News Feature: i4is delivers Communications Study to Breakthrough Starshot

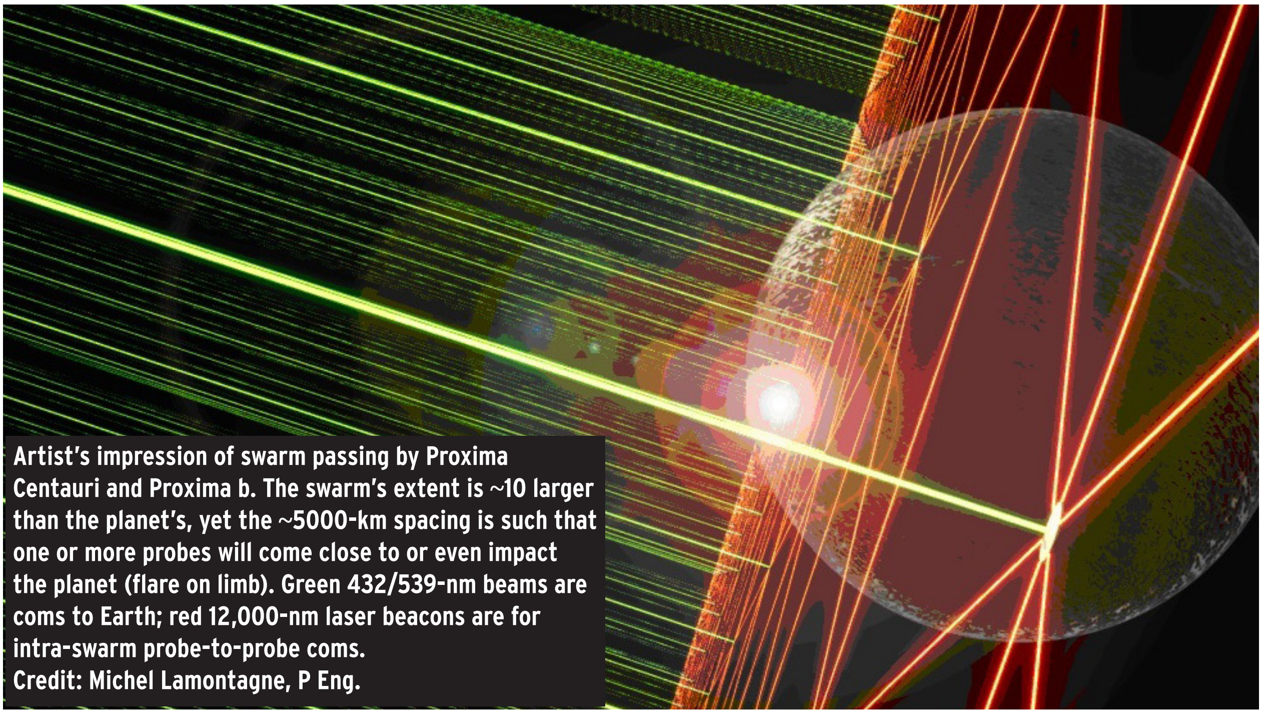
Swarming Proxima Centauri: Optical Communication Over Interstellar Distances

John I Davies and Robert G Kennedy

Pushing an interstellar lasersail with beamed power in order to fly by Earth's closest neighbour Proxima b, four light-years away at near-relativistic speeds is less than half the battle. With such a tiny mass budget – 1 gram payload per probe – the bigger challenge is getting back any data at all [1].

Introduction

On Monday 24 April 2023, after a year of preparation and a year-and-a-half of contracted work, Institute for Interstellar Studies-US delivered its final systems engineering analysis and conceptual design to the Breakthrough Starshot Foundation. Our work, which contains six broad innovations, demonstrates that it is not impossible to get optical data back from a large swarm of gram-scale probes flying by Proxima Centauri b four light-years away at 20% of light speed.



Artist's impression of swarm passing by Proxima Centauri and Proxima b. The swarm's extent is ~10 larger than the planet's, yet the ~5000-km spacing is such that one or more probes will come close to or even impact the planet (flare on limb). Green 432/539-nm beams are coms to Earth; red 12,000-nm laser beacons are for intra-swarm probe-to-probe coms.
Credit: Michel Lamontagne, P Eng.

