L_0)), 63 GGWh elect (assume unity eff), 6.3 P$ elec (0.1$/KWh)**
    - **For ref US GDP (2023) = 26T$ → electrical energy cost alone would be 242 years of US 2023 GDP!**
    - **For another ref – Saturn V first stage ~ 50 GW (>CA Peak) at launch … 10 PW = 200,000 Saturn V eq power for >1 yr!**
  - **Option – use Unobtanium (it exists on Pandora!) or go SLOWER or smaller mass missions… E($/launch) scales roughly as KE = $m_0(\gamma-1)c^2 \rightarrow m_0v^2/2$ non rel**
  - **Ex: 1 g preliminary 0.2c scouting missions (Starshot) ~ 10^{-10} lower launch cost than Avatar or ~ 0.5M$/launch for a 1g bare spacecraft at 0.2c.**
  - **Use our relativistic photonic mission calculator to design your own mission.**
  - https://www.deepspace.ucsb.edu/projects/starlight
  - https://www.deepspace.ucsb.edu/wp-content/uploads/2023/05/Relativistic-Laser-Propulsion-Classical-1D-Standalone.html

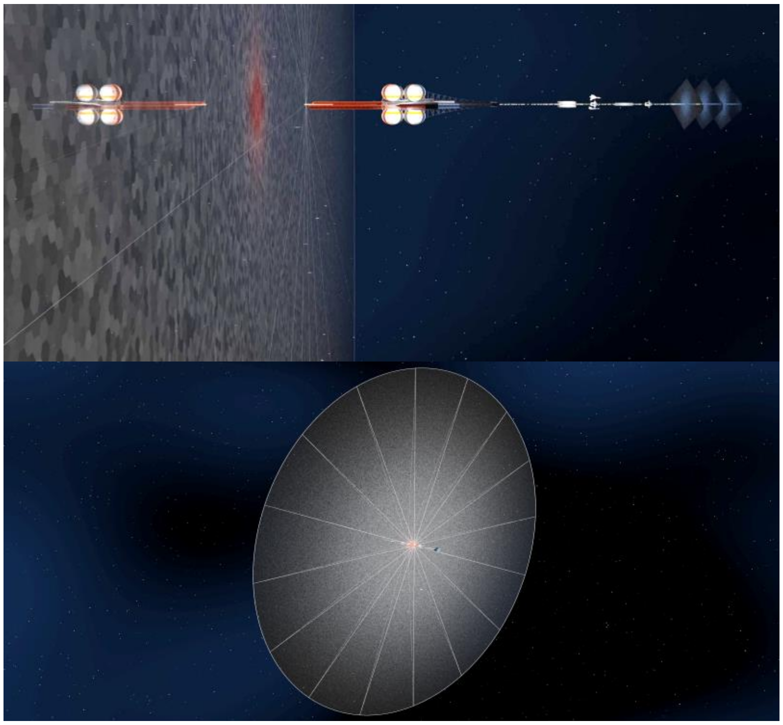


Figure 10 – Avatar ISV Venture Star analysis of system requirements for a 1000 mt crewed mission to 0.7c. The reflector is 36km diameter for a 1 micron thickness.

