The Interstellar Downlink

Principles and Current Work

John I Davies

Inevitably the problem of reaching the universe beyond the solar system has been dominated by the propulsion challenges inherent in distances measured in light-years. However sending a probe to the stars is essentially pointless from the human point of view unless that probe can communicate its findings to us. This is the problem of the Interstellar Downlink.

Recent work supported by Breakthrough Starshot and others has begun to advance this technology. In May this year several i4is technical team members were invited to contribute to a workshop organised by Breakthrough Initiatives as part of its Starshot programme. The workshop addressed this major challenge for any interstellar probe - communication with Earth - and specifically the downlink, from the probe to Earth.

Here John Davies introduces the problem and reviews the current status of the subject. See elsewhere in this issue for a report by Robert Kennedy on the i4is contribution to the Breakthrough Starshot Communications Workshop

1 Introduction

This article will introduce the fundamentals of Interstellar Communication, especially the distance and the inverse square law - "The Douglas Adams Problem squared!" It will introduce some Communications Basics, how communications engineers analyse their problems, and early work including the BIS Daedalus project and internet pioneer Vint Cerf's work on an interplanetary internet.

And finally current work, summarising some founding papers by the Breakthrough Starshot team.

2 Basics of Interstellar Communication

2.1 The Douglas Adams Problem squared!

The root of the problem of Interstellar Communication is distance. All known communications technologies rely on electromagnetic transmission. Short of stringing telephone wires from here to Alpha Centauri, electromagnetic transmission is subject to the inverse square law and four light years is a lot of metres to be squared!

The order of magnitude of the loss of signal power this implies are best illustrated by some familiar examples -

- Distance to your local mobile base station: The base technology for wide area mobile communications is GSM and the original maximum distance assumed between your mobile and your serving base station was 35 km (en.wikipedia.org/wiki/GSM#Base-station_subsystem).
- Distance to a LEO communications satellite: The Iridium system uses satellites in medium Earth orbit at about 800 km altitude (en.wikipedia.org/wiki/Iridium_satellite_constellation#Overview).
- Distance from Pluto for the New Horizons probe: Pluto is about 40 astronomical units from Earth (www.nasa.gov/audience/forstudents/5-8/features/nasa-knows/what-is-pluto-58.html). Since the Earth-Sun distance is about 150 million km that's 150*40 = 6,000 million km.
- Distance to Alpha Centauri system: Perhaps the number best known to all interested in matters interstellar - about 4 light years.

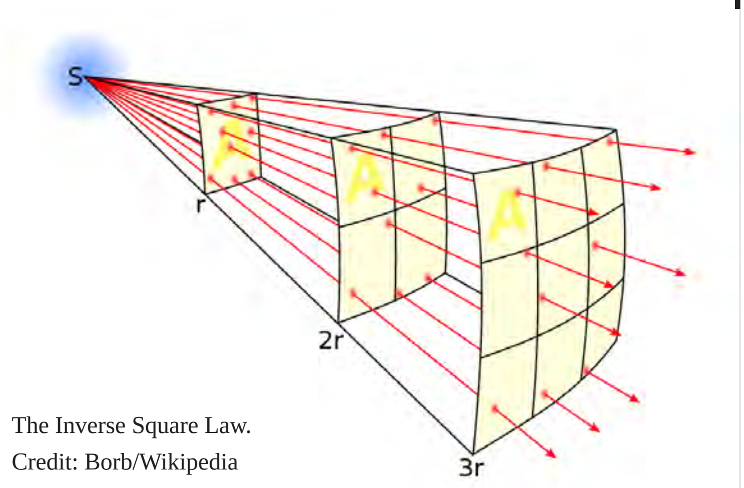
Light speed is about 300 million (300,000,000) metres per second and there are about 32 million (32,000,000) seconds ($=3.2*10^7$) in a year so 4 light years is about 4*300*32 million million metres or 40 thousand million million metres. Written out that's 40,000,000,000,000,000 metres. In handier floating point form that's $4*10^{16}$ metres.

The Inverse Square Law

How does the inverse square law work?

