The downlink from swarming micro-probes

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Of the two probably feasible means of reaching interstellar distances, tiny laser propelled sailcraft and multi-thousand ton fusion rocket propelled vehicles, the former look the most promising in the next few decades. The downlink transmission of information from either is challenging, given the distances involved but tiny sailcraft present the larger challenge. Earlier pieces in Principium have examined the problem; here we look more closely at the class of solutions which exploit the fact that these sailcraft, can be very numerous since they are individually relatively inexpensive and thus may operate in swarms.

This article is prompted by work in progress by an i4is team. Principium will summarise this work in a later issue. Peter Milne commented most usefully on a draft version. Any errors remain with the author.

Introduction

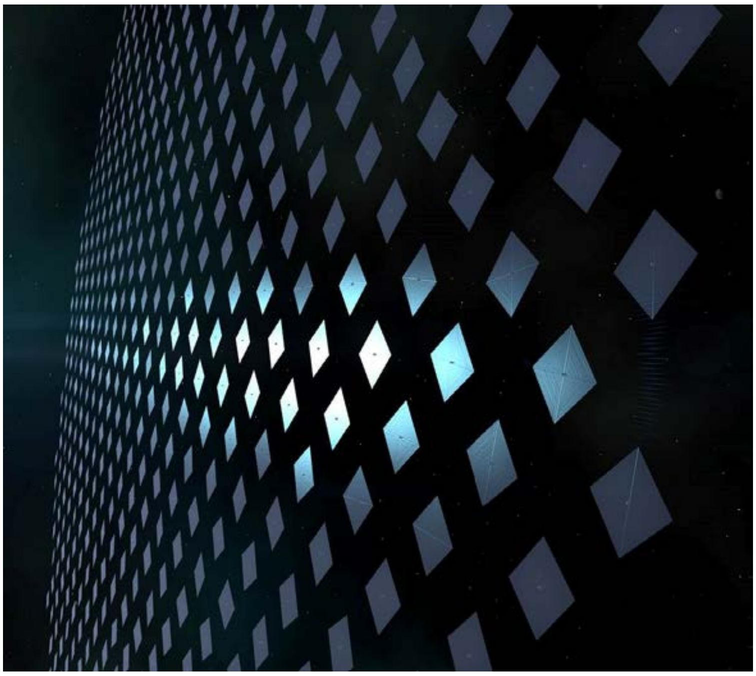
The scale economies made possible by the relatively low cost of tiny sailcraft relative to the very large cost of the multi-Gigawatt laser beamer used to propel them naturally lead to the idea of co-operation between large numbers of probes heading for a single target system. There are at least two ways of exploiting this - a relaying chain of probes reducing the transmit power required by each probe and a swarm of more or less simultaneously arriving probes forming a co-operating array of transmitters. This article will survey both of these, with the emphasis on the swarm approach.

Launching the swarm

The base scenario envisaged by Breakthrough Starshot is a single very large laser array propelling a succession of probes. The economics of this can be (over!) simplified in a linear equation of the form y=ax+b. Specifically -

Total cost = (cost per probe+energy cost per launch)*(number of probes)+(build cost of the laser array) abbreviated to Ct=Cp*Np+Bc.

Since the fixed build cost of the laser array is very large and the expected cost per probe is relatively tiny the number of probes to be launched by a single array is expected to be very large. Like most engineering economics there are complications, the most prominent of which is the energy cost per launch. For the baseline scenario of acceleration to 0.2c and thus about 20 years to Alpha Centauri the re-usable ground-based components are estimated at 8 billion USD and the energy cost per shot is 6 million USD [1].


Sailcraft swarm as envisaged by Adrian Mann (bisbos.com/)

We can assume that, with thousands of tiny sailcraft, costs per sailcraft are likely to be tiny by comparison. If we keep this down to, say, the cost of a current top range smartphone this would be 1,000 USD plus 6 million USD energy cost. If we assume a "fleet" of 10,000 of these then, again very crudely, Ct=Cp*Np+Bc becomes Ct=(1,000+6,000,000)*10,000+8,000,000=60 billion + 8 billion. Even allowing for a factor of 10 underestimate of probe cost it therefore seems likely that hard engineering experience - that things wear out eventually - would mean that replacement or repair of the heavily-used ground-based components will become an important factor.

In short, swarms are cheap - and if you can reduce the energy cost per shot then it may become trivial!

