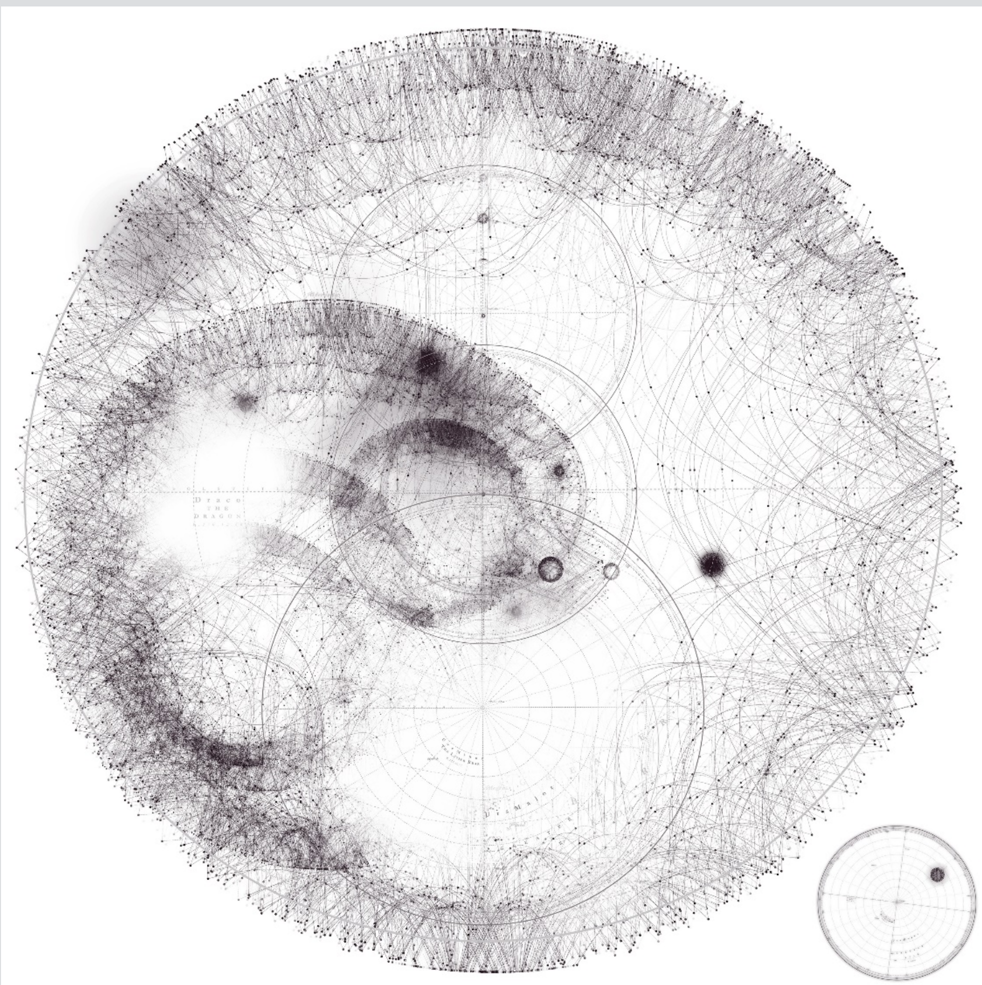
Breakthrough Starshot



Bidder's Briefing
Phase 1 Photon Engine RFP
October 2, 2017
Zoom Room

BREAKTHROUGH

INITIATIVES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BREAKTHROUGH
PRIZE

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ESO

Breakthrough Starshot

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Pete Klupar, Project Manager

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Bob Fugate, NM Tech (Emeritus)

Mark Spencer, AFRL/RDL

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* Nobel Laureate

Starshot Objectives

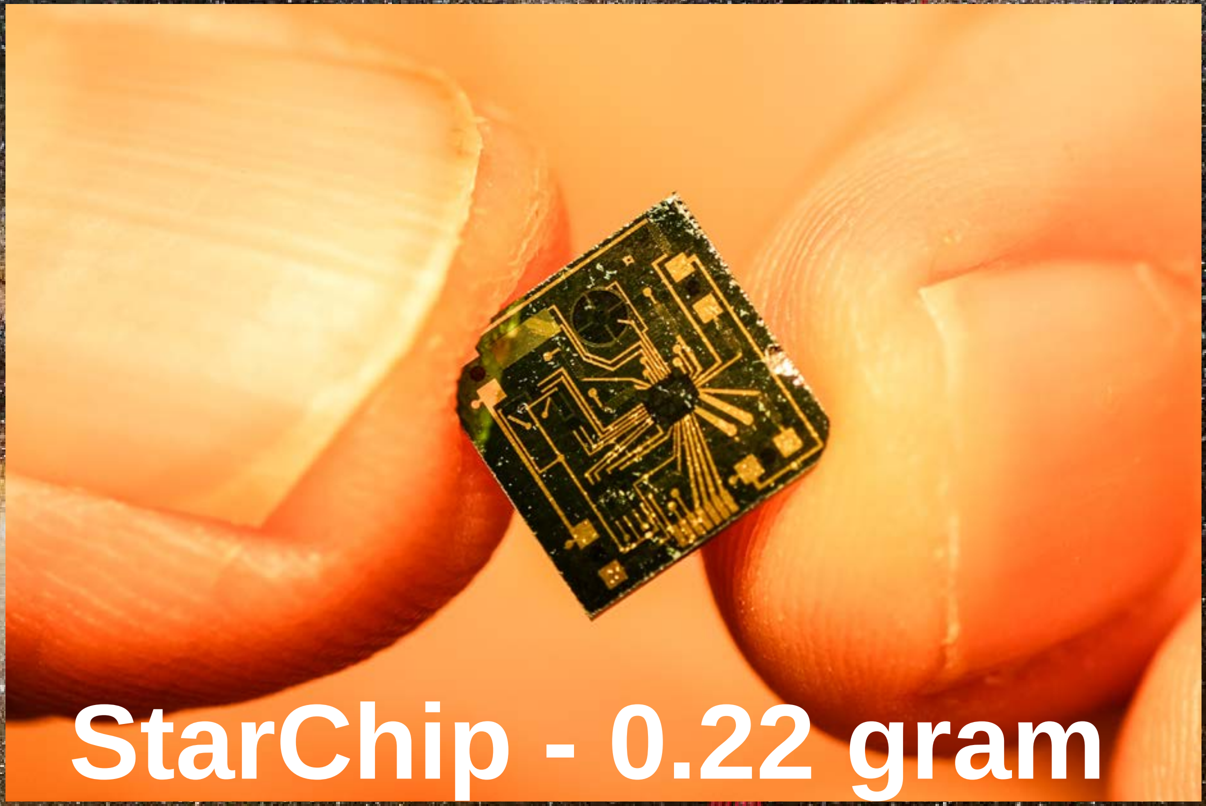
1. Send a spacecraft to nearby stars with planets in the habitable zone within 5 Parsecs of earth
2. Collect Science Data of star system focused on planets and beam data back to Earth
3. Launch within 30 years, at an affordable cost
4. Go FAST!

The Alpha/Proxima Centauri star system is the principal objective for Starshot

A planet, Proxima b, has been discovered in the habitable zone at Proxima Centauri

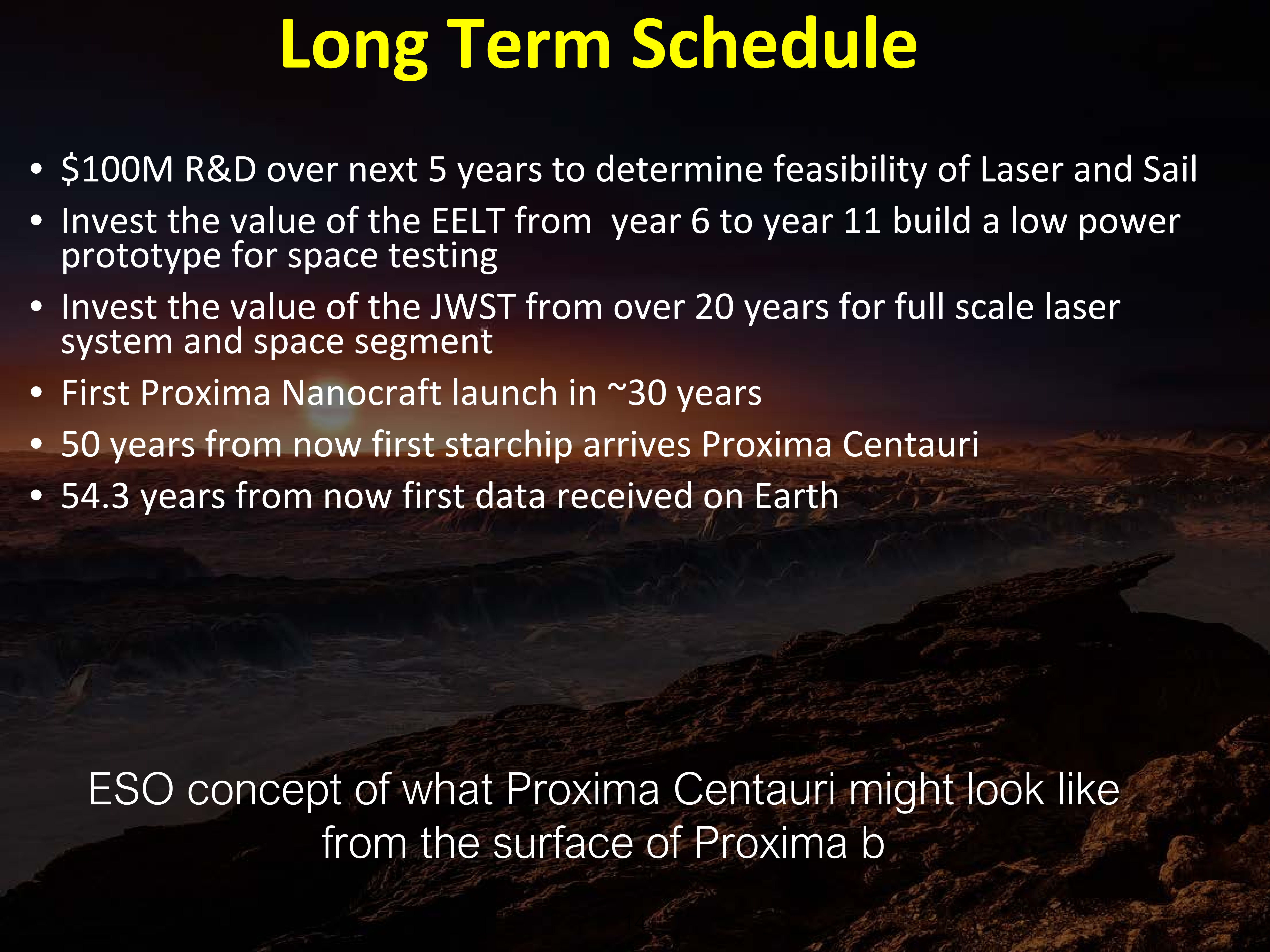
Solution to go fast

1. Lowest possible mass
2. Leave engine/fuel on Earth
3. Attach a chip to a sail
4. Laser beam is the wind



Long Term Schedule

- $100M R&D over next 5 years to determine feasibility of Laser and Sail
- Invest the value of the EELT from year 6 to year 11 build a low power prototype for space testing
- Invest the value of the JWST from over 20 years for full scale laser system and space segment
- First Proxima Nanocraft launch in ~30 years
- 50 years from now first starchip arrives Proxima Centauri
- 54.3 years from now first data received on Earth



ESO concept of what Proxima Centauri might look like from the surface of Proxima b

Photon Engine R&D Schedule

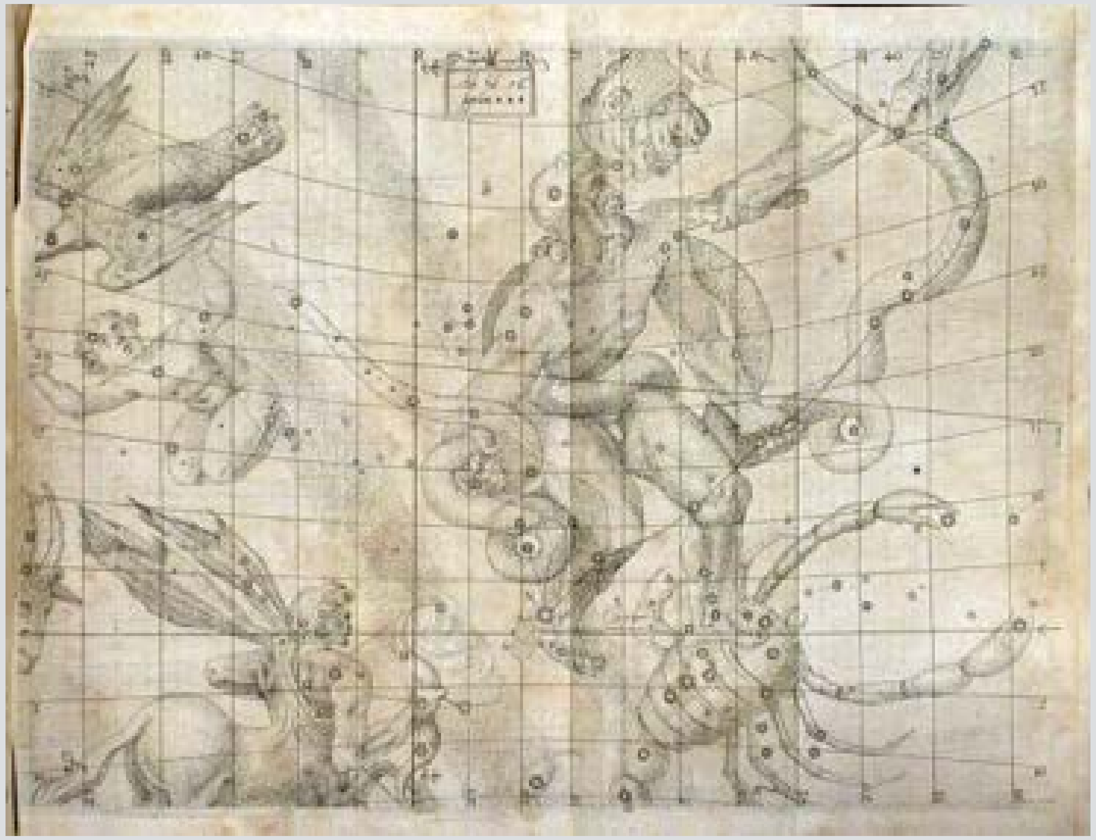
Three phases over 5 years

- Phase 1 (this RFP) Phasing Concepts and Analysis, MOPA study
- Phase 2 lab hardware validation demos, phasing and MOPA
- Phase 3 phasing field demos, high power long coherence MOPA