Think about the Sun. It's a sphere, roughly speaking. What is the surface area of a sphere? It's $4\pi r^2$ so the surface area is proportional to the square of the radius. Now think about where you are sitting, basking in the Sun I hope! All the light emitted from the Sun's surface (at radius about 430,000 miles or 700,000 kilometres) has to pass through a sphere of radius one astronomical unit (AU) where you are sitting. That's a much bigger sphere than the Sun.

So how much less frazzled are you going to be than if you were at the Sun's surface? It's the same amount of radiation spread, pretty evenly, over that larger sphere. That's an area of $4\pi r^2$ where the r is the astronomical unit, 93 million miles or 150 million kilometres. So it's going to be weaker in proportion to the square of the difference in radius. The same applies to your signal from Alpha Centauri. Your antenna allows you to concentrate your signal beam in the right direction but once the radiation is on its way it diverges just like the light from the Sun.



The Inverse Square Law.
Credit: Borb/Wikipedia

The very approximate numbers above give you the scale. As the great English humorist said "Space is big. Really big. You just won't believe how vastly hugely mind-bogglingly big it is. I mean, you may think it's a long way down the road to the post office, but that's just peanuts to space."* If he was still around and engaged with matters interstellar - as I am sure he would be - he might also remark that your signal is very handicapped. Your paraplegic mate Dave is Superman by comparison; Your signal takes four times the effort to go twice as far as him and a hundred times the effort to go only ten times as far.

Looking at the distances in metres using our trusty spreadsheet we find -

Downlink from -	**Distance (approx)**	**Unit**	**Conversion factor to metres**	**Distance in metres**
Terrestrial Mobile (GSM)	35	km	1,000	35,000
sci	4.E+01	km	1.E+03	4.E+04
LEO (Iridium satellite)	800	km	1,000	800,000
sci	8.E+02	km	1.E+03	8.E+05
Pluto (New Horizons probe)	40	AU	149,597,870,700	5,983,914,828,000
sci	4.E+01	AU	1.E+11	6.E+12
Alpha Centauri	4	ly	9,460,730,472,580,800	37,842,921,890,323,200
sci	4.E+00	ly	9.E+15	4.E+16

The rows labelled **sci** are the same numbers in scientific notation, spreadsheet style - and, looking at that 17 digit number for the distance in metres to Alpha Cent. you can see why engineers and scientists prefer that exponent notation.

*Douglas Adams, The Hitchikers Guide to the Galaxy en.wikipedia.org/wiki/The_Hitchhiker's_Guide_to_the_Galaxy

My infallible (I hope) spreadsheet also tells me -

Downlink from -	**Distance (approx)**	**Unit**	**Conversion factor to metres**	**Distance in metres**	**Order of magnitude (distance in metres squared)**	**Ratio* of signal to Terrestrial Mobile (GSM)**	**Ratio* of signal to LEO (Iridium satellite)**	**Ratio* of signal to Pluto (New Horizons probe)**	**Ratio* of signal to Alpha Centauri**
Terrestrial Mobile (GSM)	35	km	1,000	35,000	1,225,000,000	1	0	3.42E-17	8.55E-25
sci	4.E+01	km	1.E+03	4.E+04	1.E+09	1.E+00	2.E-03	3.E-17	9.E-25
LEO (Iridium satellite)	800	km	1,000	800,000	640,000,000,000	522	1	0.000000000000018	4.469E-22
sci	8.E+02	km	1.E+03	8.E+05	6.E+11	5.E+02	1.E+00	2.E-14	4.E-22
Pluto (New Horizons probe)	40	AU	149,597,870,700	5,983,914,828,000	35,807,236,668,758,300,000,000,000	29,230,397,280,619,000	55,948,807,294,935	1.00	0.0000000250
sci	4.E+01	AU	1.E+11	6.E+12	4.E+25	3.E+16	6.E+13	1.E+00	3.E-08
Alpha Centauri	4	ly	9,460,730,472,580,800	37,842,921,890,323,200	1,432,086,737,197,100,000,000,000,000,000	1,169,050,397,711,920,000,000,000	2,237,635,526,870,470,000,000	39,994,338	1.00
sci	4.E+00	ly	9.E+15	4.E+16	1.E+33	1.E+24	2.E+21	4.E+07	1.E+00

* the ratios are multipliers eg the signal from Alpha Centauri is 39,994,338 times weaker than from Pluto.