[1] The challenge is outlined in *The Interstellar Downlink, Principles and Current Work* in Principium 31 November 2020 i4is.org/wp-content/uploads/2021/08/The-Interstellar-Downlink-Principium31-print-2011291231-opt.pdf

The team was composed of:
- T Marshall Eubanks, President, Space Initiatives Inc – Principal Investigator.
- Andreas Hein, PhD, Executive Director, Initiative for Interstellar Studies – Systems Engineering.
- Robert G Kennedy III PE, President, Institute for Interstellar Studies-US – Systems Engineering.
- W Paul Blase PE, Space Initiatives Inc – Systems Engineering.
- Adam Hibberd, Initiative for Interstellar Studies – Trajectory Dynamics.

Credit also to the remarkable Michel Lamontagne, PEng, our French-Canadian artist-engineer.

Background and Remit

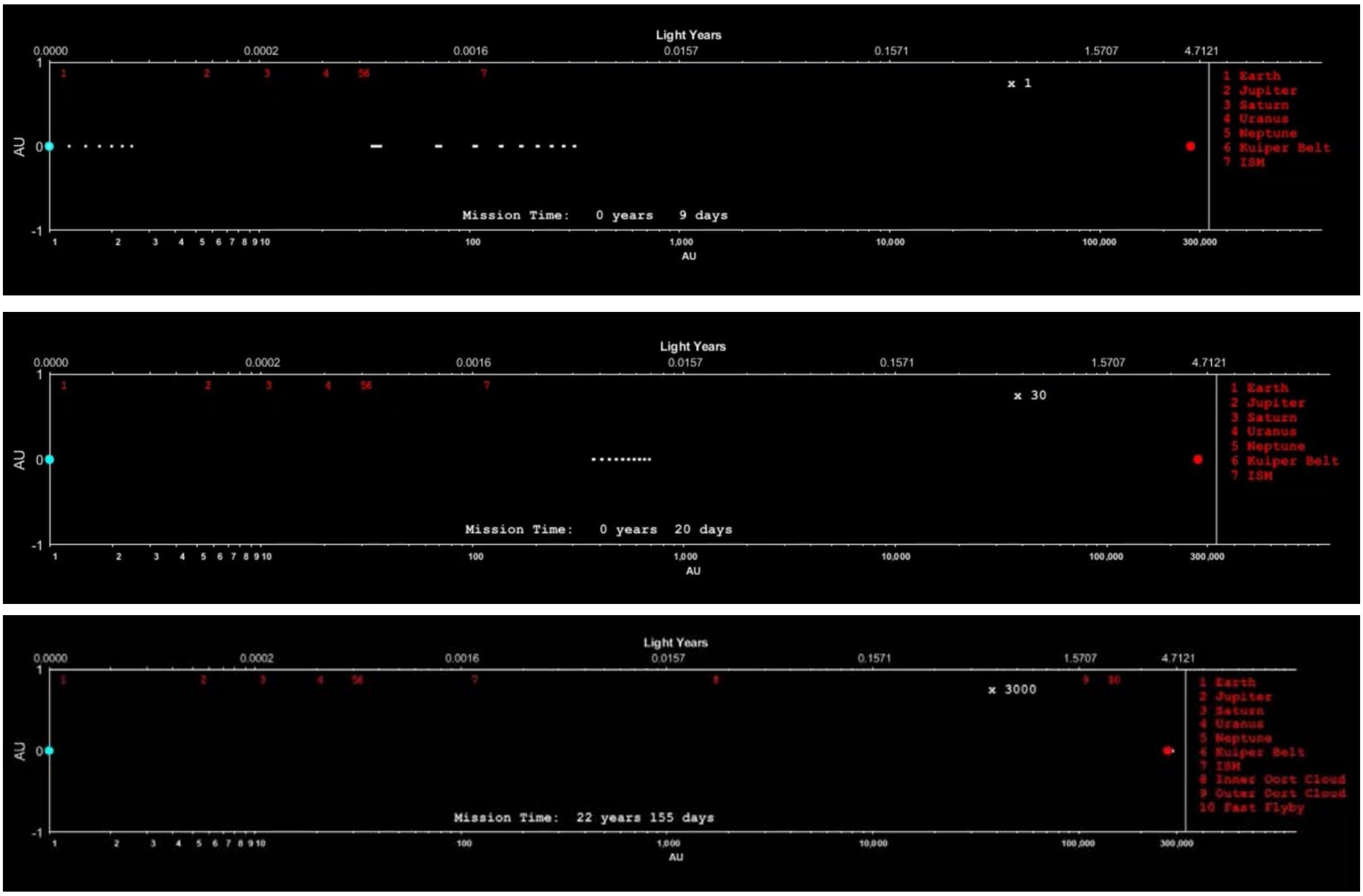
i4is, on both sides of the Atlantic, started preparing for this opportunity from the Breakthrough Starshot (BTS) Foundation in 2017 long before it was awarded to the "American branch", ie Institute for Interstellar Studies-US (I4IS-US). We won this contract in February of 2021 in an open competition with first-rank research institutions world-wide. The contract between I4IS-US and BTS was formally executed by both parties on 21 June 2021. Several dozen other teams, broadly divided into Launch, Power and Communications groups were contracted by BTS as well. Our remit during this "Phase 1" work was to find any "showstoppers" in the communications challenge, an analysis that ultimately necessitated we independently develop a full system concept, still compliant with the basic givens and constraints (one gram payload per probe, 150K data return within one year of encounter), which informed a mass partition and defensible power budget. On 10 March of this year, having satisfied the requirements of the contract, I4IS-US was paid in full by BTS. We continue to participate in periodic technical meetings of the Communication Group, and have established relationships with other teams, to prepare for possible follow-on opportunities.