Up to

- 11 awards Phase 1
- 5 awards Phase 2
- 3 awards Phase 3

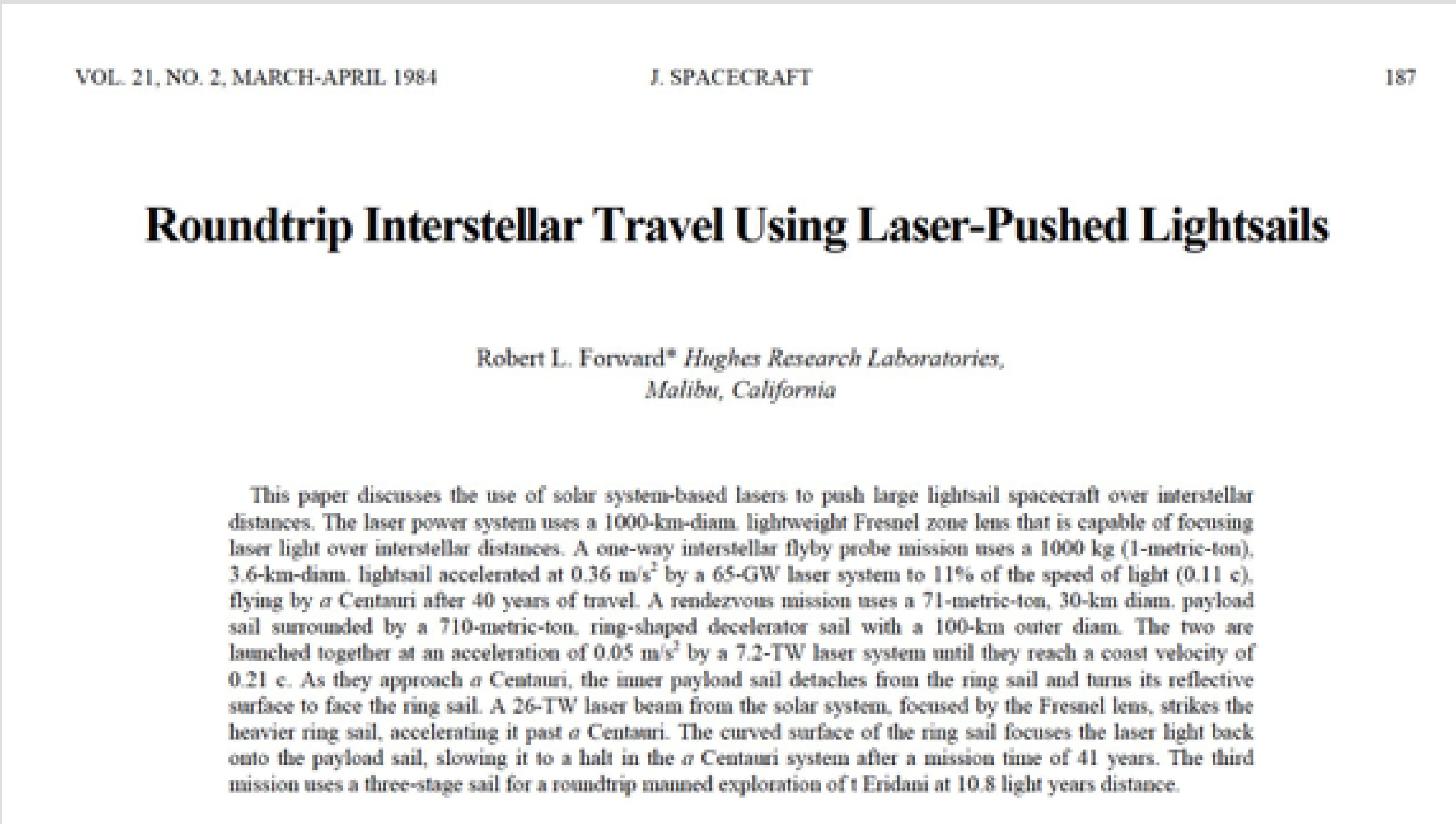
Can we sail to the stars?



Concept is not new. Kepler letter to Galileo, 1610:

"With ships or sails built for heavenly breezes, some will venture into that great vastness."

Robert Forward, 1984



VOL. 21, NO. 2, MARCH-APRIL 1984 J. SPACECRAFT 187

Roundtrip Interstellar Travel Using Laser-Pushed Lightsails

Robert L. Forward* *Hughes Research Laboratories, Malibu, California*

This paper discusses the use of solar system-based lasers to push large lightsail spacecraft over interstellar distances. The laser power system uses a 1000-km-diam. lightweight Fresnel zone lens that is capable of focusing laser light over interstellar distances. A one-way interstellar flyby probe mission uses a 1000 kg (1-metric-ton), 3.6-km-diam. lightsail accelerated at 0.36 m/s^2 by a 65-GW laser system to 11% of the speed of light (0.11 c), flying by α Centauri after 40 years of travel. A rendezvous mission uses a 71-metric-ton, 30-km diam. payload sail surrounded by a 710-metric-ton, ring-shaped decelerator sail with a 100-km outer diam. The two are launched together at an acceleration of 0.05 m/s^2 by a 7.2-TW laser system until they reach a coast velocity of 0.21 c. As they approach α Centauri, the inner payload sail detaches from the ring sail and turns its reflective surface to face the ring sail. A 26-TW laser beam from the solar system, focused by the Fresnel lens, strikes the heavier ring sail, accelerating it past α Centauri. The curved surface of the ring sail focuses the laser light back onto the payload sail, slowing it to a halt in the α Centauri system after a mission time of 41 years. The third mission uses a three-stage sail for a roundtrip manned exploration of ε Eridani at 10.8 light years distance.

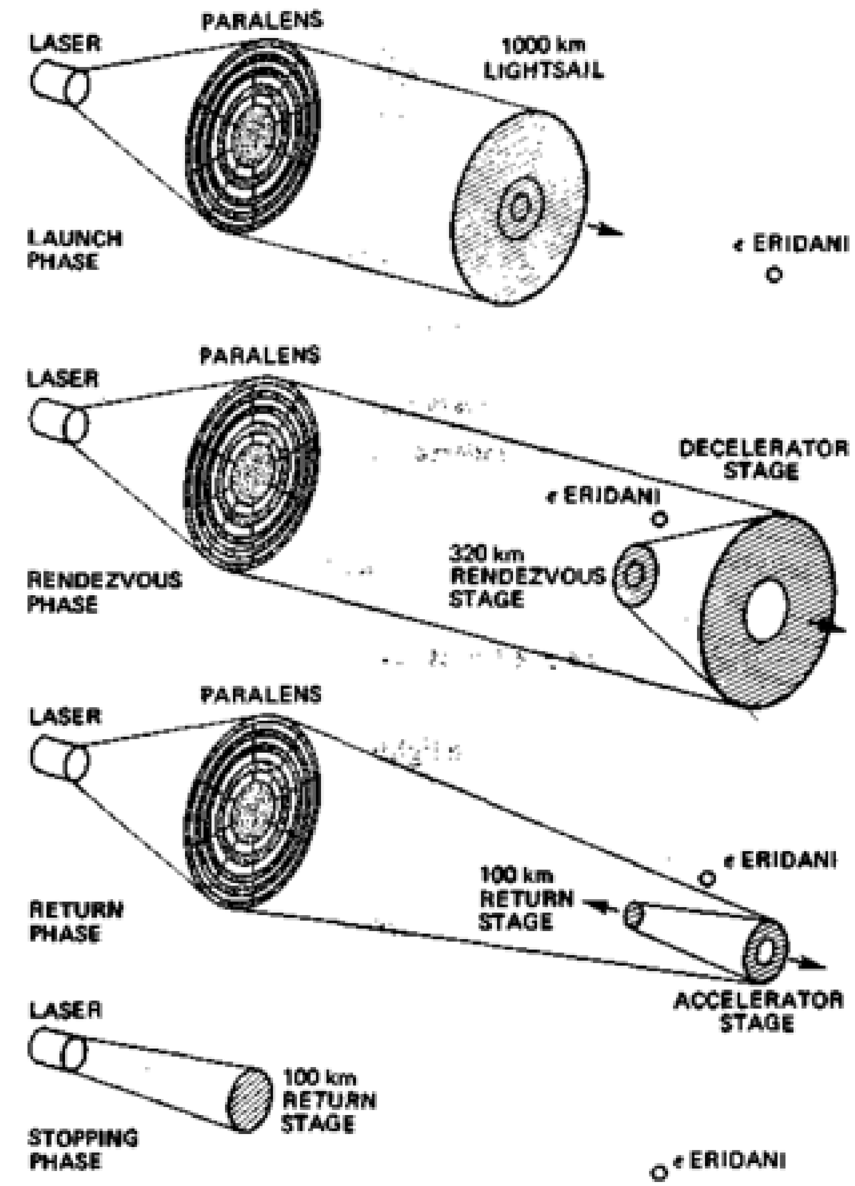


Fig. 5 Propulsion phases of roundtrip interstellar travel using laser-pushed lightsails.

"The purpose of this paper is to show that interstellar flight by laser-pushed lightsails is not forbidden by the laws of physics. Whether it can be engineered and is financially or politically feasible is left for future generations to determine."

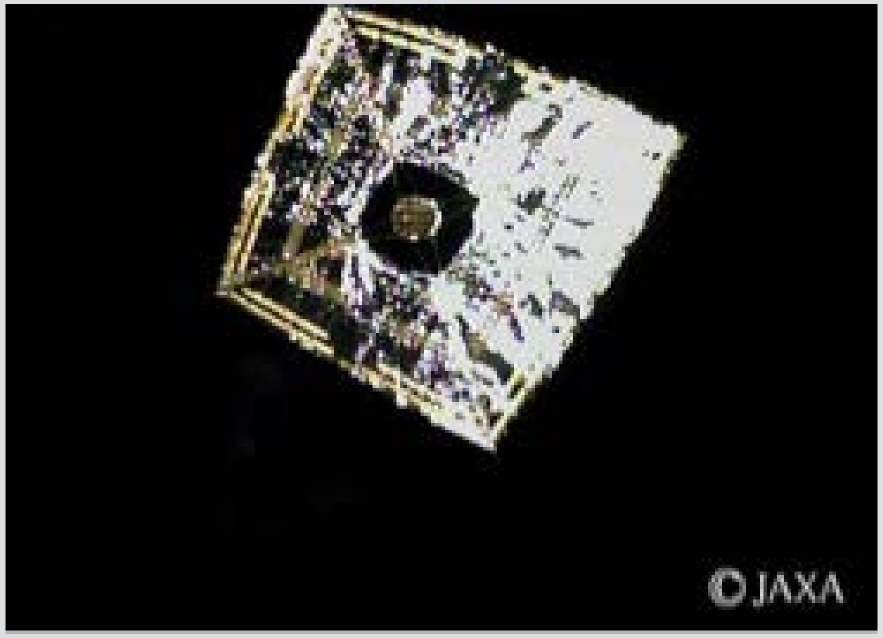
Robert Forward, 1984.

We have arrived at those future generations.