Again the rows labelled **sci** are the same numbers in scientific notation, spreadsheet style

Distance to your local mobile base station: The base technology for wide area mobile communications is GSM and the original maximum distance assumed between your mobile and your serving base station was 35 km (en.wikipedia.org/wiki/GSM#Base-station_subsystem).

35 km = $3.5 * 10^4$ metres.

Squared this is $12.25 * 10^8$ or $1.225 * 10^9$

Order of magnitude = 10^9

Distance to a LEO communications satellite: The Iridium system uses satellites in medium Earth orbit at about 800 km altitude (en.wikipedia.org/wiki/Iridium_satellite_constellation#Overview).

800 km = $8*10^5$ metres.

Squared this is $64*10^{10}$ or $6.4*10^{11}$

Order of magnitude = 10^{11} - the signal is 10^3 weaker - or 1000 times weaker than for your terrestrial mobile phone

Distance to Pluto for the New Horizons probe: Pluto is about 40 astronomical units from Earth (www.nasa.gov/audience/forstudents/5-8/features/nasa-knows/what-is-pluto-58.html). Since the Earth-Sun distance is about 150 million km that's 150*40 =

6000 million km or $6*10^9$ km.

Squared this is $36*10^{18}$ or $3.6*10^{19}$

Order of magnitude = 10^{19}- the signal is -

$10^{(19-11)} = 10^8$

- or 100 million times weaker than the Iridium signal and

$10^{(19-9)} = 10^{10}$

- or 10 billion times weaker than for your terrestrial mobile phone

Distance to Alpha Centauri system: Perhaps the number best known to all interested in matters interstellar - about 4 light years.

Light speed is about 300,000 km/sec and there are about 32 million seconds ($=3.2*10^7$) in a year so

4 light years is about $4*3.2*^7$ km or $12.8*10^{10}$ metres.

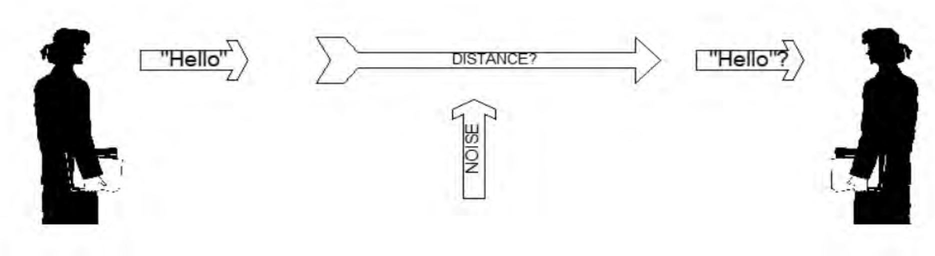
Squared this is about $164*10^{20}$ or $1.64*10^{22}$

Order of magnitude = 10^{22} is $10^{(22-19)} = 10^3$

- or one thousand times weaker than for Pluto

2.2 The Communications Basics

Any communication can only take place if the sender and the receiver understand one another and their means of communication works. If you don't speak my language or you speak too quietly in the circumstances then I will not understand you. Communications engineers characterise this as a "link budget". Here's a crude example of Alice on the left speaking to Jane on the right.



Am I loud enough? Are you near enough? Is the room quiet enough? Is your hearing OK? Do you speak English?

The received signal (which we hope is "Hello") is the sum of an equation - Received signal = transmitted signal (which really **is** "Hello"!) * clarity of speech * distance loss * noise loss * misunderstanding.

In the real world all those multiplying factors are less than one so what arrives is less than what is sent.

In the same way your satellite TV reception depends upon -

- Quality of signal - especially extra information to correct errors
- Satellite transmit power
- Satellite transmit dish size
- Distance to your receiving dish - mainly as input to the inverse square law, which is simple geometry as in the 2.1 *Douglas Adams Problem squared* above.
- Noise - which can be artificial (another satellite perhaps) or natural (from the Sun, the rest of the universe and even the famous cosmic microwave background)
- Your receiver dish size
- Sensitivity of your receiver electronics
- Ability of your receiver to correct errors

The same sort of calculation applies to the signals to and from your mobile phone, how well your wifi works and even how well your old fashioned medium wave "steam radio" works.