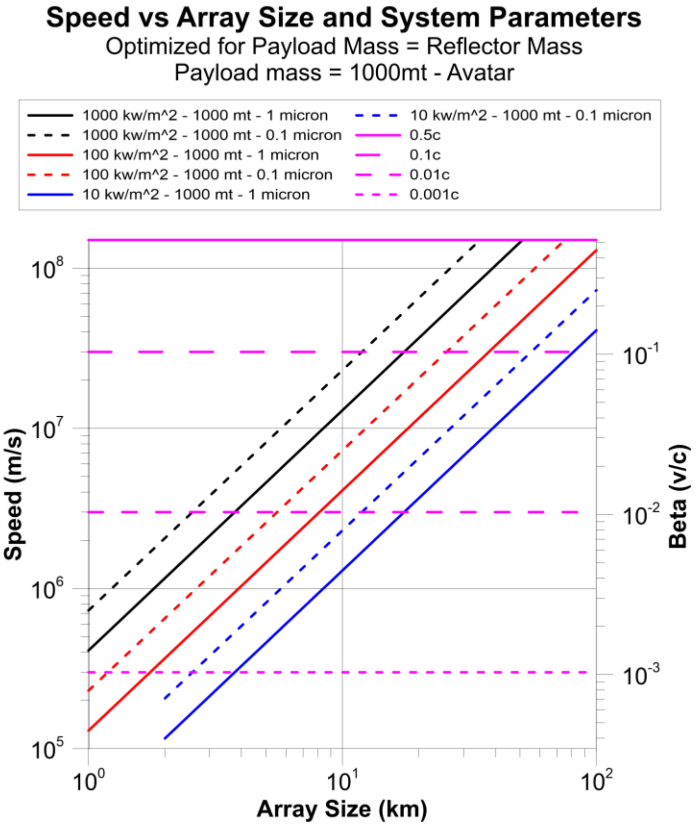


Figure 11 – Speed vs array size needed for the Avatar 1000 mt to 0.7c mission. Note the extremely large power and array size needed (10 PW – 100 km array). Daunting though not "impossible".

Economics Considerations – One of the fundamental issue to realization of photonic propulsion is the ability to “afford to build it”. Since photonics is an exponential growth field the overall system cost become much lower with time and much like in the field of large scale LED and soon laser lighting there are dramatic increases in performance and reductions in costs. We have an analytic cost model for the DDM system cost with various cost parametrizations. This is discussed in detail on our paper on ***The Economics of Interstellar Flight*** – *Acta Astronautica 2022*, http://arxiv.org/abs/2112.13911. In the optimized solution the take away is that the active photonics (laser) costs are 2/3 of the total and the optics cost is 1/3 of the total cost. This is shown below for an example of building a system that enables achieving 0.2c with a 1g bare payload. In the optimized (achieving maximum speed) the bare spacecraft mass is equal to the reflector mass.