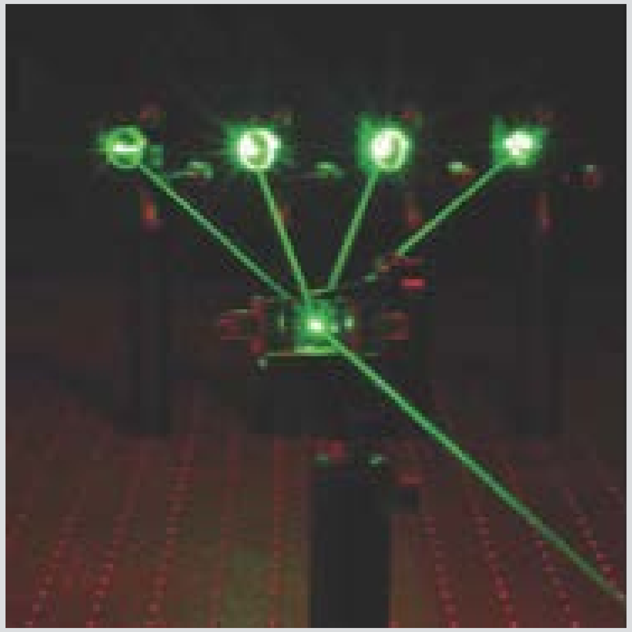
Robert Fugate, 2017

Recent technology trends

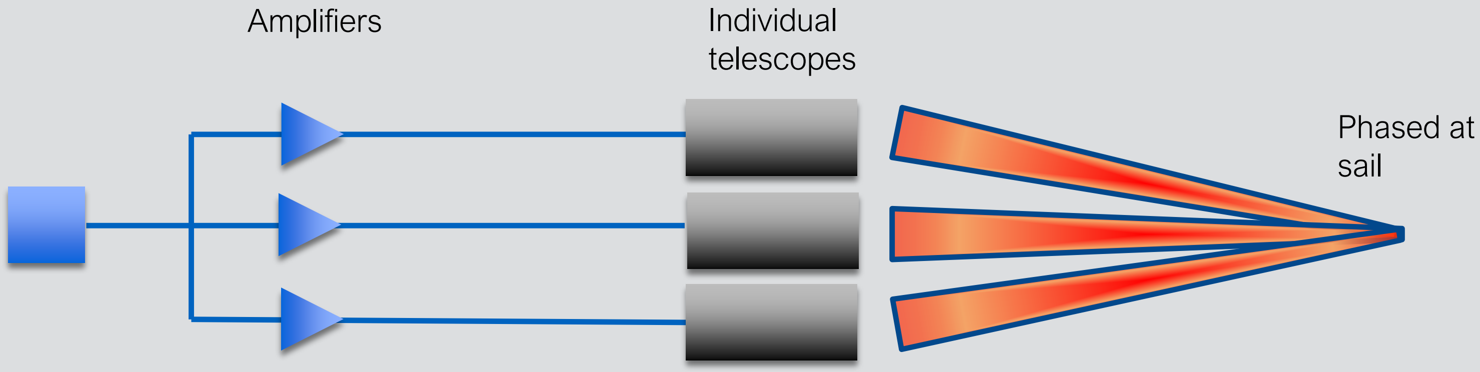
Miniaturization of electronics

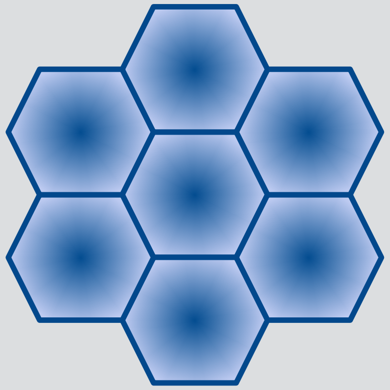


Nanotechnology Material Sciences

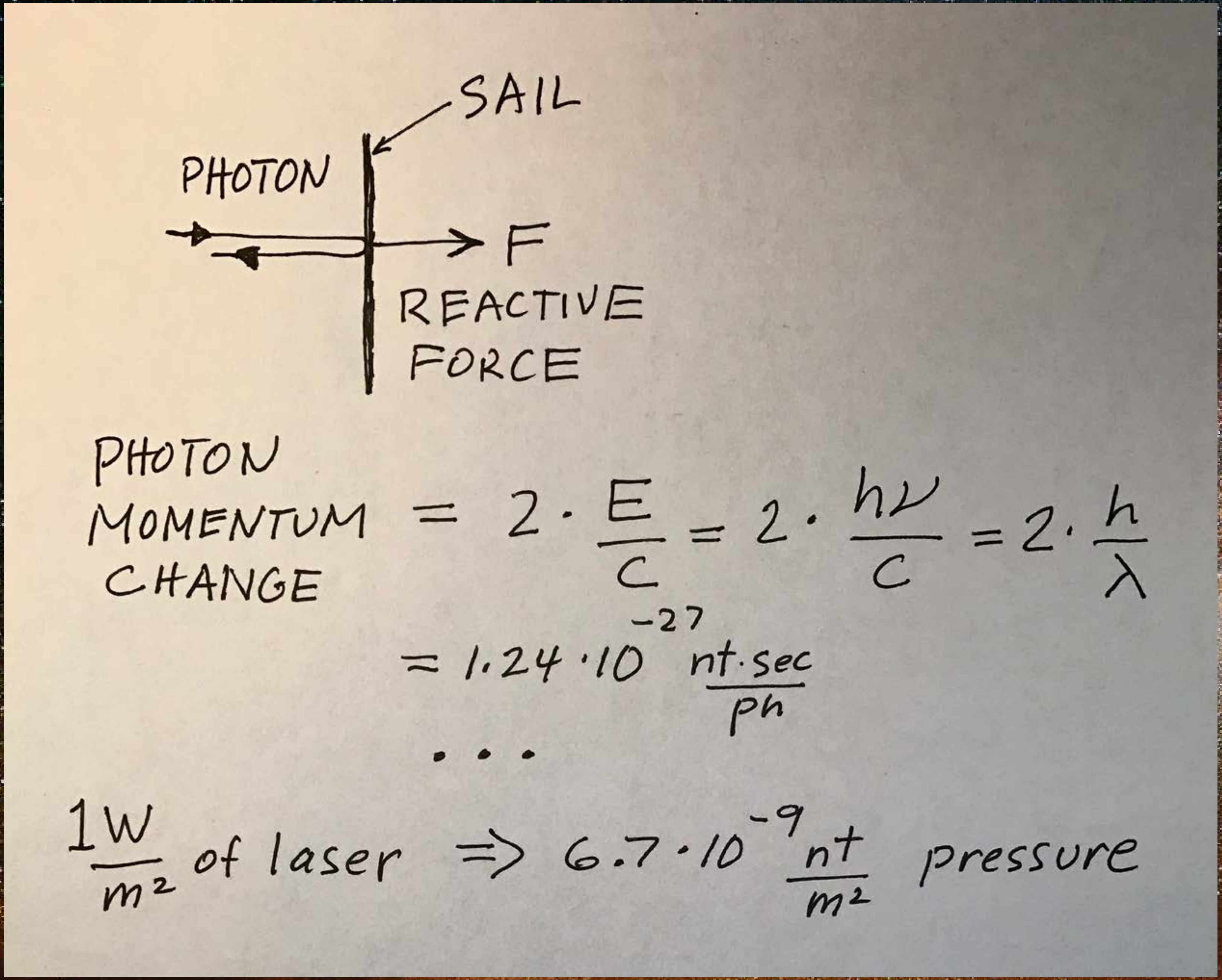


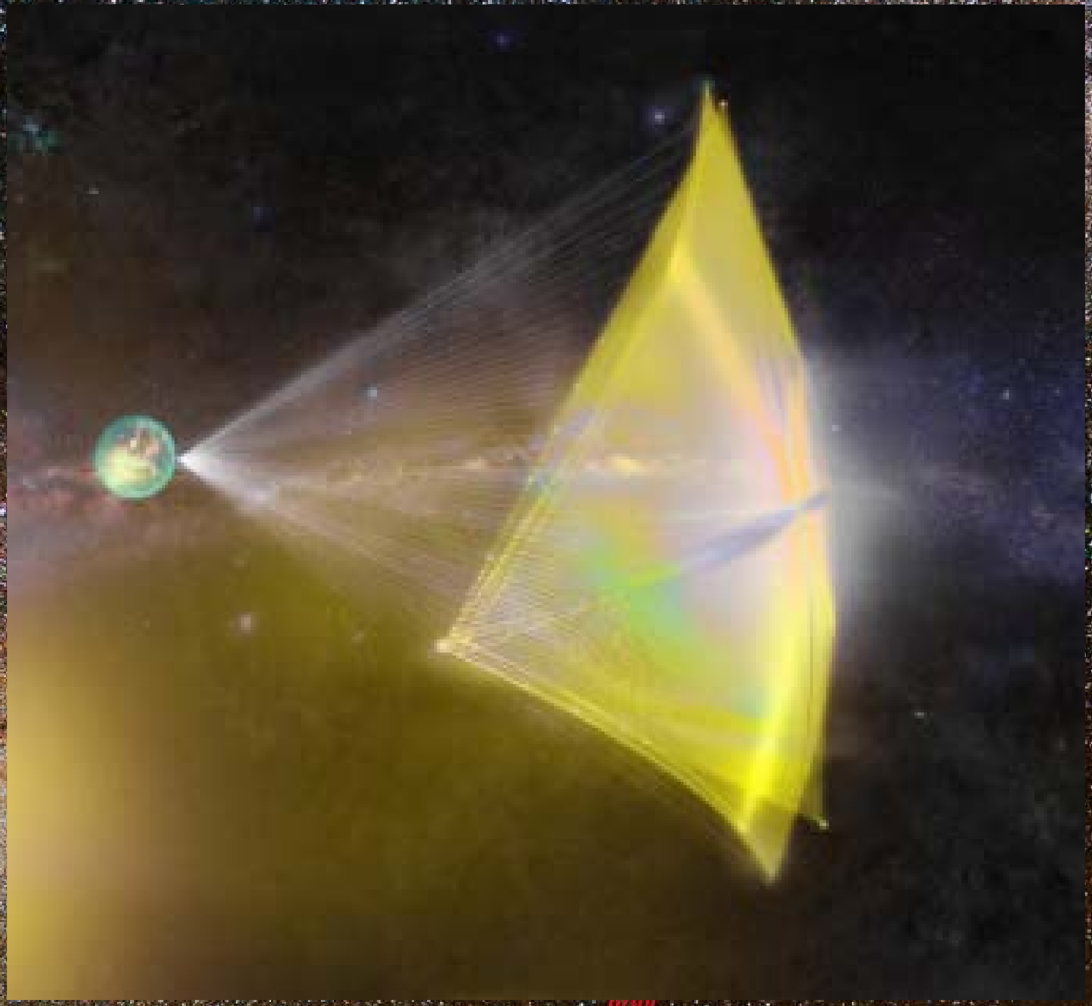
Fiber Laser Technology





Phased Array Technology





So, how big does the laser need to be?

Short answer: 50-100 GW and 1-5 km aperture

Concept Scenario

Payload: 0.5 g
Sail size: 3.78 m square
Sail thickness: 50 nm
Sail Density: 0.7 g/cm^3
Sail reflectivity: 0.99995
Sail Absorptivity: 0.001
Sail emissivity: 0.5
Laser array size: 4km square
Total optical power: 70 GW
Beam efficiency: 0.5

Sail mass: 0.5 g
Total mass: 1 g
Laser power at sail: 35 GW
Flus on sail: 2.45 GW/m^2
Peak accel: 2.33e+5 m/s^2
Accel time: 247 sec
Final speed: 0.192 c
Kinetic energy: 1.6e+12 J
Sail equil temp: 216K
Laser comm flux: 8.2e-4 ph $s^{-1}m^{-2}$

The constraints are:
Speed: 0.2 c
1064 nm wavelength
60 Mm initial range

Input parameters are:
Cost of lasers $/W
Cost of optics $/m^2
Cost of power, energy storage $/kWh
Sail parameters

System Model
Minimizes Photon Engine aperture to reach final speed
Aperture vs transmit power trade to minimize cost
50% wall plug efficiency

System Level Design Example

Circular Dielectric Sail –Reconverged 16 April 2017

Constraints

1.064 micron wavelength
0.2 c target speed
60,000 km initial sail displacement from laser source

Sail
1 g payload
0.2 g/m^2 areal density
0.001% absorptance
70% reflectance
970 K maximum temperature
1.6 effective emissivity (2-sided)

Beam Director
0.1 $/Watt laser cost
100 $\$/m^2$ aperture cost
100 $/kWh storage cost
Beamer *minimum* diameter such that final speed is reachable.
Beamer diameter traded vs. transmit power such that capital cost is minimized.
50% wallplug to laser efficiency

Results

$12.6B CAPEX comprised of:
$5.3B lasers
$3.9B optics
$3.3B energy storage

3.0 m sail diameter (for minimum cost)
2.4 g sail mass

53 GW transmitted power
1,115 sec (19 min) pulse length
33 GWh stored pulse energy

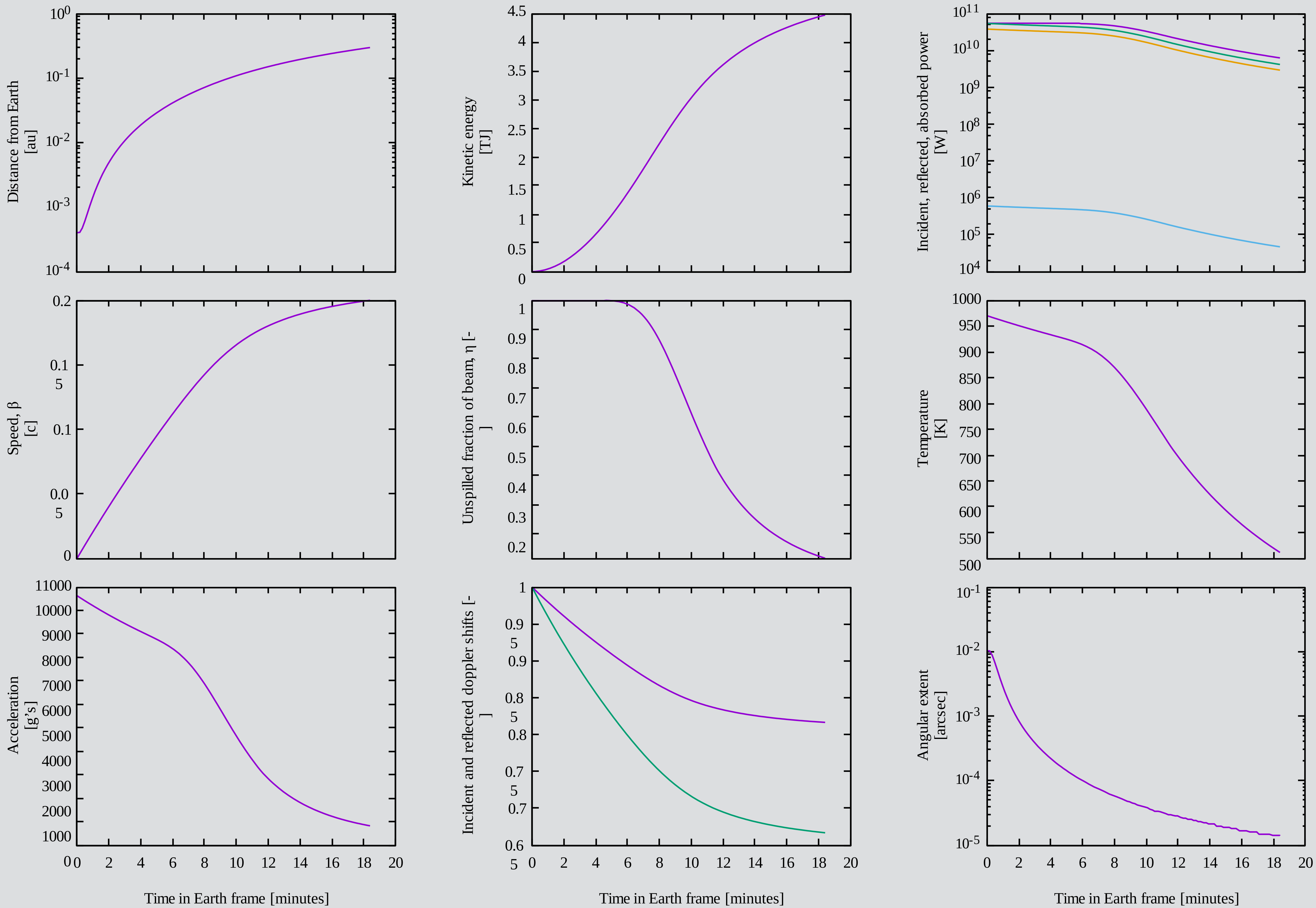
10,600 g's initial acceleration (60,000 km from source)
800 g's final acceleration (at 0.3 au from source)

7.6 GW/m^2 initial average beam intensity over sail
36 Pa initial photon pressure
249 N initial photon force
7.1 km array effective diameter

- Yes, optics cost is low and array diameter is high
- 10,000 $\$/m^2$ aperture cost (100x higher than baseline) increases CAPEX by 4x and decreases diameter by 4x
- $/Watt must fall to keep CAPEX below $10B, but assumed laser cost is still well above current cost of microwaves
- Array losses and atmospheric losses yet to be incorporated