Communications engineers adopt an accountancy term for this calculation - they discuss "link budgets".

2.3 Link Budget

Now the link budget for a distant probe such as New Horizons out at Pluto is a calculation with some very small multipliers in it. Communications engineers use a logarithmic measure in link budgets, decibels (dB), so link budget can use addition and subtraction rather than multiplication. These are logarithms to base 10, as in those "log tables" the older ones amongst us had to use in school.

Decibels are tenths of a bel so imagine a decimal point in any value of dB you see. The distance loss from Voyager is around 308 dB, so that's 10 to the power 30.8, $10^{30.8}$ which means that the transmitted signal power is reduced by about 6,300,000,000,000,000,000,000,000,000,000 times between the Voyagers and Earth. This may not be too much of a problem for the big transmitters and dishes on earth (the uplink) but getting information from a Voyager (the downlink) is a considerable challenge.

Now consider a probe at Alpha Centauri, four light years away rather than the 15-20 light hours of the Voyagers. And recall that the inverse square law applies so a difference of distance 4*365*24 hours versus 15 hours 35,040/15 = 2336 means a loss of 2336 squared = 5,456,896. So the signal from Alpha Centauri is 5 million times weaker than from the Kuiper Belt where the Voyagers are.

Again, it all depends upon the size of your hardware. The Daedalus probe specifies a 450 ton payload and the later Icarus Firefly study aims for a 150 ton payload and a small nuclear reactor. The downlink challenge is much more severe for the gram scale probes envisaged by Breakthrough Starshot or even the kilogram scale probe envisaged the i4is Andromeda study*.

* The Andromeda Study: A Femto-Spacecraft Mission to Alpha Centauri, Hein et al 2017, https://arxiv.org/abs/1708.03556

2.4 "Say again?"

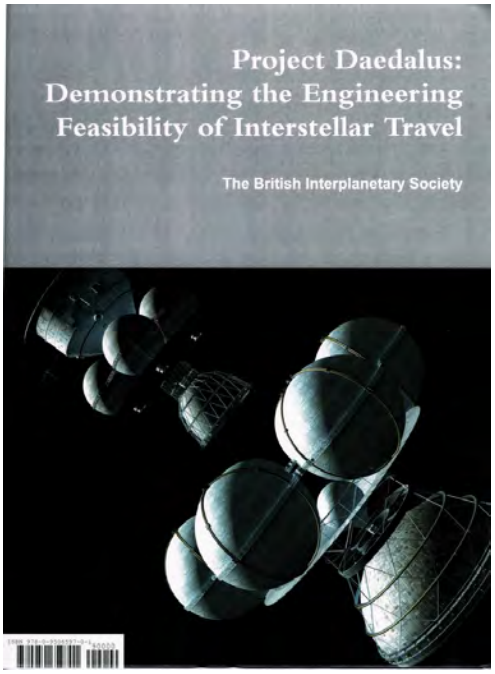
In both military and amateur radio communications there is a standard response when you can't understand what the other person has just said. The phrase is "Say again" - asking the speaker to repeat what they just said. In data communications protocols there are equivalent mechanisms called ARQ, Automatic Repeat reQuest. But users of mobile telephones don't expect to have to do this - or at least not often! So the protocols for this include mechanisms described as Forward Error Correction (FEC).

The interstellar downlink cannot tolerate "Say again" or ARQ. The delay would be the entire roundtrip, at least 8 years, and probe would need a very sensitive receiver to hear the "Say again".

FEC has limitations set by Claude Shannon's noisy-channel coding theorem (en.wikipedia.org/wiki/Noisy-channel_coding_theorem) and the proportion of errors which can be corrected depends upon how many additional data bits are added to the transmission to provide the correcting information. Mobile phone protocols protect against errors in digitised speech as part of the analogue/digital conversion process by defining codecs (coder/decoder - see www.etsi.org/technologies/codecs for examples). The Breakthrough Starshot studies are investigating FEC - as you will find in the final section of this article- 4 *Current Work* below.