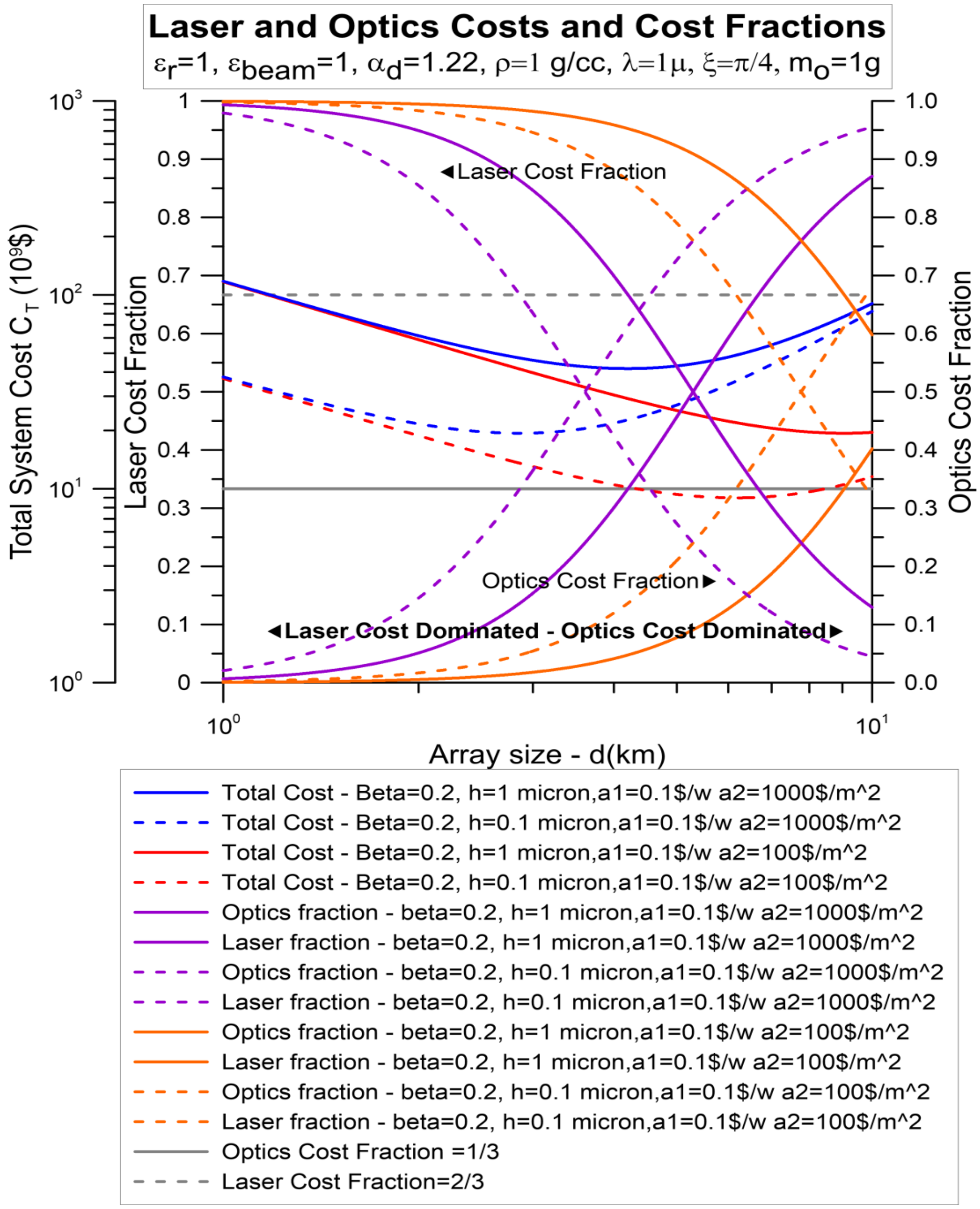
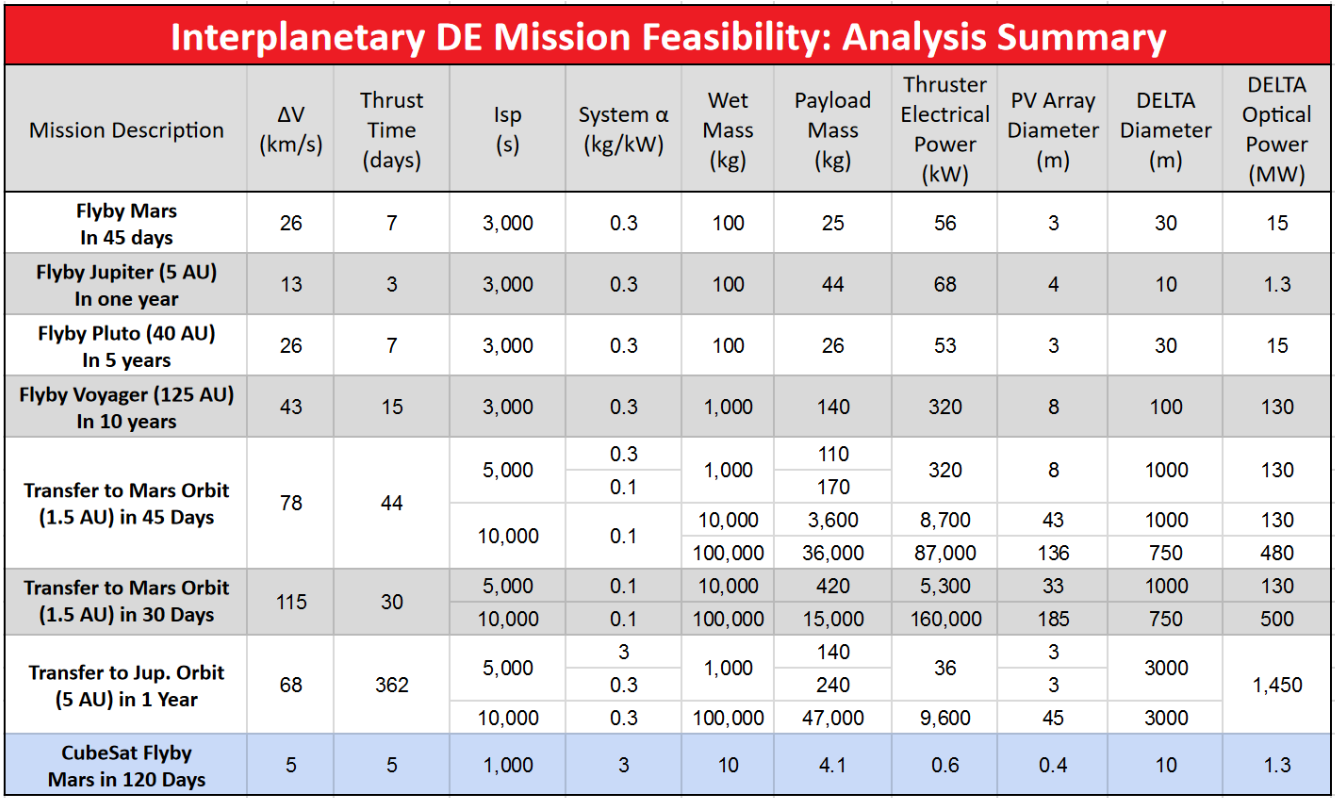