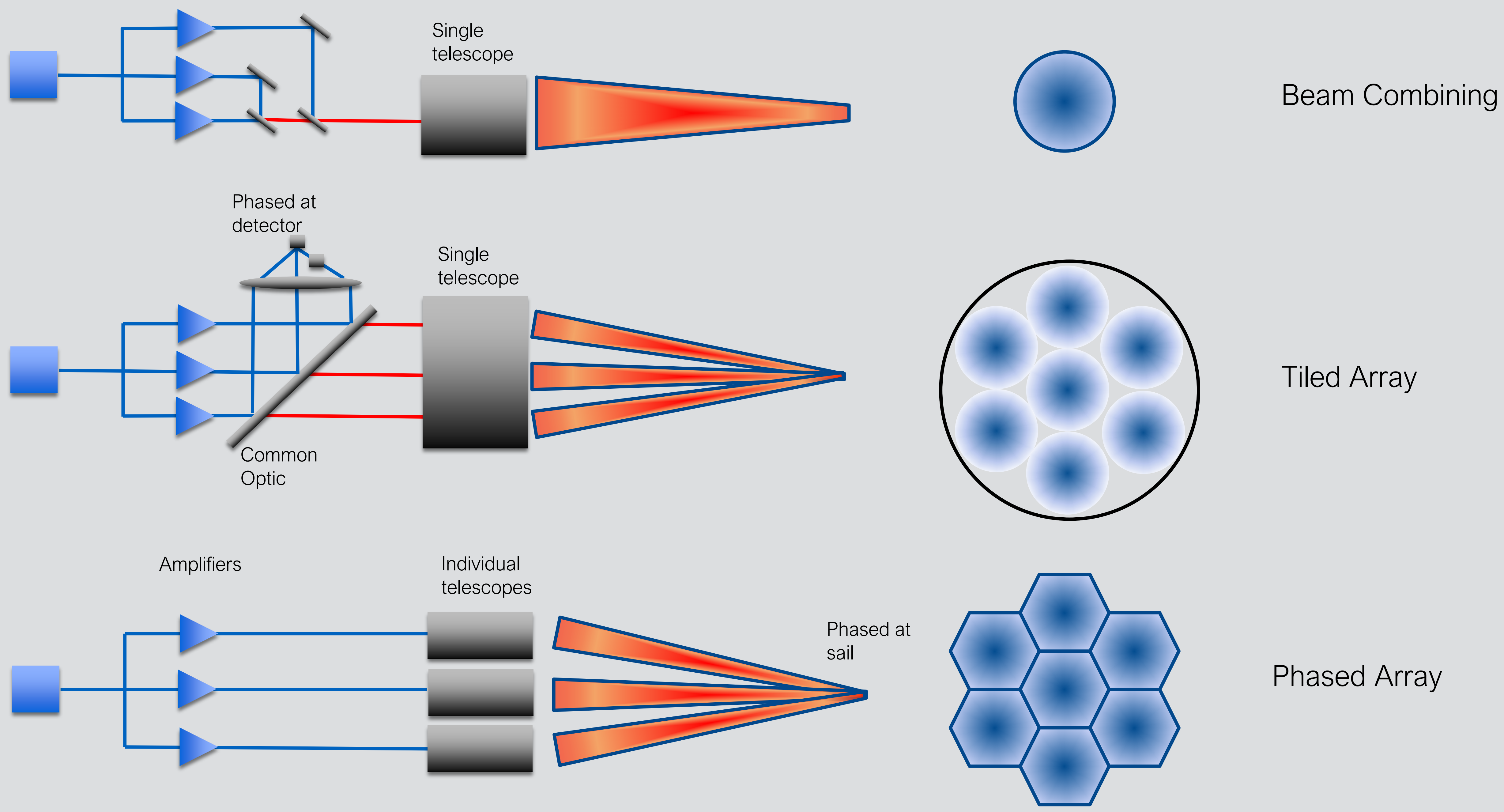
Parkin Research

Reference Point Design Example:
Trajectory - Circular Dielectric Sail – Reconverged 16 April 2017



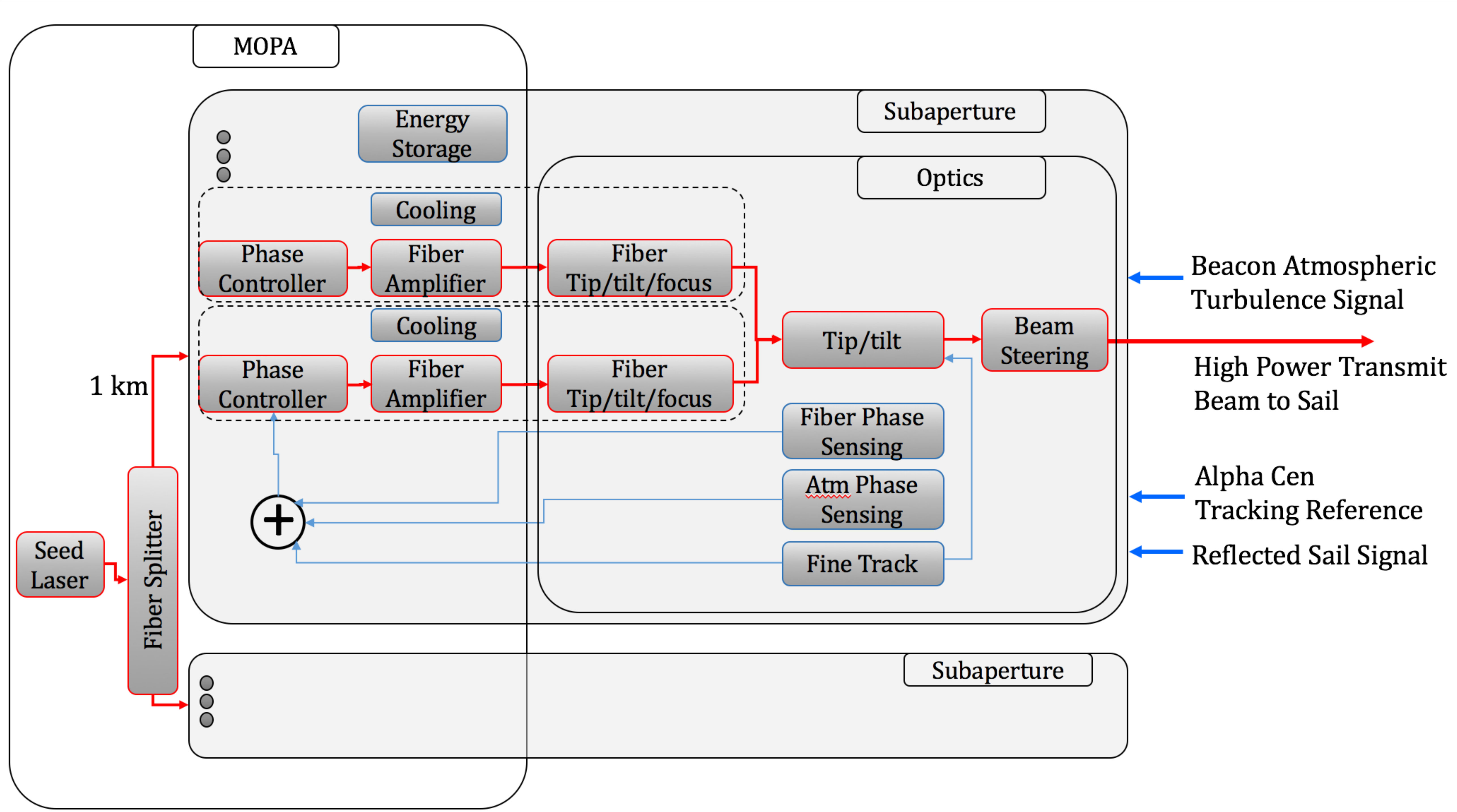
Parkin Research

Principle coherent phasing methods

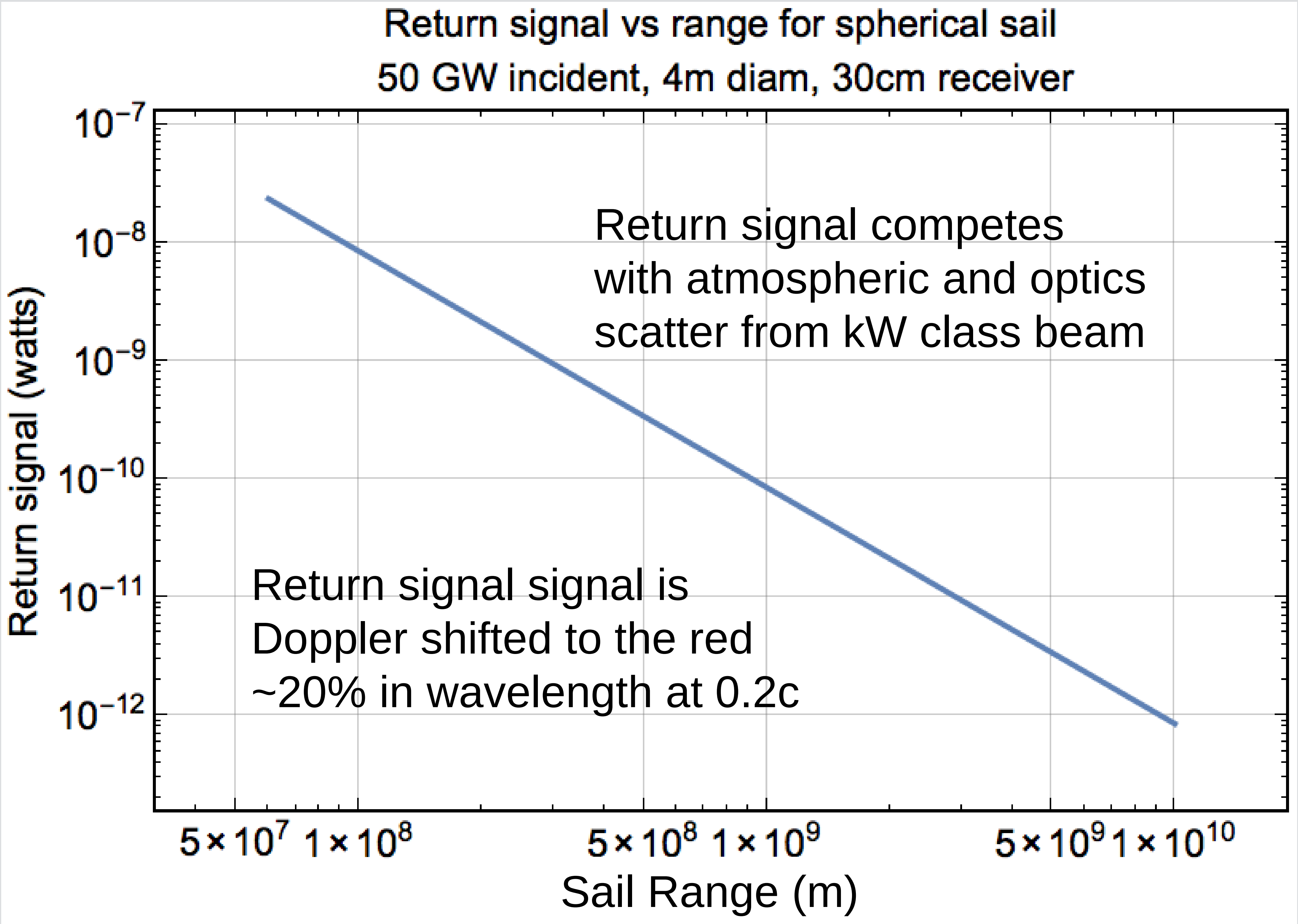


- Many demos of tiled arrays and beam combining through a common aperture.
- Only one known demo of phasing an array of separated telescopes.
- Maximum fiber power demonstrated at required coherence length is ~400 W.
- Phased arrays for Starshot have significant unsolved phase sensing and control problems. TRL 1.

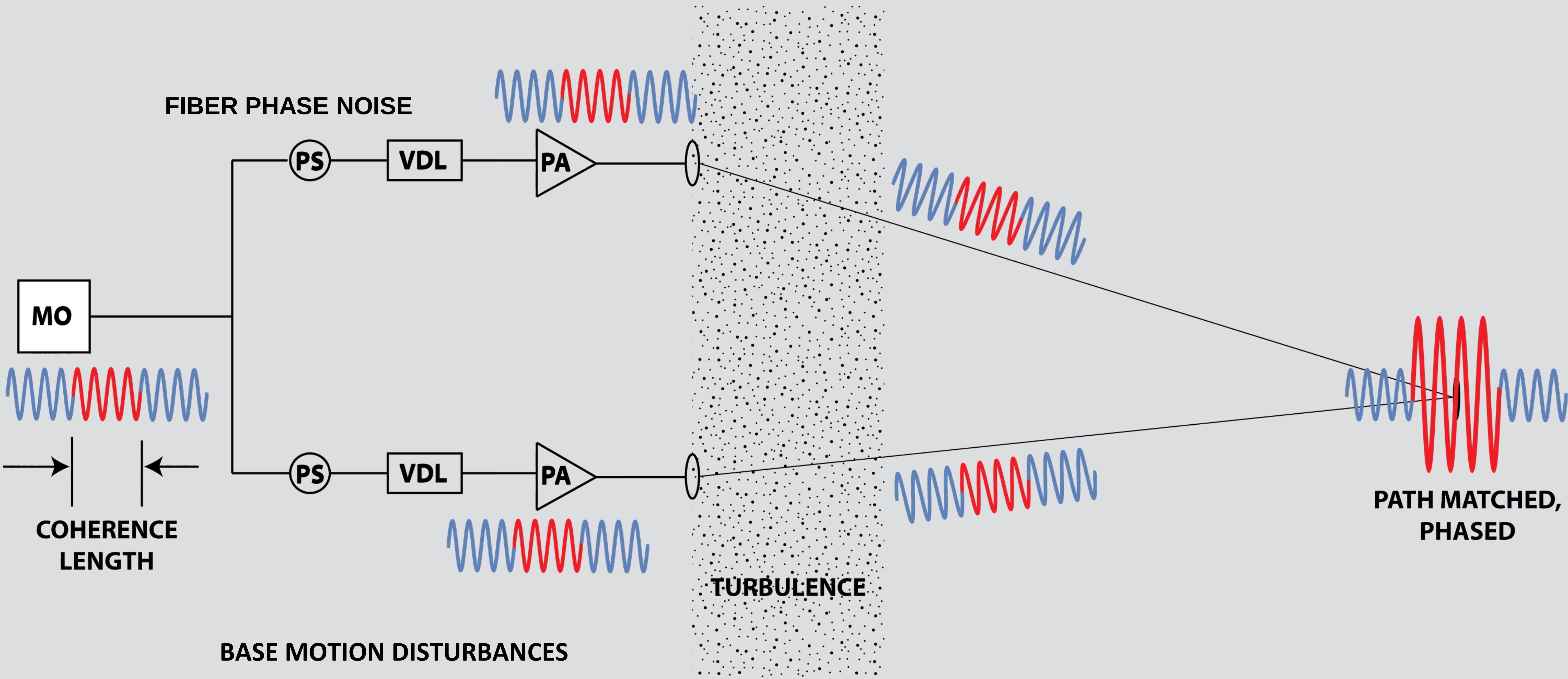
Parameter	Today	Starshot	Delta
Aperture	<1 m	~1 km	10^3
Power	100 kW	100 GW	10^6
Coherence Length	3 cm @ 1 kW 24 m @ 420 W	3 km @ 1kW	10^5 125
Cost	$10/W (large quantity scaling)	$0.05/W	200
Turbulence	Horizontal, distributed, strong, branch cuts	Vertical, near aperture, weak, no branch cuts	Starshot turbulence easier
Control loop	Power in the bucket on target	Cooperative coherent beacon	Beacon is non-trivial
Range	~10 km	~ 10^7 km	10^6
Target	Uncooperative	Ultra high acceleration and speed	Open loop pointing and control