The Study

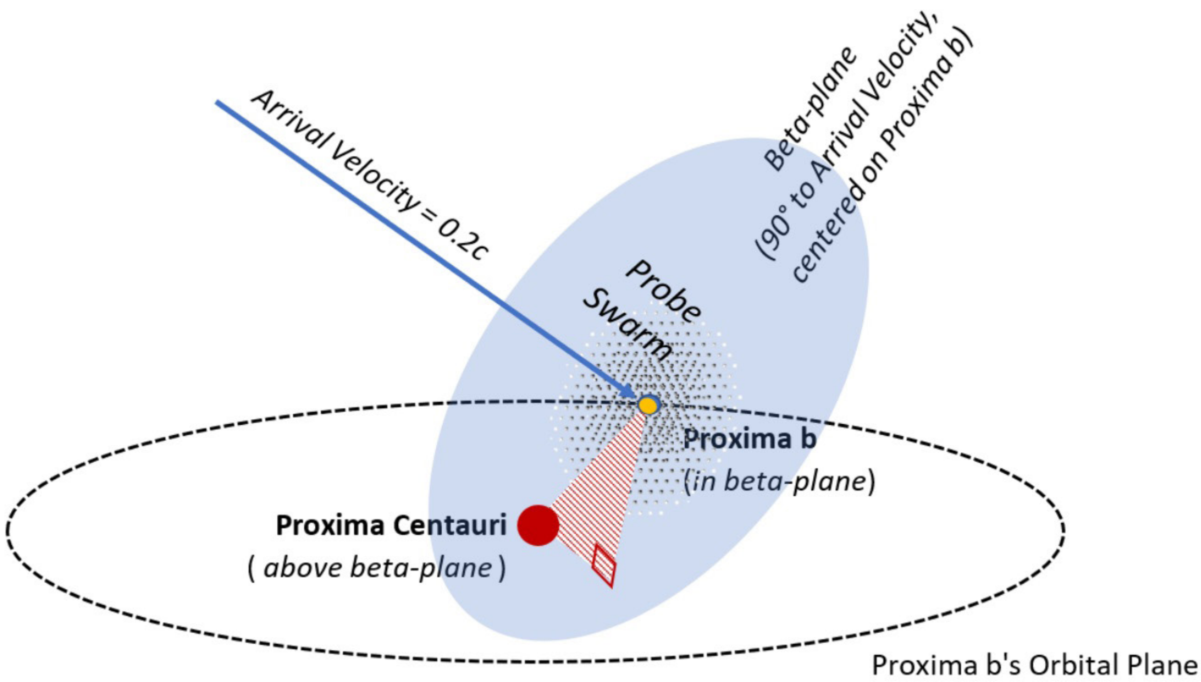
The i4is team concluded that interstellar optical communications are achievable with gram-scale spacecraft using swarm techniques introduced herein if an adequate energy source, clocks and a suitable communications protocol also exist. The team showed that the challenge could be met applying six broad innovations that they developed:

- In the first place, rather than sending a single lasersail, launch a string of 100s–1000s of spacecraft in order to mitigate collision risk during boost and attrition during cruise. Synchronise the probe swarm during flyby to optically transmit a useful number of primary signal photons (~10^{19} per bright short nanosecond "chirp" at Proxima b, a few hundred photons of which could be caught by ~1 km^2 of cheap "light buckets" on Earth) supplemented by digital signal processing (DSP) that is effectively infinite and free. Thus a swarm provides the basis for an optical comlink that easily satisfies the requirement to receive a minimum 100-kilobyte image with a year after encounter.
- Forming up the swarm utilizing the military time-on-target (ToT) technique by grossly modulating the initial velocity of each probe during launch in 2050 such that the tail of the string swarm catches up with the head during cruise resulting in a swarm.
- Autonomously applying a finer "velocity-on-target" (VoT) technique to dump speed during the two decades of cruise by adjusting each probe's attitude with respect to the interstellar medium (ISM) in order to keep the swarm together after it coalesces. Note each disc-shaped probe must fly edge-on most of the way to minimise the extremely high radiation dose (~100 gigarad) induced by travelling through the ISM at 20% of light speed. Even a single neutral hydrogen atom packs a 20-MeV punch at this relative velocity. Full autonomy is necessary because remote control with feedback from Earth will rapidly become impractical due to latency that is continuously increasing at the rate of 4.8 hours of time-lag per day of flight, to an 8-year round-trip delay by the time of flyby.

- Establishing secondary communication within the swarm by infrared (IR) optical means for probes to discover each other and coalesce a mesh network – in effect a distributed "hive mind" – and then use that swarm as a synchronized optical signalling array for data return back to Earth on the primary near-UV channel.
- Applying state-of-the-art microminiaturized space-rated optical clock metrology combined with time- and frequency-bandpass filtering to improve data collection and downlink signal-to-noise ratio. Squeezing a given number of signal photons into a very short transmission window of order nanoseconds wide by synchronizing them greatly increases the brightness of the "chirp" by ~2 orders of magnitude relative to the background noise from Proxima Centauri and the Milky Way as a whole. Assuming continual albeit time-lagged coms with Earth, and extrapolating 80 years of monotonically-increasing progress in the horological art, we can expect that the Swarm will always know exactly what time it is (within ~10s of picoseconds inside the Swarm) and therefore exactly where it is (range within order ~4000 km, about the size of our Moon), even with 4.24 years of time-lag by flyby in 2070.
- Rediscovering an extremely compact long-lasting form of onboard energy storage at nuclear energy density, solid state with no moving parts, namely a betavoltaic cell consisting of the common cheap strontium-90 isotope derived from nuclear waste sandwiched between common photovoltaic material, sufficient to provide ~10 milliwatts of electric power per probe for decades of autonomous operation, timekeeping, computing, and ~1 mW per probe for signalling, ie ~1 watt optical power for the swarmfleet. Such a cheap simple long-lasting nuclear battery could be ready for market within a decade for a modest engineering effort, say low $10s of million. This capability would have profound utility for deep-space exploration missions inside our own solar system.



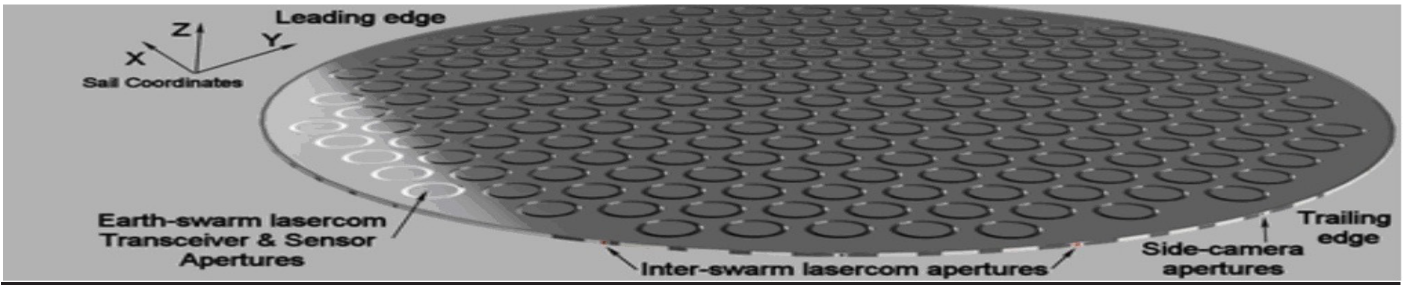
The probes are launched one at a time from Earth and assemble into a cohesive mesh network en route. Note the distance scales (AU and light years) are logarithmic - image based on CG animation at www.youtube.com/watch?v=jMgfVMNxNQs
Credit: Adam Hibberd