Figure 12 – Economic cost analysis showing the minimum in cost for various system parameters. This particular case is for a 1g wafer scale spacecraft propelled to 0.2c.

Indirect Drive Mode – IDM for high mass missions in our solar system – One of our NASA program was to study the use of DE to power ion engines on the spacecraft. We studied a variety of mission profiles from small test missions (CubeSat class) to 100 mt human missions to Mars including entering orbit at Mars. For the Mars mission orbit insertion is critical and rather than requiring a second DELTA on Mars, we can project the beam from Earth (or the Moon) and simply reverse the ion engine thrust (rotate ion engine). We also studied missions to Jupiter, Pluto and the edge of our solar system (catching up to Voyager). These are summarized in the table below and are discussed in detail in a long paper on this. As part of the “roadmap” the use of a small (10m diam – 1 MW) DELTA can be used to send a 10 kg (wet) mission to Mars faster than any chemical solution. This is a very cost effective way to begin a photonic propulsion program as the “buy is low.



Interplanetary DE Mission Feasibility: Analysis Summary

Mission Description	ΔV (km/s)	Thrust Time (days)	Isp (s)	System α (kg/kW)	Wet Mass (kg)	Payload Mass (kg)	Thruster Electrical Power (kW)	PV Array Diameter (m)	DELTA Diameter (m)	DELTA Optical Power (MW)
Flyby Mars In 45 days	26	7	3,000	0.3	100	25	56	3	30	15
Flyby Jupiter (5 AU) In one year	13	3	3,000	0.3	100	44	68	4	10	1.3
Flyby Pluto (40 AU) In 5 years	26	7	3,000	0.3	100	26	53	3	30	15
Flyby Voyager (125 AU) In 10 years	43	15	3,000	0.3	1,000	140	320	8	100	130
Transfer to Mars Orbit (1.5 AU) in 45 Days	78	44	5,000	0.3	1,000	110	320	8	1000	130
				0.1		170				
			10,000	0.1	10,000	3,600	8,700	43	1000	130
					100,000	36,000	87,000	136	750	480
Transfer to Mars Orbit (1.5 AU) in 30 Days	115	30	5,000	0.1	10,000	420	5,300	33	1000	130
			10,000	0.1	100,000	15,000	160,000	185	750	500
Transfer to Jup. Orbit (5 AU) in 1 Year	68	362	5,000	3	1,000	140	36	3	3000	1,450
				0.3		240		3		
			10,000	0.3	100,000	47,000	9,600	45	3000	
CubeSat Flyby Mars in 120 Days	5	5	1,000	3	10	4.1	0.6	0.4	10	1.3