MOPA
Subaperture
Energy Storage
Optics
Cooling
Phase Controller
Fiber Amplifier
Fiber Tip/tilt/focus
Cooling
Phase Controller
Fiber Amplifier
Fiber Tip/tilt/focus
Tip/tilt
Beam Steering
Beacon Atmospheric Turbulence Signal
High Power Transmit Beam to Sail
1 km
Fiber Phase Sensing
Atm Phase Sensing
Fine Track
Alpha Cen Tracking Reference
Reflected Sail Signal
Seed Laser
Fiber Splitter
Subaperture

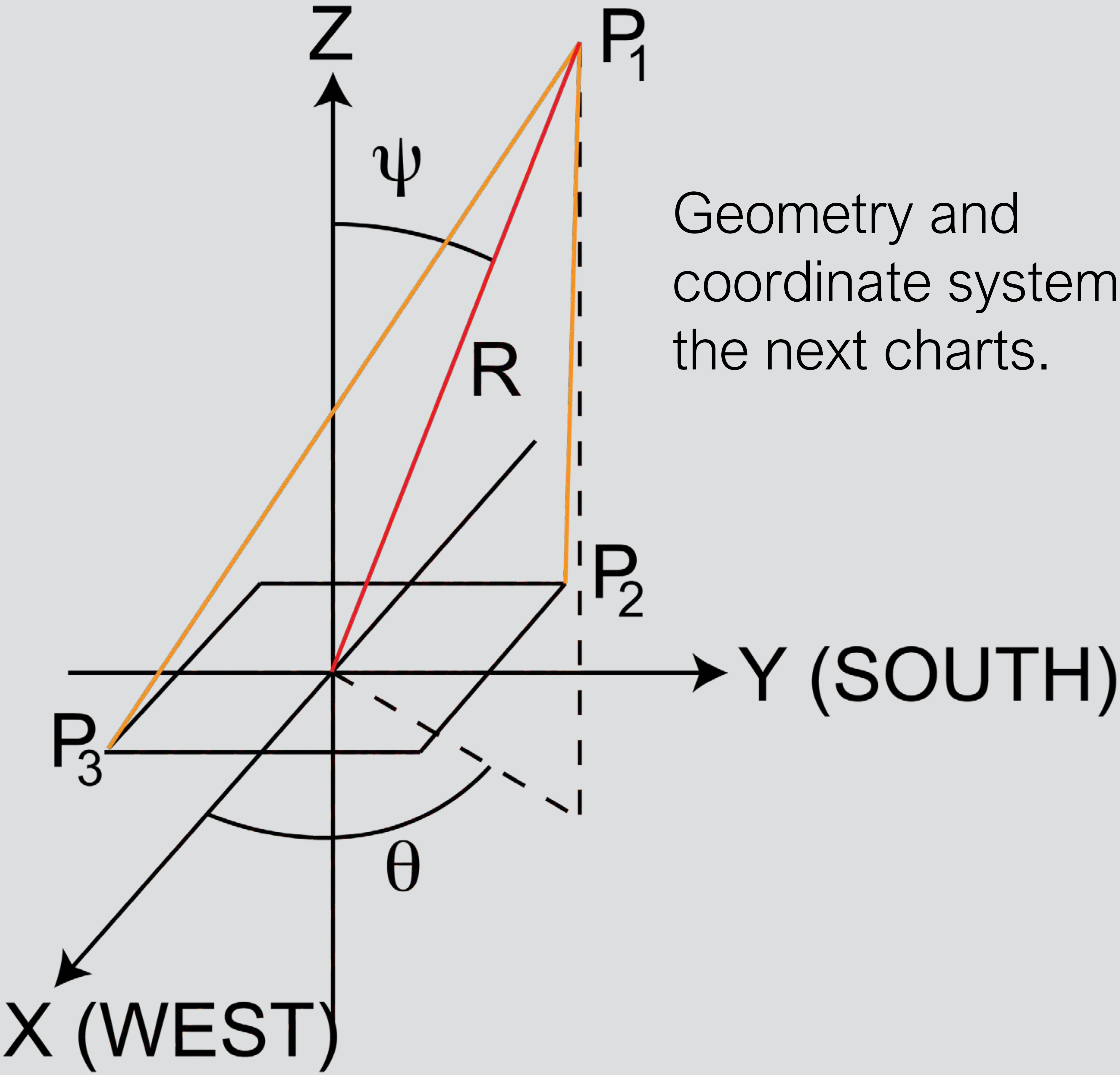
Return Power vs Range



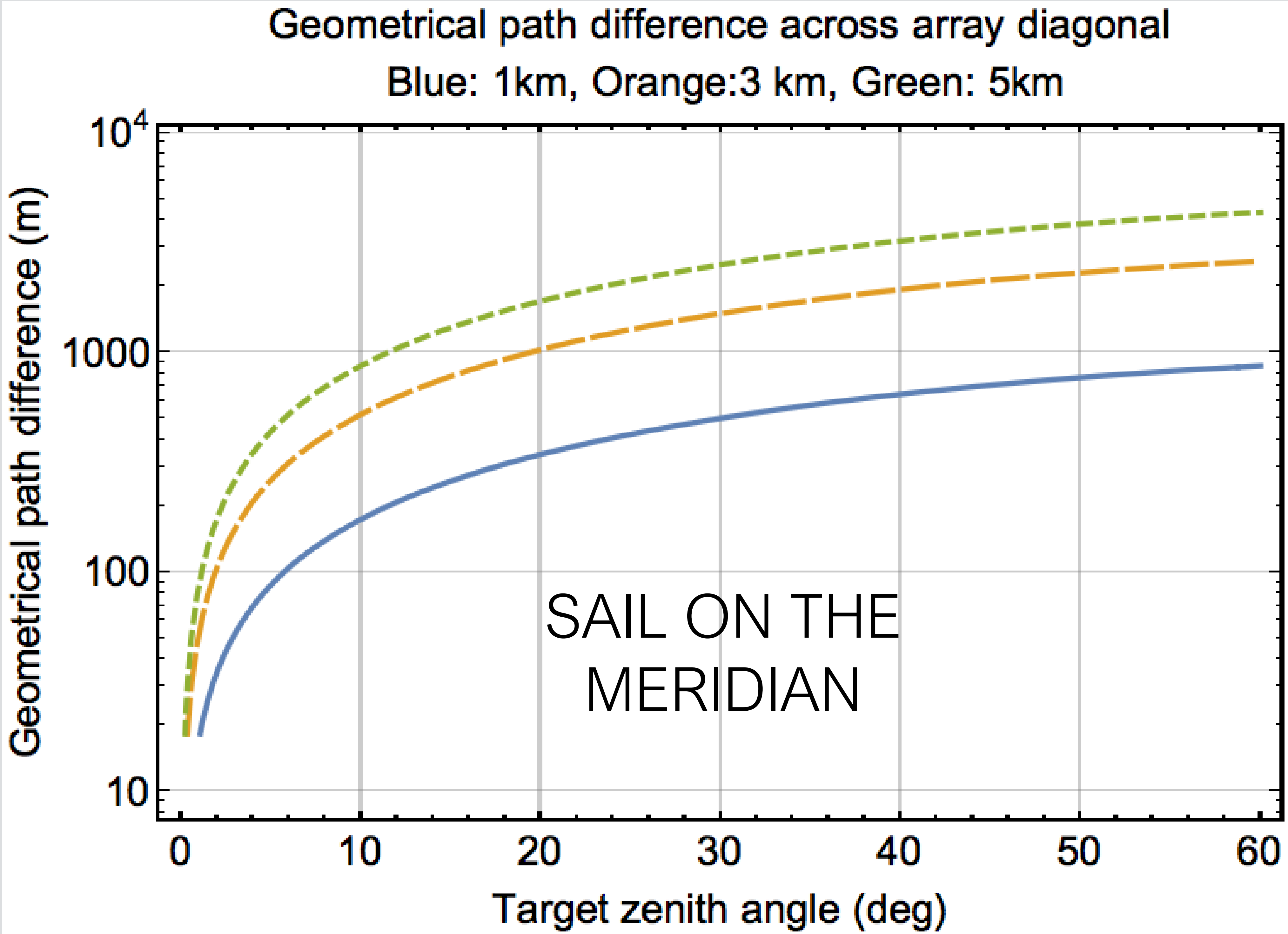
Path Matching and Phasing Requirement

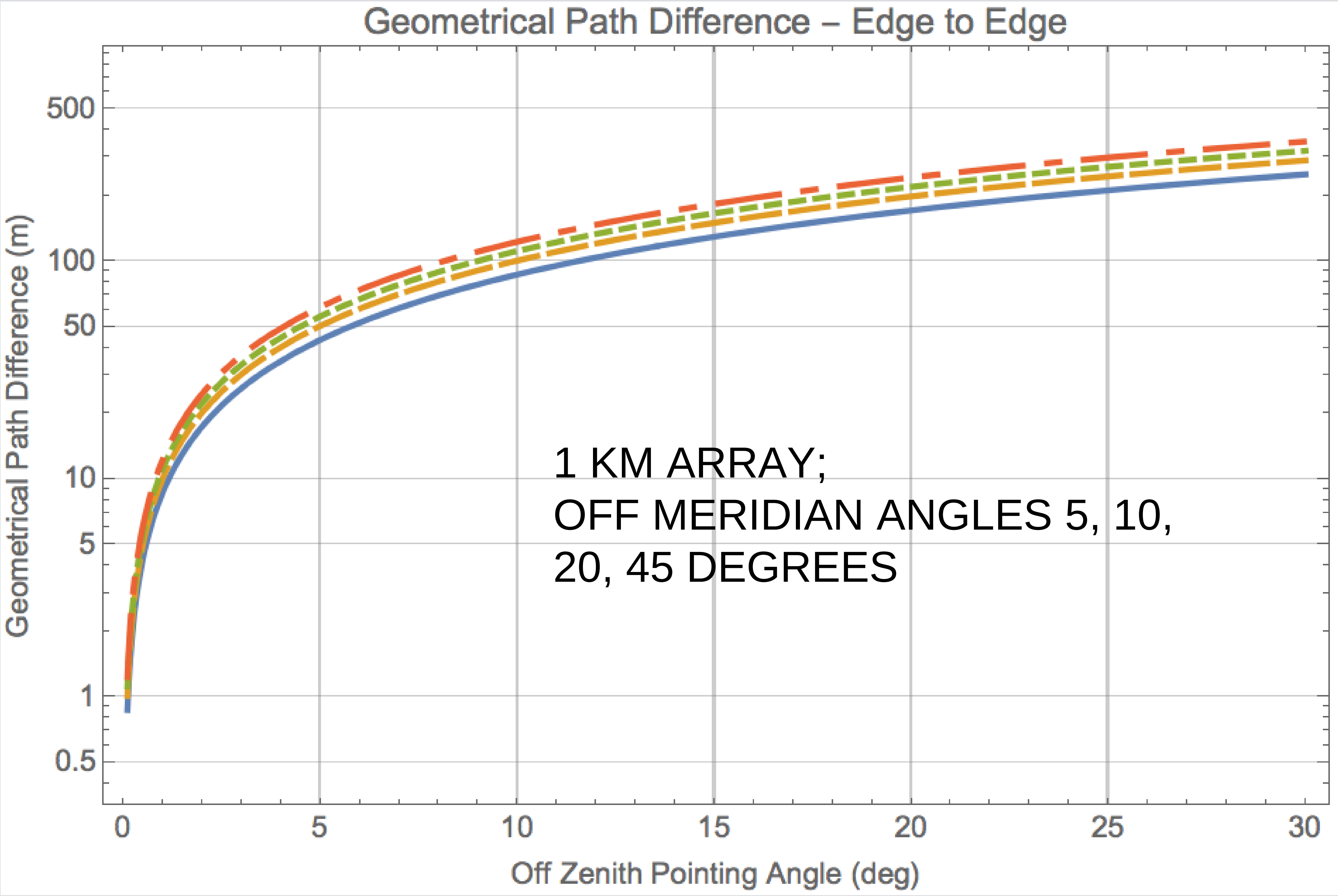


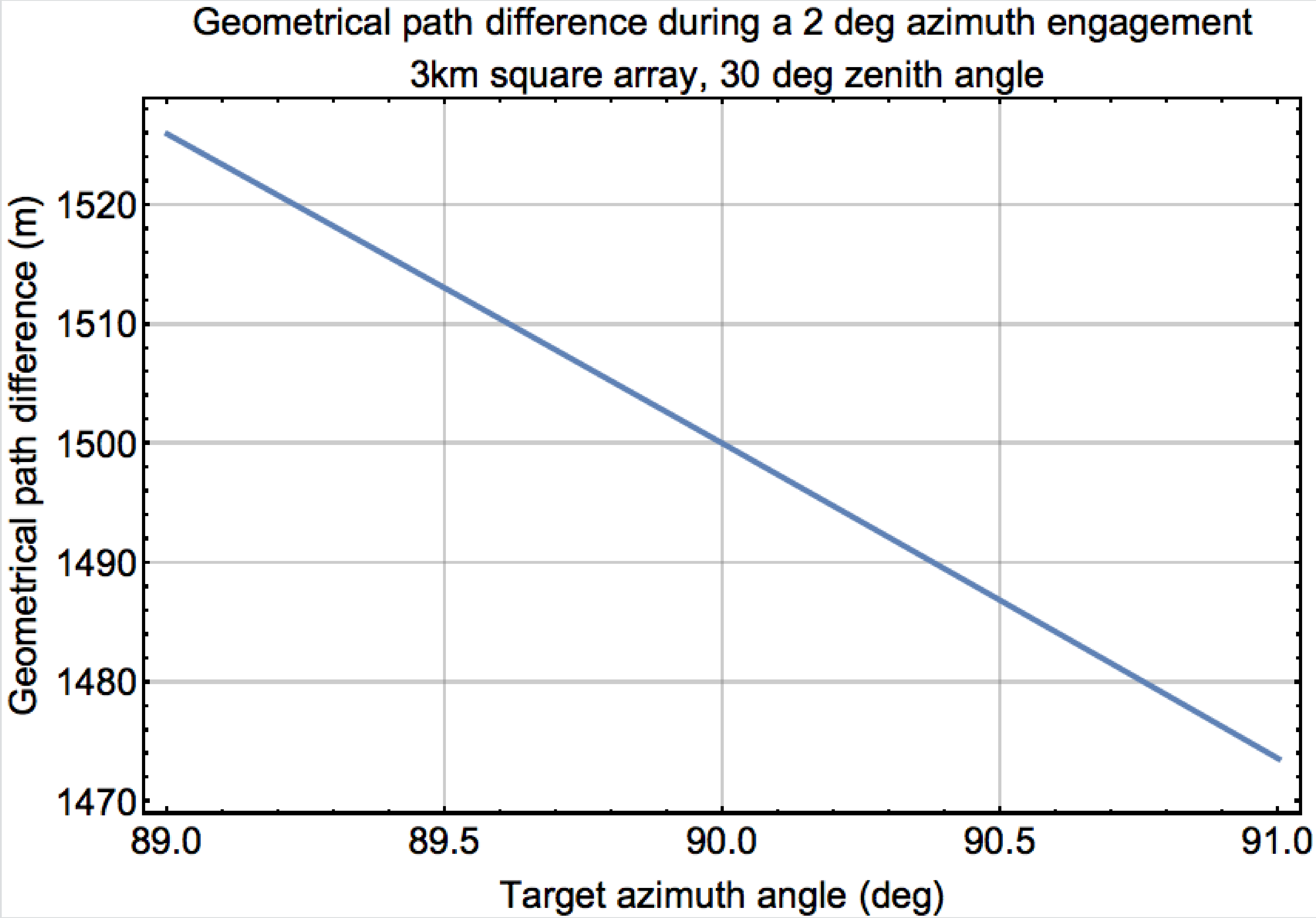
THE OPTICAL PATH LENGTH $\int n(z)dz$ FOR ALL LASERS MUST BE WELL WITHIN THE COHERENCE LENGTH AND THE PHASING BETTER THAN $\lambda/10$ BETWEEN ALL BEAMS. WE MUST ALSO MATCH THE POLARIZATION OF ALL BEAMS AND MINIMIZE POINTING JITTER.