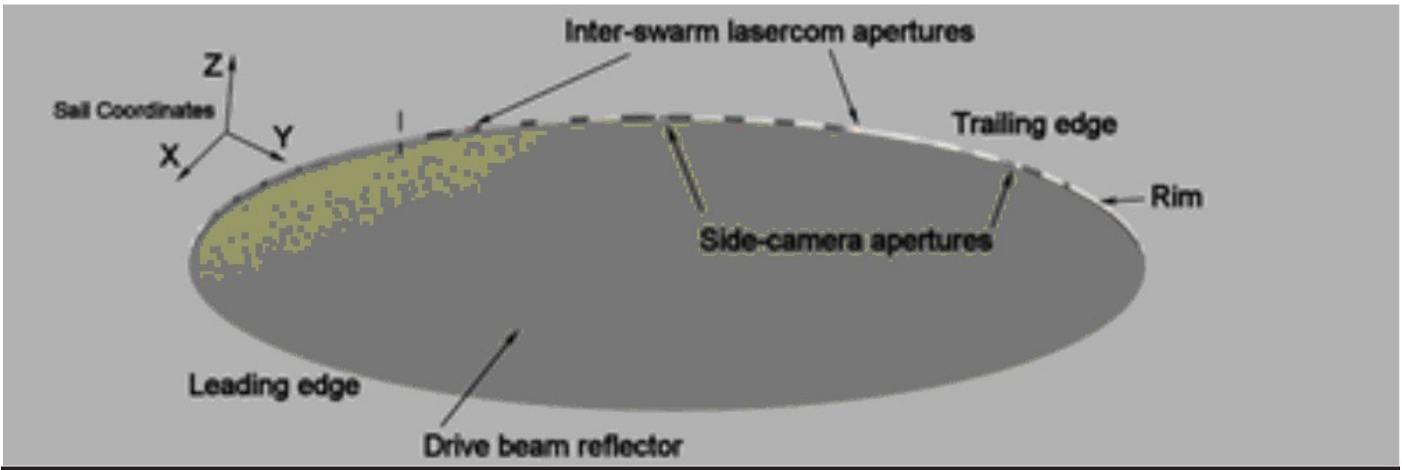
Geometry of swarm's encounter with Proxima b in gibbous phase. Host star Proxima Centauri is in advance of the Encounter Beta-Plane, the orientation of which is not known at this time! Defining Proxima b's ephemeris requires getting to work now! Text relating to the swarm italicized; text relating to objects in the Proxima system bolded.
Credit: Adam Hibberd

The team also conceived and proposed utilizing the 100-gigawatt (GW) beamer on Earth: (a) at lower power during the two-decade cruise for one-way in-flight coms and synchronizing time between the Swarm Fleet and Earth and (b) at full power, also as an "interstellar flashlight" to illuminate the path ahead in real time to identify dark objects and for obstacle avoidance. Upon the Fleet's arrival, the 100-GW beamer on Earth would have more than enough optical power if fired 4.24 years ahead of time to serve as an adjunct external apparatus to support science at the target system, such as transmission spectroscopy, which could not be provided in any other way by instruments limited to a point of view only from Earth.

Under i4is's concept, each 4-m diameter probe would have to be fabricated as single monolithic device based on additive techniques at atomic scale, similar to the wafer-scale-integration that produces 30-cm-diameter supercomputer chips today. For redundancy, resilience, and radiation hardness enroute, a probe has no heart, rather its important bits (isotopic batteries, ultracapacitors, computation, infrared lasers for inter-probe/intra-swarm coms, conductive paths for same) are distributed around the thickened "armoured" 2-cm rim, resembling a red blood cell. Inside the rim the central disk consists of a thin membrane of aerographene – a high-strength extremely-low-density meta-material, about the same density as helium gas at STP (!) sculpted to atomic precision in order to eliminate mascons during the 100,000-g launch – composing a phase-coherent array of flat optics roughly similar to a compound Fresnel lens (247 individual 25-cm diameter optical wells pictured), for both imaging the target and transmitting the data and picture(s) back to Earth. Although we assess by launch in 2050 that space-rated clocks will not be quite small/reliable enough to make the entire 100,000-km diameter swarm phase-coherent during flyby in 2070, the arrays on each individual 4-m diameter probe would be phase-coherent, which greatly increases pointing and signal:noise ratio.



Oblique view of the top/forward of a probe (side facing away from the launch laser) depicting array of phase-coherent apertures for sending data back to Earth, and optical transceivers in the rim for communication with each other.
Credit: (image and caption) W Paul Blase



Oblique view of bottom / aft of a probe (side facing the launch laser) depicting dielectric boost layer and and optical transceivers in the rim.
Credit: (image and caption) W Paul Blase

Conclusion

Our results contained in this 30-page work are enough to inform at least three separate professional papers in this field.
Please stay tuned to the pages of this magazine.