[1] *The Breakthrough Starshot system model*, Kevin L G Parkin, Acta Astronautica V152, Nov 2018 open access parkinresearch.com/wp-content/uploads/2018/07/starshotmodel.pdf

The Bucket Brigade - relaying probes

A paper published last year (2020), *Relaying Swarms of Low-Mass Interstellar Probes* [1] examined the idea of relaying the results from very small probes via a chain of similar probes to overcome the challenge of the inverse square law operating over light years. This was suggested in a proposal by i4is to NASA NIAC [2]. More about this in an earlier issue of Principium, P31[3], reporting from a Starshot workshop with major contributions from the i4is team [4].

The Light Brigade - Swarming at AlphaC

Principium readers are likely to be familiar with co-operation between astronomical telescopes to achieve results which surpass what can be achieved by any single instrument. This is now possible with both optical and radio telescopes and examples range from the UK MERLIN system (www.e-merlin.ac.uk) and worldwide co-operations to single site systems of "antenna farms" such as the Atacama Large Millimeter/submillimeter Array (ALMA) currently in operation [5] or the Square Kilometre Array (SKA) being built at two sites - in Australia and South Africa (www.skatelescope.org).

These are receivers but can this work for transmitters? One obvious example is the use of phased arrays for radar. This is a mature technology developed for military use since the 1950s.

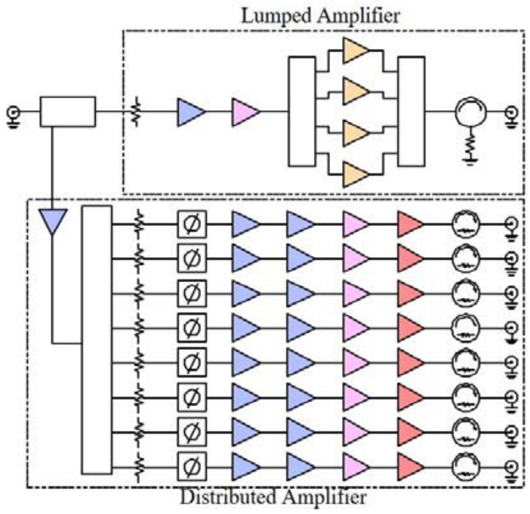


Figure 6. SSPA RF Section

An early example a multiple antenna downlink

Solid State Power Amplifiers (SSPAs) driving multiple transmit antennas in the MESSENGER spacecraft to Mercury [8]

Credit: Robert E Wallis, Sheng Cheng,

The scale economies of laser propulsion, massive expensive laser arrays but tiny and comparatively cheap probes, mean that a large fleet of probes can be propelled by a single laser array. Each probe has very limited capabilities and it is therefore interesting to consider how they might co-operate.

Given the challenges of the downlink this leads to two possible approaches –

- Relaying between probes – each receiving a signal from an earlier probe and transmitting it to a later probe in a “bucket brigade” fashion to overcome the effects of the inverse square law, see *The Douglas Adams Problem squared!* in P31 [6].
- Organise probes as a swarm of widely-separated small spacecraft to behave as a single distributed entity to increase the total transmitted power and narrow the beam transmitted so that more of the signal may be received, see *A Starshot Communication Downlink* in P31 [7].

The recent i4is work addresses the second of these.

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[1] *Relaying Swarms of Low-Mass Interstellar Probes*, David Messerschmitt (UC Berkeley), Philip Lubin (UC Santa Barbara) and Ian Morrison (Curtin University, Australia), July 2020, arxiv.org/abs/2007.11554

[2] Reported in the section *Robert Kennedy's observations on Group 8 - Accommodating and exploiting multiple probes* in the Principium article *News Feature: Breakthrough Starshot Communications Workshop* - May 2020 Principium 31 November 2020 page 70

[3] *News Feature: Breakthrough Starshot Communications Workshop - May 2020 Summary and i4is contributions*, Principium 31 November 2020 page 70 - see i4is.org/wp-content/uploads/2021/08/News-Feature-Breakthrough-Starshot-comms-workshop-Principium31-print-2011291231-opt.pdf.

[4] *Starshot Communications Workshop report from Interconnect focus group*, Jacobs, Hein, Swinney, Kennedy (private communication)

[5] *ALMA uses interferometry to combine signals* www.almaobservatory.org/en/about-alma/how-alma-works/.

[6] *The Interstellar Downlink - Principles and Current Work, 2.1 The Douglas Adams Problem squared!* Principium 31 page 28 and i4is.org/wp-content/uploads/2021/08/The-Interstellar-Downlink-Principium31-print-2011291231-opt.pdf.