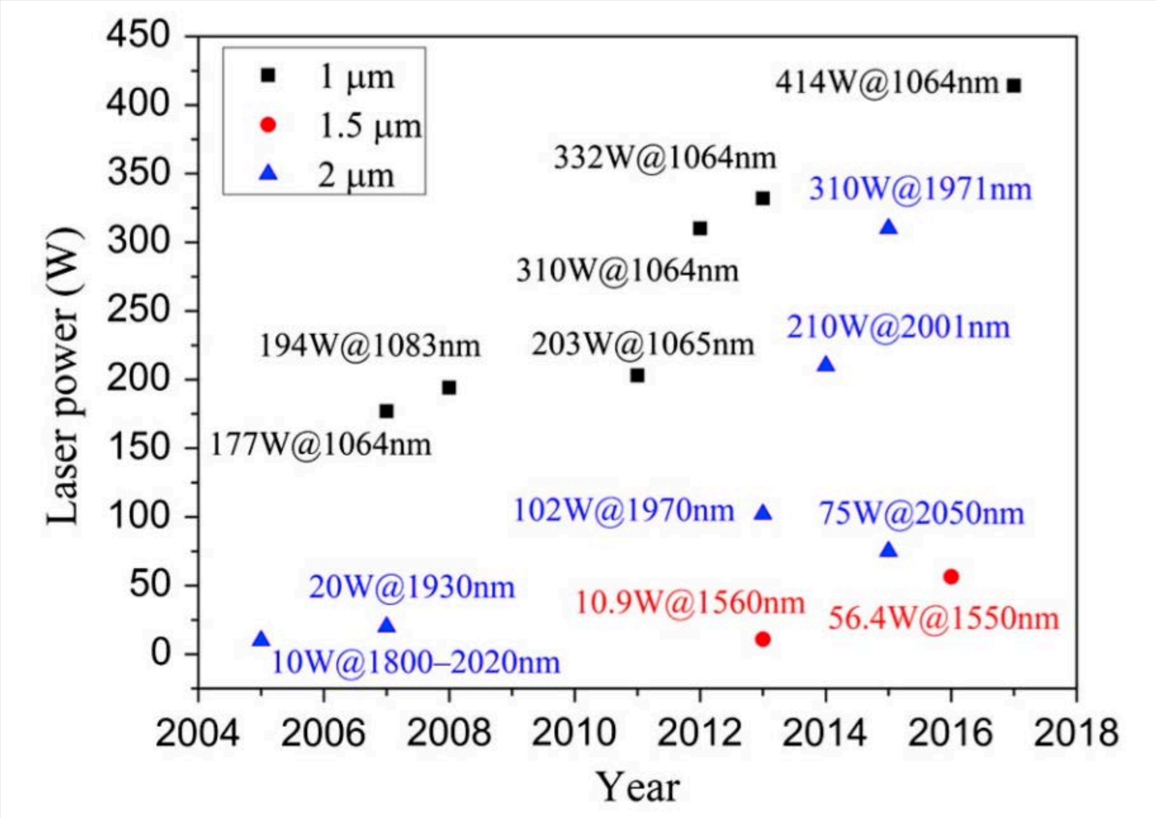
Geometry and coordinate system for the next charts.

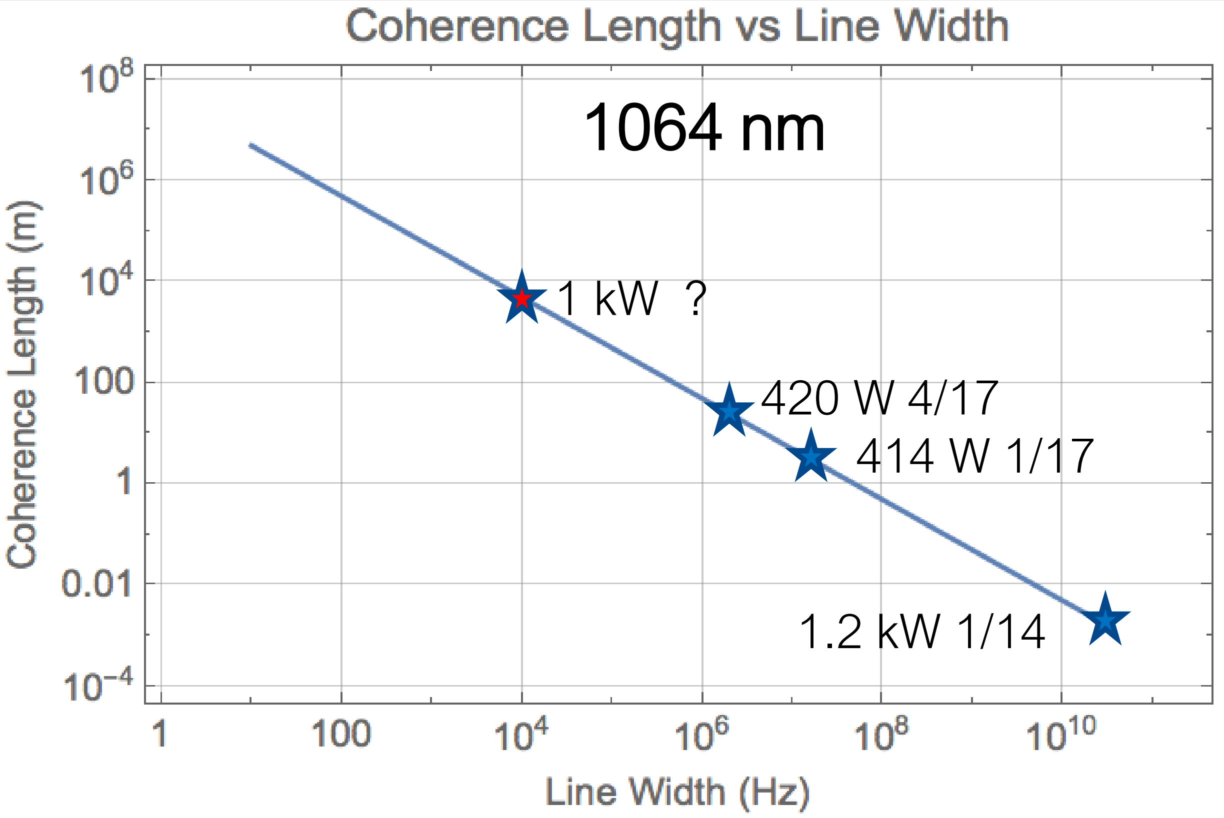

Geometrical path difference across array diagonal
Blue: 1km, Orange:3 km, Green: 5km
10^4
1000
100
10
Geometrical path difference (m)
0
10
20
30
40
50
60
Target zenith angle (deg)
SAIL ON THE
MERIDIAN


Geometrical Path Difference – Edge to Edge
Geometrical Path Difference (m)
500
100
50
10
5
1
0.5
0
5
10
15
20
25
30
Off Zenith Pointing Angle (deg)
1 KM ARRAY;
OFF MERIDIAN ANGLES 5, 10,
20, 45 DEGREES

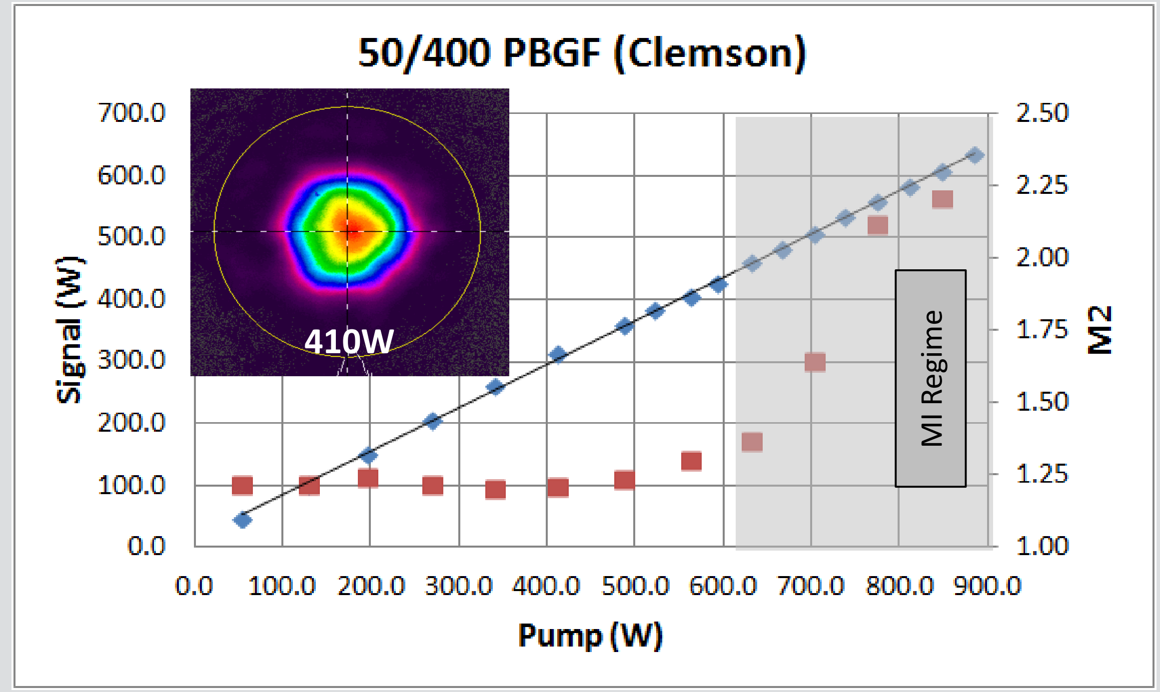

Geometrical path difference during a 2 deg azimuth engagement
3km square array, 30 deg zenith angle
Geometrical path difference (m)
1470
1480
1490
1500
1510
1520
89.0
89.5
90.0
90.5
91.0
Target azimuth angle (deg)