Figure 13 – IDM solar system missions for high mass (up to 100 mt) in the solar system, including a crewed mission to Mars in 30 days. **Fast Solar System Exploration Powered by Directed Energy,** ***Acta Astronautica 179,78, Feb 2021***

Ground vs Space Deployment - It would be far simpler and less expensive if we could deploy the main DE driver on the ground vs in space. In Lubin and Hughes 2015 we discuss the issue of ground, airborne and space deployment options for our related technology work on DE planetary defense [9,16]. The primary concern for ground deployment is the perturbations (seeing) of the atmosphere. With typical “seeing” at “good” mountain top sites of a bit better than 1 arc second (~ 5 micro-rad) this is far from the

0.1 nrad required. Even the best adaptive optics system fall far short of this. With the upcoming 30m class telescopes we hope to be able to get to decent Strehl ratios with multi AO systems but at much larger diffraction limited values than we need. Ground based interferometry in the visible is done with 10m class telescope with modest success and this is encouraging. The two Keck telescopes on Mauna Kea are about 85 m apart, while the VLT's can be up to 200m apart and the NPOI (Navy Precision Optical Interferometer) has a 440m baseline for example. This is encouraging. The key will be to high fractional encircled energy, (Strehl). **The ground based option is where we must start for practical and economic reasons> The phased array is ideal for adaptive optics use, since by its very nature it is an adaptive optics system.** It is a part of the roadmap we propose but it is not clear we can get good Strehl (power on target) with the kind of system we propose for ground deployment even with the most complex AO we can imagine and it is extremely far from any current systems or imagined systems. We have also considered hybrid system using ground based deployment for the critical DE components and phase conjugating orbital beam directors that correct the atmospheric distortions in each sub element and then "redirect" to the spacecraft. It is not clear that this is feasible for the very fine targeting we need. It also remains an option to explore in optimizing cost and deployment. Airborne (aircraft, balloons etc) are an intermediate approach and also a part of the deployment roadmap for testing small systems (few m diam) but full scale deployment on such platforms is extremely problematic due to the scale required. The optimization of where to deploy in space is also a part of a longer term analysis (LEO, GEO, lunar, L2 etc). These are not only very cost sensitive optimizations but suitability for maintenance is also a significant factor. **During the development and test phase of the roadmap we will explore the limits of ground based deployment to better quantify this.** Smaller arrays, say 0.01-1 km, should be built for ground use before going to space. Ground does offer much lower cost and the option of much higher areal power density to offset the reduced array size. In addition, the ground based solution is complicated by the atmospheric air glow and non-thermal processes such as OH lines in particular [27]. An onboard local oscillator to tune the beacon laser if needed could be commanded from the ground using the laser array to transmit a command to the spacecraft. Uplinking commands is feasible (modulo TOF) using the laser array to transmit. Weather is also an issue as is water vapor fluctuations [25,26]. The atmospheric emission is mitigated by using a very narrow linewidth laser for communications since the data rates are low. Uplinking commands is feasible (modulo TOF) using the laser array to transmit. Once the spacecraft is far away the TOF will be complicated and tracking and beacon locking will be challenging in all cases whether in space or on the ground. In order to minimize backgrounds for reception it is highly desirable to fully synthesize the received beam as discussed above. This requires knowledge of the location of the spacecraft and knowledge of both the astrometry and ephemeris as (sub) nrad levels. This is not trivial. Ground deployment should be explored before the space option primarily due to the dramatic reduction in cost and ease of maintenance and expansion.