[7] *The Interstellar Downlink - Principles and Current Work, 4.2 A Starshot Communication Downlink* citing a paper of that title by Kevin L G Parkin, May 2020, see link in previous reference

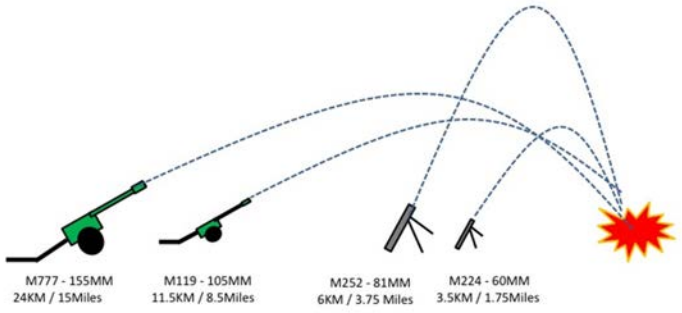
[8] *Phased-Array Antenna System for the MESSENGER Deep Space Mission*, R E Wallis and Sheng Cheng, "Phased-array antenna system for the MESSENGER deep space mission," 2001 IEEE Aerospace Conference Proceedings 2001, pp. 1/41-1/49 vol.1, Open access messenger.jhuapl.edu/Resources/Publications/Wallis_Cheng.2001.pdf

Where multiple transmitters are sending the same information then receivers, whether single or multiple, need to be able to add the signals together to have the best chance of reconstructing the information which has been transmitted. The most prevalent modern example is in distributed mobile networks such as in the 3G, 4G and 5G standards which serve the billions of mobile phones worldwide. These most recent standards provide for multiple base stations to serve any one mobile. Clearly the received signals will not be in step since they have travelled over different distances (and in typical terrestrial settings there will also be reflected signals, sometimes even stronger than the direct signal) [1]. The classic example of this, as seen by a user, is "ghosting" in early television services.

The limitations of very small probes propelled by a very large laser bank suggest that co-operation between them is an idea worth exploring. There are two major challenges in achieving this - bringing a large number of probes together to co-operate at the target star and organising the co-operation between them so that their transmission add together at the receiver.

Assembling the swarm

In order to assemble a swarm at the target star the members of the swarm need to be launched in quick succession or their speeds must vary so they arrive together. The time between launches is referred to as the launch cadence. There is a clear military analogy here, "time on target" to concentrate artillery fire from separate sources on a single target at an agreed time [2].



Time on target - showing simultaneous arrival of multiple projectiles at same aiming point..

Credit: adapted from MS302, ROTC Department of Military Science, St John's University - sjumilitaryscience.weebly.com/

Recall that the Starshot benchmark speed is 0.2c or about 60,000 km/second so with a single laser array and an acceleration time of 9 minutes (see Parkin, *The Breakthrough Starshot system model*, cited above) the inter-probe distance would be 9*60*60,000=32.4 million kilometres. That's more than 84 times the distance to the Moon, 384 thousand km. There are three main ways to achieve simultaneous arrival -

- Change the transmitted beam power so that earlier probes receive slightly less acceleration and thus later probes catch up and all arrive together.
- Increase sail size or reflectivity for later probes so that these probes receive slightly more acceleration.
- Decelerate probes as the target stars are reached - slowing earlier probes more than later probes. Deceleration also allows more time for observation.

More about this in a news item *Slow Down!* in P32, February 2021 page 21 and one way of doing this in an earlier issue*"Slow down!": How to park an interstellar rocket* by Tishtrya Mehta in P21, May 2018 page 3.

To get the signal back from all of the swarm their transmissions need to add together - this is called phase coherence.

For the Earth-based beamer proposed in the benchmark Starshot model there are additional constraints -

- Target probe visibility to the beamer on a rotating Earth
- Availability of power for the beamer in the required amounts at the required times including the effects of pricing in a regional or possibly even global energy grid

The former problem disappears for a space based beamer and the latter may be reduced substantially since solar radiation is an "always on" power source. Here there is a possible conflict with the possibility of space-based power generation for terrestrial use. This would produce scale economies and drive innovation but might then make power for our beamer compete with more obviously economically attractive commercial use of the same or similar technology.