Status of Single Frequency High Power Amplifiers



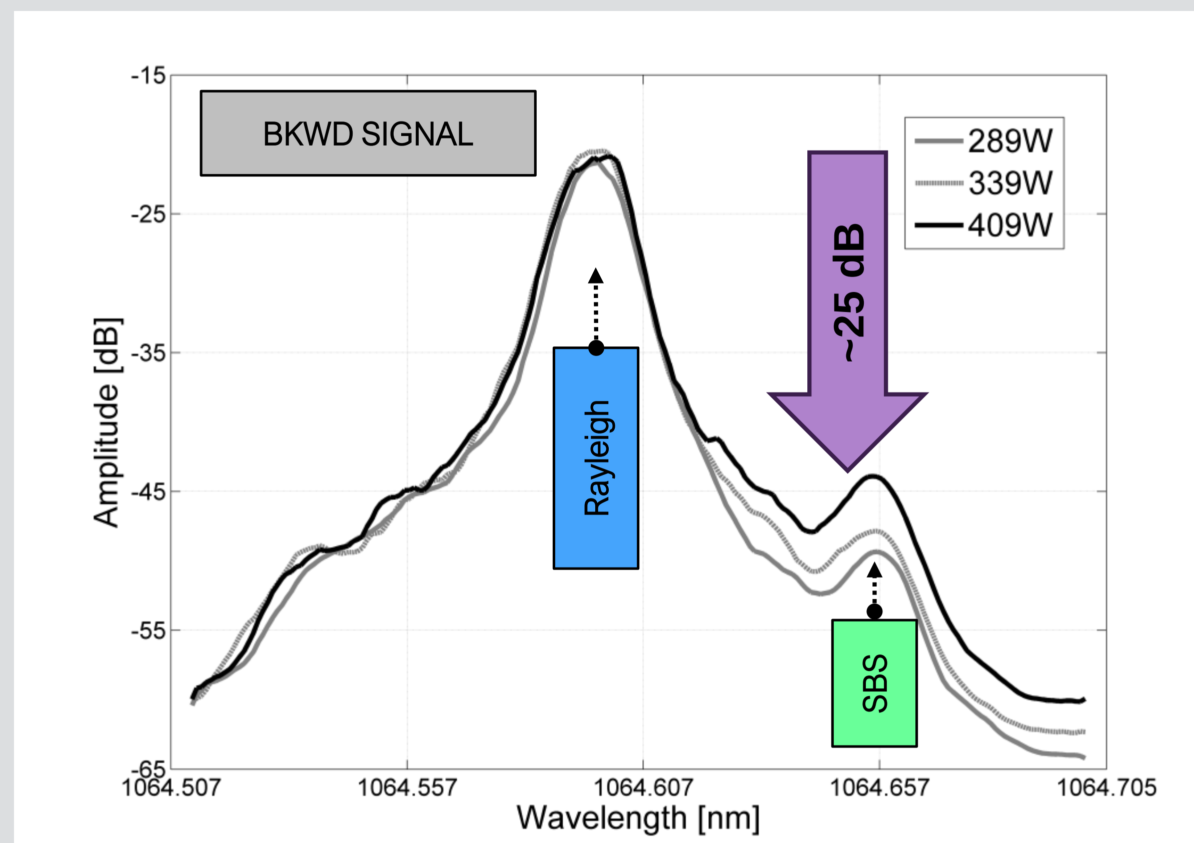


Single Frequency PBGF Amplifier

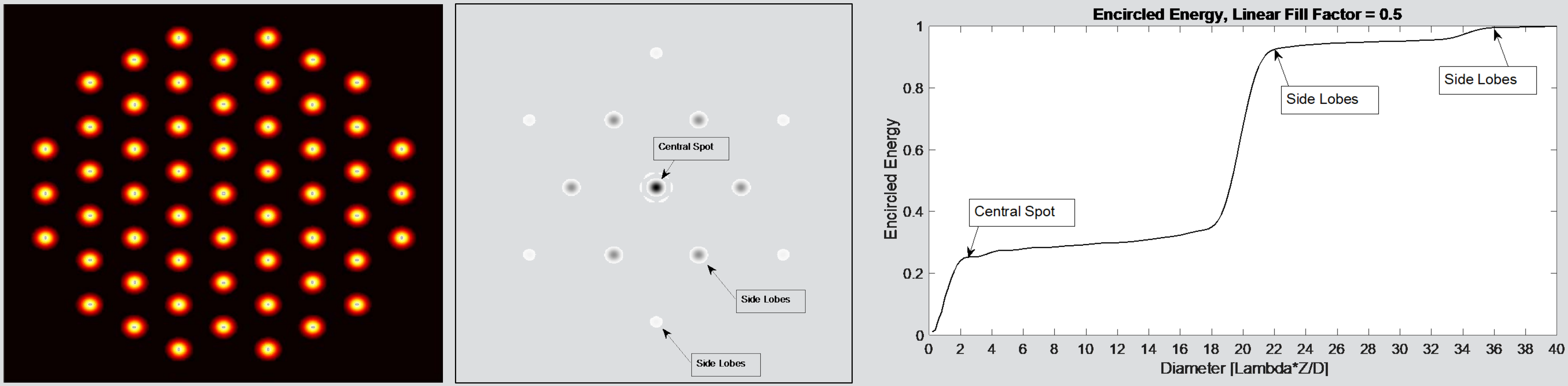


AS-PBGF (Clemson)				
λ	1064 nm		M^2	1.25
P_{out}	420W		Slope Eff.	70%
Linewidth	< 2MHz[1]		Fiber Length	7 m
PER	UNP		Core Dia.	~50 µm