Limitation of Ground based Array Deployment – One key complication of a ground based deployment is the limited target and the limited payload classes as well as laser communication data reception. This problem arises from two sources. One is for a given deployment latitude the availability of targets on the sky is limited by the fact that atmospheric perturbations become worse the further away from zenith the target. This will tend to restrict the targets to launch windows when the target declination is within a limited acceptable zenith angle. If this is combined with an orbital payload launch dispenser (OPLD) then the launch windows become even more restrictive. Combining this with the Earth's rotation and tracking requirements places further limitations on launches. Overall this will tend to restrict payloads to lower masses to meet the limited illumination times consistent with all of the above issues. Adding in weather variability will further respect the launch windows. For example, if one of the targets of interest is the

Alpha Centauri system, which is approximately declination =-63 deg, then only deployment latitudes comparable to lat=-63 would be acceptable. The acceptable zenith angle for operation would have to be determined for each site but one could imagine a zenith angle of about 30 degrees would be possible. This would then open up sites from lat=-33 to -90.

Polar Deployment – The polar regions, in particular the S. Pole area is a deployment option that should be explored. The lack of aircraft and birds and lesser number of satellite assets, improved atmospheric properties, remoteness and lesser numbers of people and animals for laser backscatter are all reasons to consider polar deployment. In addition, tracking during the acceleration phase is simplified, being azimuthal as well as much longer illumination times become possible, compared to mid latitude sites. In addition, 50% of the year is dark allowing for greatly improved data reception. However, there are a number of downsides to polar deployment. The remoteness increases the cost and the long nights make maintenance difficult. The 50% of the year that is day will make data reception much more difficult. In addition, the polar regions have auroras and line emission that must be considered. Sites such as the South Poles and the "domes" A,C,F are good candidates to explore. The S. Pole is particularly interesting given the significant infrastructure that is already present. A significant cost/ benefit analysis would have to be done to decide on which ground based sites are desired. Multiple ground based sites are also an option though this will increase the cost.

Space Based Deployment Options – Space based deployment is the preferred solution in terms of superior targeting options, in particular for larger mass payloads which require longer illumination time. The lack of atmosphere is a major advantage as well though the clear disadvantage is the vastly increased cost of deployment. While a sun synchronous LEO orbit is the lowest cost solution, there are superior longer term solutions including lunar deployment that offer advantage. For example, the back side of the moon or the lunar polar regions would be excellent sites if a lunar infrastructure were to be deployed. The slow rotation of the moon is also advantageous. Any space based solution would be part of an evolving long term program.

Conclusions – It is now feasible to seriously discuss, plan and execute a program to use directed energy to propel spacecraft to relativistic speeds allowing the possibility of realistic interstellar flights for the first time as well as using the same technology for many other applications including beamed power modes. There has been a dramatic change in the practical possibilities of using directed energy brought about by a revolution in photonics that is on an exponential rise in capability and an exponential drop in cost. While photonic propulsion has been spoken about for a very long time, it has largely been confined to dreaming and to the realm of science fiction. This has now changed to the point where a serious program can begin to enable a future no longer constrained by low speed chemical and ion propulsion. We outline a roadmap to that future with a logical series of steps and milestones. One that is modular and scalable to any sized system. The same system has many other applications and spinoffs and this will greatly aid in the cost amortization. While the roadmap to the future of directed energy propulsion is extremely challenging it is nonetheless a feasible roadmap to begin. The difficulties are many but the rewards and long term consequences are not only profound but will be transformative for humanity.

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Website: Resources are available on our website that include papers, images and videos as well as a photon propulsion calculators that implement both the non-relativistic as well as relativistic equations for various mission analyses.

www.deepspace.ucsb.edu
www.deepspace.ucsb.edu/projects
www.deepspace.ucsb.edu/projects/starlight
www.deepspace.ucsb.edu/projects/wafer-scale-spacecraft-development

Photon Propulsion Calculator:
http://128.111.23.62/wordpress/wp-content/uploads/2015/04/Relativistic-Laser-Propulsion-Classical-1D-Standalone.html

References:
Our papers, file of list of current papers, and related materials can be found here:
www.deepspace.ucsb.edu/projects/starlight
Our group papers including our work on photonics can be found on our ResearchGate link:
https://www.researchgate.net/profile/Philip_Lubin

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