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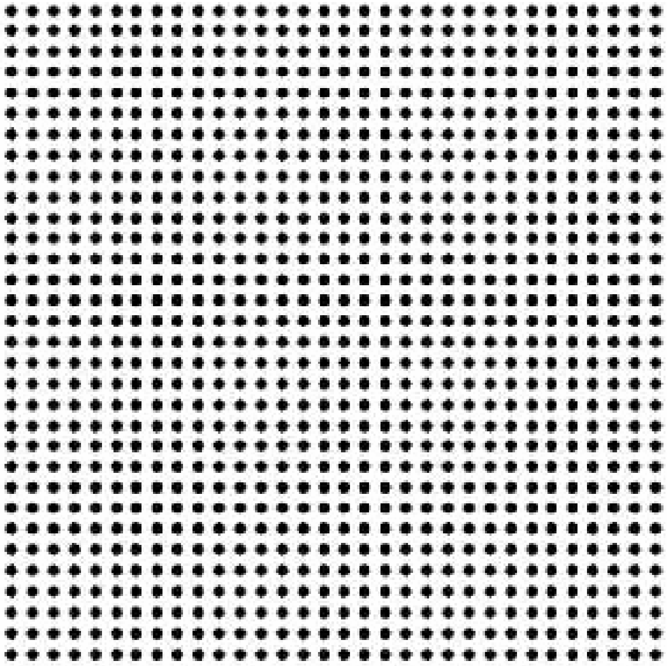
[1] Capacity Bounds and Power Allocation for Wireless Relay Channels, Høst-Madsen & Zhang, 2004, IEEE Transactions on Information Theory. Volume: 51, Issue: 6, June 2005, open access: citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.68.6975&rep=rep1&type=pdf

[2] Early uses of this artillery technique relied on a BBC time signal en.wikipedia.org/wiki/Time_On_Target

Co-operating transmissions

To achieve phase coherence transmitting probes need to synchronise their transmissions. To quote our interstellar colleague, T Marshall Eubanks, "There are few things in this world as useful as a good clock..." [1]. To enable a swarm of widely-separated very small spacecraft to behave as a single distributed entity seems to require advances in optical clocks, quantum metrology, mode-locked optical lasers, and network protocols. If we can get 1000 such micro-probes to transmit "in sync" as a single distributed entity possibly based on a master clock signal from an earth or space-based transmitter then we may have a very effective downlink strategy without requiring the massive fusion driven spacecraft of the "Heavy Brigade".



A 1024 square array, 32*32.

Credit: Wang & Pinheiro, Structural and Spectral Properties of Deterministic Aperiodic Optical Structures - Crystals, December 2016 www.researchgate.net/publication/311550549_Structural_and_Spectral_Properties_of_Deterministic_Aperiodic_Optical_Structures

A sufficiently large swarm might also support an uplink able to carry more than a synchronising signal. Control is clearly infeasible with a feedback loop over a roundtrip delay of at least 8 years but software changes are a useful possibility.

More exotic means of communication such as quantum entanglement may even abolish some or all of the problems of interstellar communication but it also offers some more immediately feasible benefits in improving clock synchronisation[2].

For both swarm and "bucket brigade" inter-probe communications links will be required. For the swarm each probe needs to be capable of communicating with at least two other probes and maintaining pointing to them for the duration of downlink communications, in addition to transmitting towards Earth.

Conclusion

There is a Yorkshire saying "Many a mickle makes a muckle" also said in Scotland and attributed to US President George Washington, Laser propelled interstellar spacecraft have a distinct disadvantage over their heavyweight fusion rocket powered cousins but human ingenuity always looks at what may be achievable with the means most immediately at hand and this is such an instance. Fusion propulsion may allow us to build probes which can provide very substantial research results in a single vehicle and may even propel worldships but they are many decades and perhaps centuries away. Thousands of tiny sailcraft can achieve much in the nearer term - and have advantages of resilience and scalability. We look forward to hearing from them and the public impact of that first close-up picture of an exoplanet can only be imagined.

The major difficulty is the energy cost per launch. If the beamer is competing with current electricity costs on Earth then it may be a "show stopper". If space-based power is available then the situation may be reversed since power generated in space is most easily used there.

[1] Harrison's chronometer made determination of latitude feasible back in 1730 en.wikipedia.org/wiki/John_Harrison.

[2] A Quantum Network of Clocks, P Kómár et al, Nature Physics, 15 June 2014, DOI: 10.1038/NPHYS300 jila.colorado.edu/sites/default/files/2019-07/ClockQuantumNetwork_NatPhys2014.pdf.