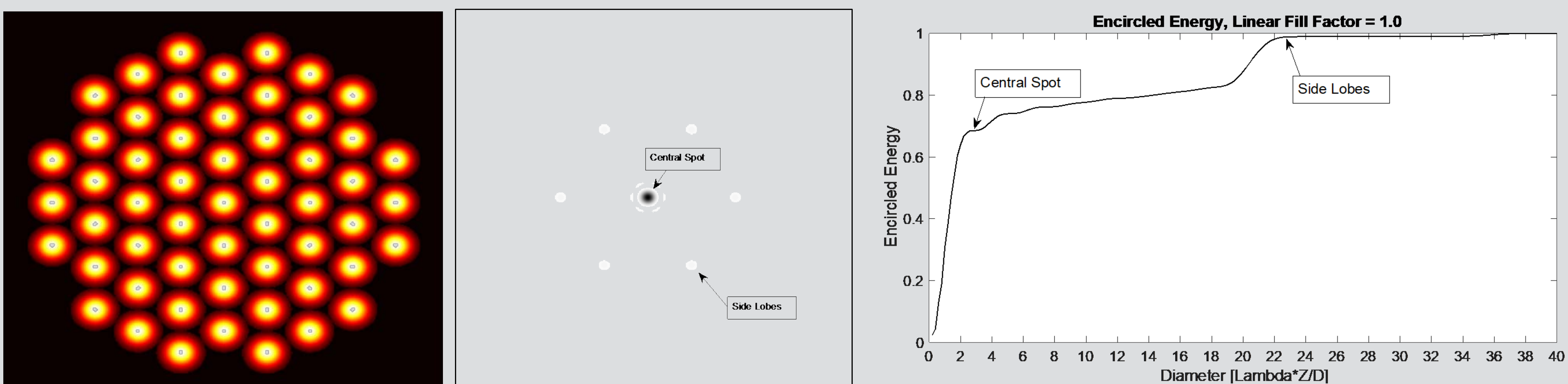
1. Fabry Perot Meas. Limited



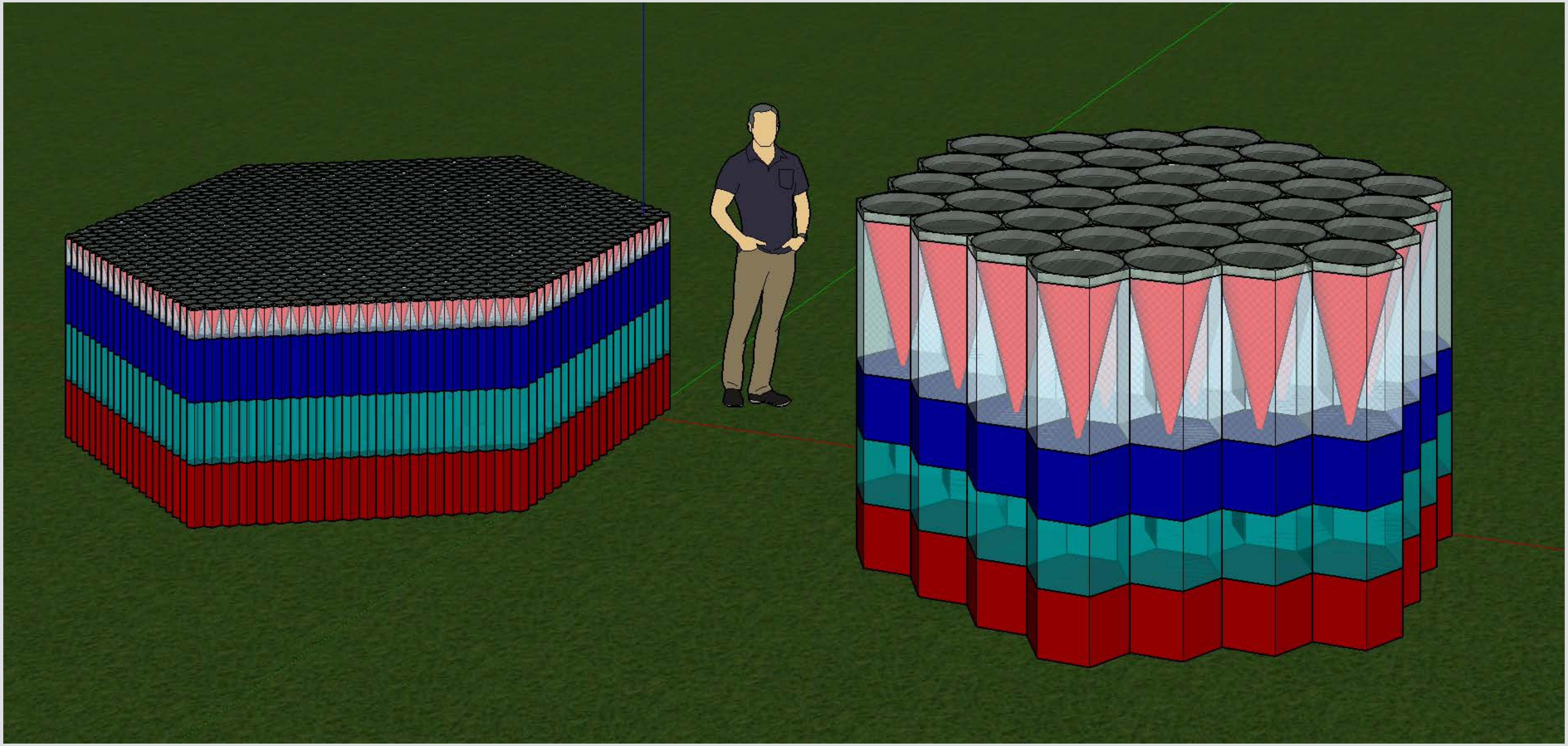
High Fill Factor is Required



SPARSE ARRAY

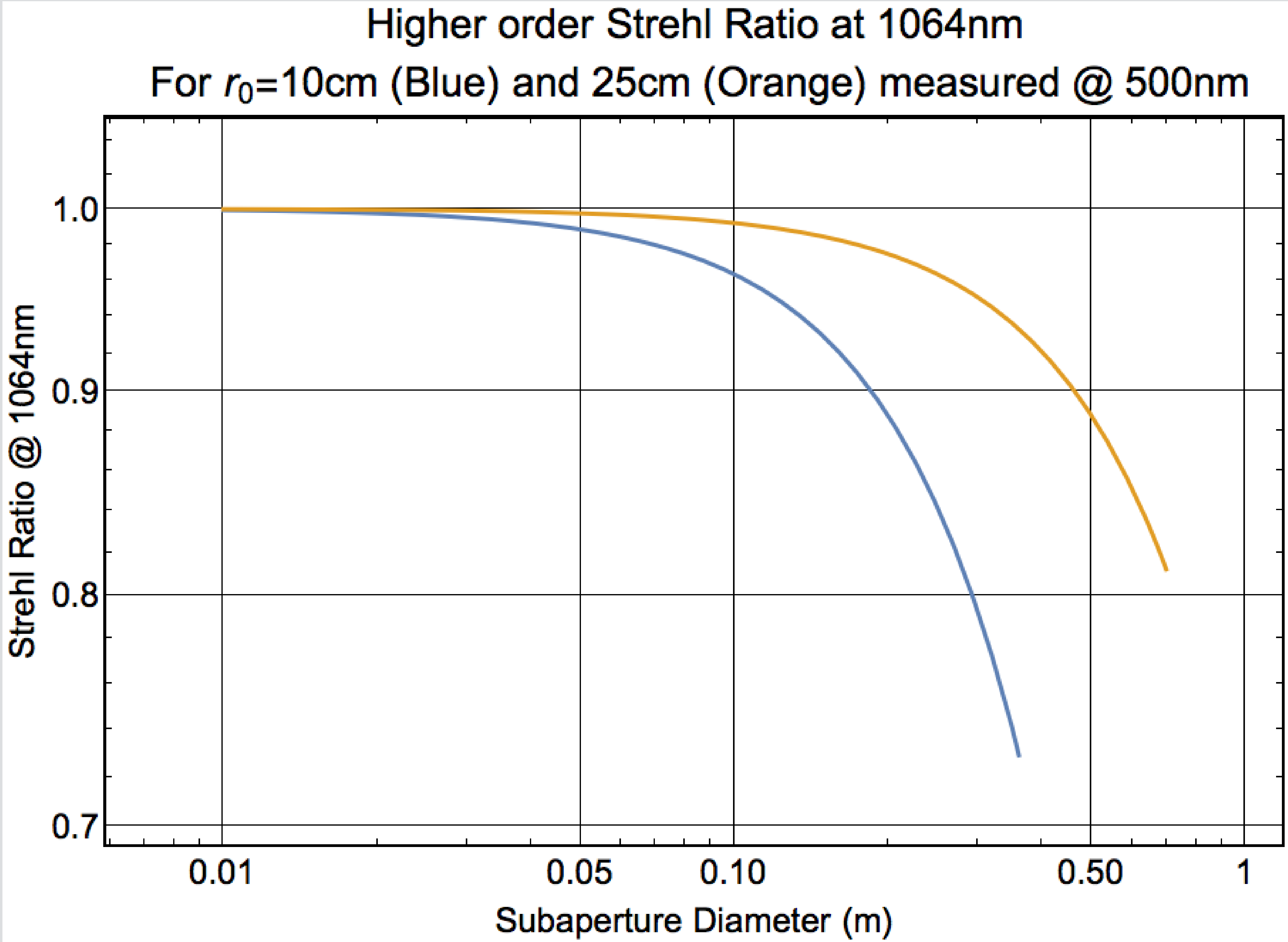


FILLED ARRAY

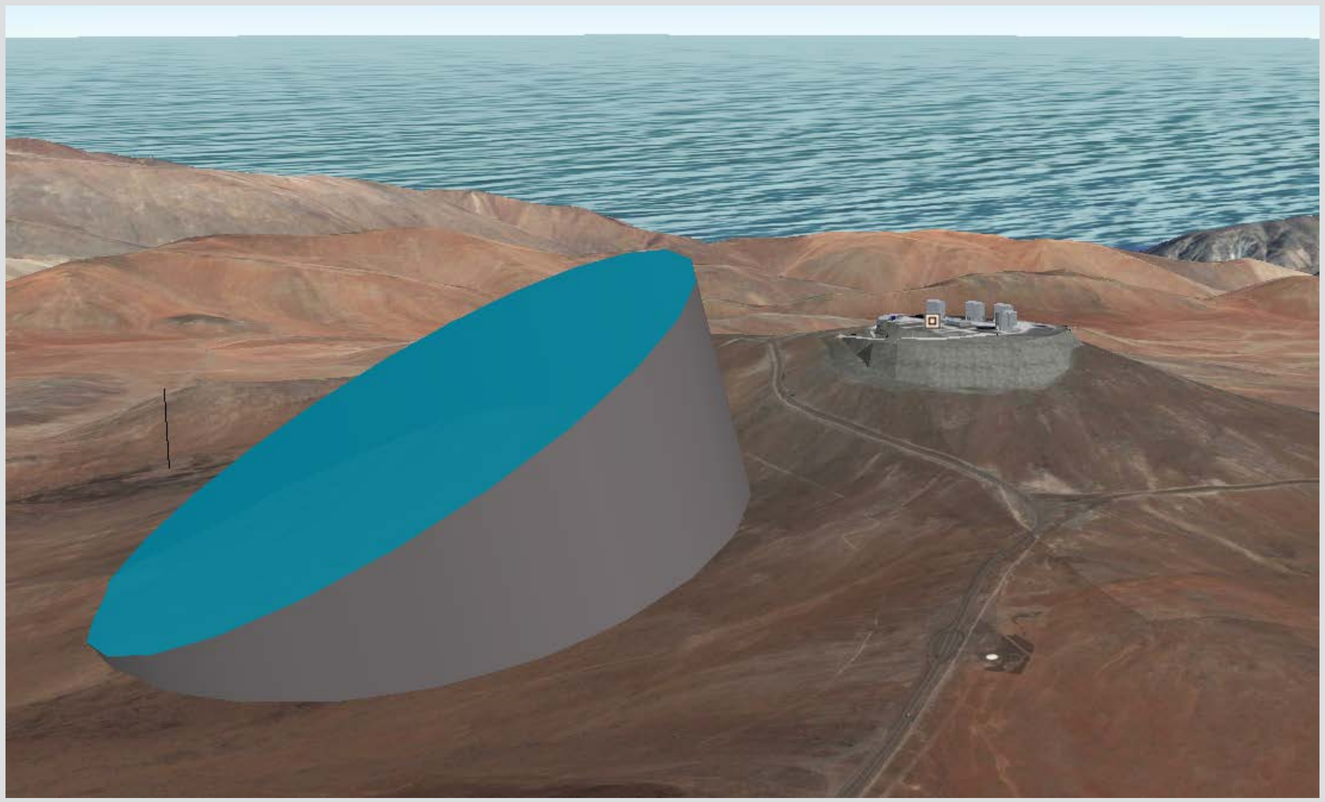


10 cm subapertures

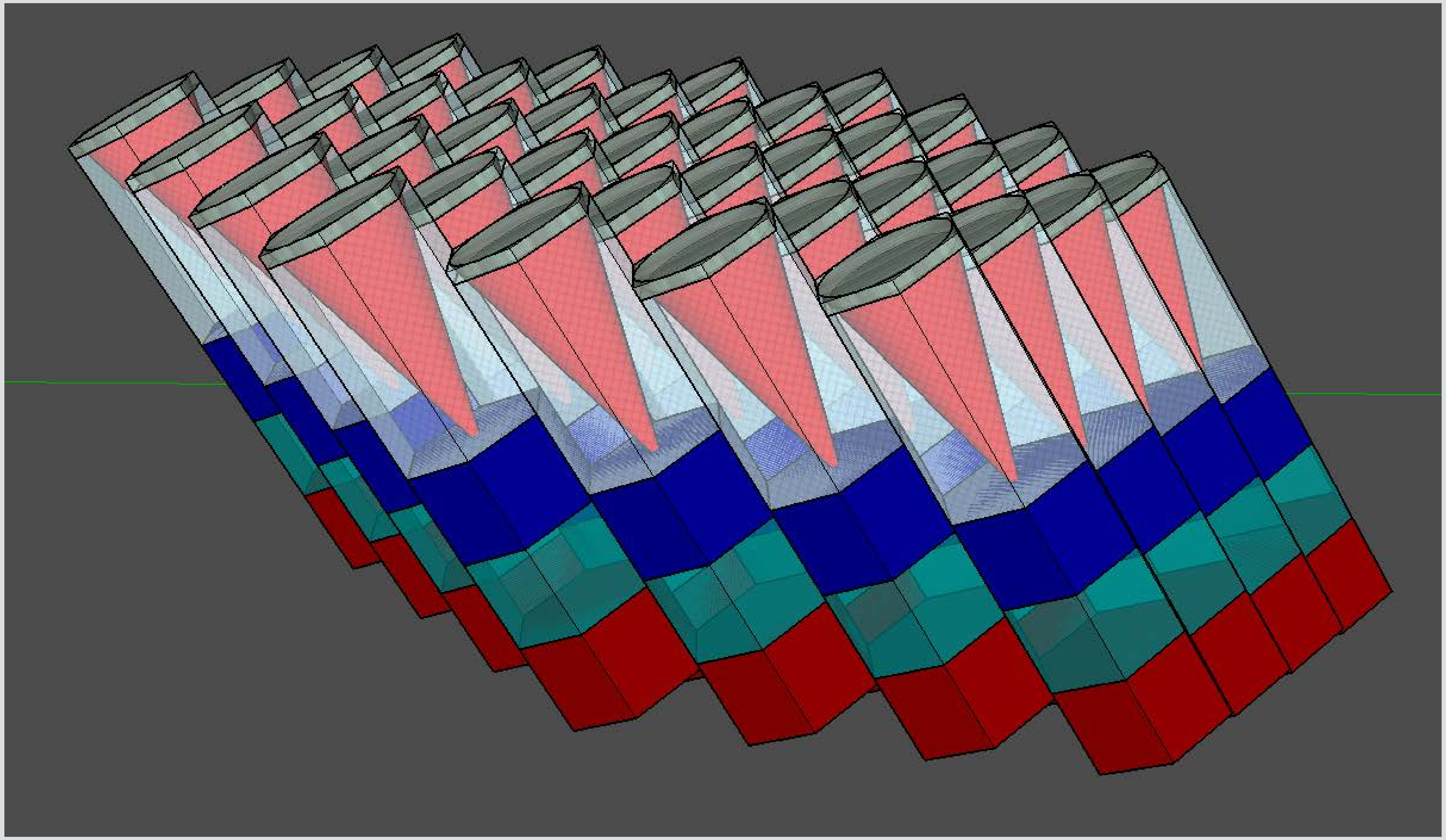
50 cm subapertures


Higher order Strehl Ratio at 1064nm
For r0=10cm (Blue) and 25cm (Orange) measured @ 500nm
Strehl Ratio @ 1064nm
1.0
0.9
0.8
0.7
0.01
0.05
0.10
0.50
1
Subaperture Diameter (m)

Crescent Dunes solar collector 1.25 km diameter

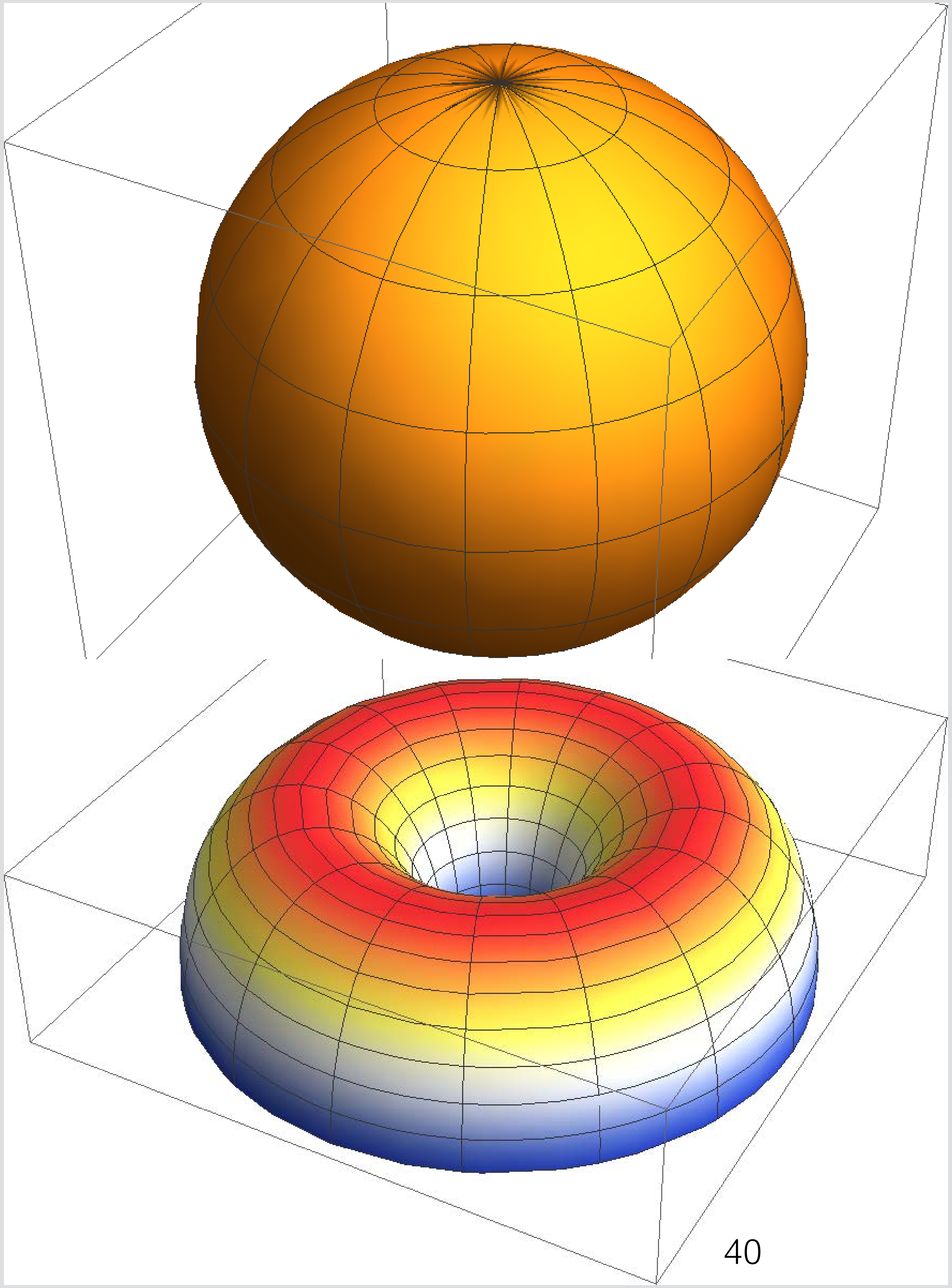


1 km array compared to ESO VLT at Paranal



Stepped array to allow operation at off zenith angles.

Beam Shaping at the Sail is Required



One concept for stable beam riding. The beam profile has a potential well in the middle and the spherical sail rides in this well.

Top Level Photon Engine Requirements (1/3)

- **Total output power: 50-100x10^9 Watts (50-100 Gigawatts), continuous wave**
- **Maximum mission rate: One Nanocraft launch every 24-48 hours (TBR)**
- **Run time: up to several hundred seconds at full power**
- **Nominal wavelength: 1060±20 nm (other wavelengths can be proposed)**
- **Laser output aperture size (required): 1 km**
- **Laser output aperture size (anticipated upper limit): less than 5 km**
- **Location: Earth-based in the southern hemisphere**

Top Level Photon Engine Requirements (2/3)

- **Maximum beam irradiance at the sail: 8 GW/m2 (TBR)**
- **Beam profile on the sail: Gaussian or ring-like symmetry, minimum in the center (TBD by Sail committee)**
- **Beam irradiance profile (required): ±30% (TBR) of the specified profile**
- **Beam irradiance profile (goal): ±10% (TBR) of the specified profile**
- **Total encircled power incident on sail (required): 30% of output power, all ranges**
- **Total encircled power incident on sail (goal): 50% of output power, all ranges**

Top Level Photon Engine Requirements (3/3)

- Laser pointing accuracy wrt fixed stars: ±3.5 microradians (1 au at 4 ly)
- Minimum range for sail illumination: 60,000 km
- Maximum range for sail illumination: as large as a few times the Rayleigh range of the laser system
- Laser system minimum operating elevation: 70 (TBR) degrees
- Laser system maximum operating elevation: 90 degrees
- Laser system azimuth angle operating range: 180 degrees (south)±5 degrees (TBR)
- Final sail velocity uncertainty: ±1.5% (TBR)

PE – Major Technical Challenges

- Finding and optimizing an architecture for coherently combining unlimited numbers of lasers in km sized array
- Developing high-power, long coherence length amplifiers
- Generating required beam profile for stable beam riding
- High aerial fill factor
- Large field of regard
- Sail acquisition, target star tracking, coherent beam jitter, and absolute pointing (point-ahead for proper motion correction)
- Daytime operation

The Phase 1 RFP addresses the first two challenges

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- We will protect all Export Controlled data as marked.
- We have Export Controlled approved Email, servers and storage facilities.
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- Envision a period of exclusive use by the developing contractor then a transfer to free and open use for funded IP.
- All proprietarily or confidential material will be protected as marked

Phase 1 Scope (1 of 2)

- Design a Photon Engine architecture to coherently combining a very large number of Earth-based lasers to meet the technical requirements listed above.
- Describe in detail how a specified beam irradiance profile at the sail and maximum deviation from the desired profile as a function of range will be achieved (e.g. by controlling the phase and amplitude of individual lasers in the array) and describe a sail beam-riding solution to show how the sail can remain stable on the beam for the given beam profile and sail shape.

Phase 1 Scope (2 of 2)

- Recommend a development path for low-cost, high volume manufacturing capabilities for any or all of the elements, including the laser amplifier and cooling, integrated photonics modules, fiber splitters, phase modulators, and lenses used in the conceptual design.

RFP Schedule

- **Final RFP release: 6 October 2017**
- **4 page proposals due: 3 November 2017**
- **Invitation to submit final proposals: 10 November 2017**
- **Finalist will be notified and contracts awarded winter of 2018**

Information for Bidders

- Proposals may include all or part of the requested work
- Multiple awards are anticipated (approximately $150K each)
- Deliverables are a final report documenting concepts, analyses, and simulations, and status and financial reports. No hardware – Phase 1 is a paper study
- Bidding is a two step process
  - Step A 4 pages (evaluation may involve phone discussions and even site visits)
    - Evaluators are Bob Fugate, Wesley Green, Kevin Parkin, Mark Spencer and Pete Klupar
  - Step B by invitation 15 pages - more detail, best and final
    - Other evaluators maybe included in discussions
    - Source Selection Authority Executive Director Breakthrough Starshot Foundation LLC

Information for Bidders

- Evaluation Criteria
  - Demonstrated understanding of the problems
  - Evidence of innovation and creativity
  - Responsiveness to the requirements
  - Relevant past performance and experience, including applicable delivered hardware
  - Documented expertise of bidder’s staff
  - Cost
  - In-kind contributions are encouraged
  - Minimizing Overheads charges is encouraged
- BT reserves the right to make awards to bidders that provide the best value and reject and select any offer for any reason – we do not operate under the FAR.

Longer Term Photon Engine Issues

- **Cost**
- **Site selection (Southern Hemisphere)**
- **Energy production, storage, and discharge**
- **Acquisition, pointing and tracking of mothership, sail, and objective star**
- **Mothership orbit and beacon design**
- **Beam acquisition of sail once dispensed from mothership**
- **Space policy**