3 Earlier Work

3.1 Daedalus



As in almost all things related to interstellar probes let's refer first to the relevant paper published as part of the BIS Daedalus study in the 1970s, *Project Daedalus: the vehicle communications system* in the *Project Daedalus Final Report* (PDFR)*. For an introduction to the whole Daedalus study see *Project Daedalus –A Beginners' Guide*, Patrick J Mahon, in Principium | Issue 24 | February 2019, page 30.

The Daedalus communications paper was written by Tony Lawton and Penny Wright, both of EMI Electronics. The paper deals with two principal communication requirements, the downlink from the main vehicle to earth and the link between the main vehicle and 18 sub-probes to be deployed on approaching the target star system. Recall that Daedalus is a "flyby" mission at 12% of the speed of light and transit time through the system is short. This means that the observation challenges have similarities to those for the Breakthrough Starshot study, which envisages a flyby at 20% of light speed. There are major differences in the flyby. Daedalus would be a single probe with a 450 ton payload (including the 18 sub-probes) using the electronic technology known in the mid 1970s while Starshot would be a very much large number of gram scale probes using the technology of the 2030s or later.

The Daedalus downlink during and after the encounter would be microwave transmission at 11.4 cm or 2.6 GHz, "A radio link is far more efficient than a laser system for long distance communication due to the much lower background photon noise" (Lawton/Wright, PDFR page s145). But laser signalling is envisaged for boost phase telemetry when radio frequency interference (RFI) from the fusion drive would be a problem and for the links between sub-probes and the main vehicle during the encounter phase. The radio frequency power would be one MW (PDFR page s166, table 6) using the second stage fusion reaction chamber as a dish antenna to deliver at downlink data rate of 864 kbps over an RF bandwidth of 432 kHz using "bi-tonal frequency shift keying" or binary frequency shift keying (FSK) mentioning that this "is superior to a simple pulsed system in terms of signal to noise ratio. This is because there is a continuous carrier wave for the receiving system to detect and lock onto." Contrast the techniques suggested by the Starshot researchers in section 4 *Current Work* below.

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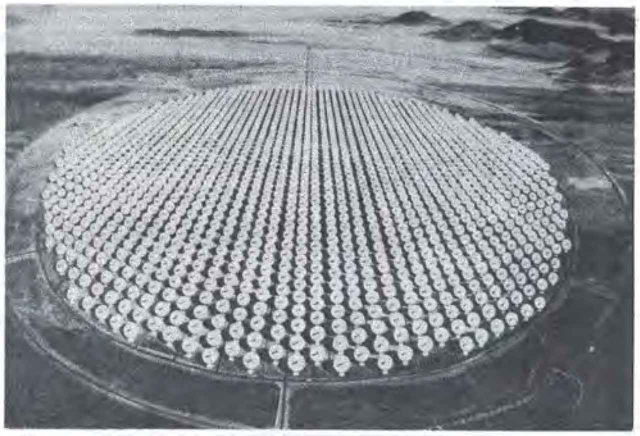
* Lawton, A T and P P Wright. "Project Daedalus: the vehicle communications system." JBIS 31 (1978): S163-S171. This and all the Daedalus papers are collected in the BIS book. Project Daedalus: Demonstrating the Engineering Feasibility of Interstellar Travel, www.bis-space.com/eshop/products-page-3/merchandise/books/project-daedalus-demonstrating-the-engineering-feasibility-of-interstellar-travel/

The technology available at the time led to the choice of High Powered Klystrons (HPK). Klystrons were an invention of the radar engineers of the second world war and are still in use for applications demanding higher power levels than available from semiconductors (for example the Cloudsat radar - earth.esa.int/web/eoportal/satellite-missions/c-missions/cloudsat - uses an Extended Interaction Klystron (EIK)). Again the contrast with the Starshot downlink transmitter is clear and a natural consequence of the relative scale of the probes as well as the 45 year technology gap.

The receiving end is labelled the Solar System Receiving Station (SSRS). This could be Earth or space based and built during the coast phase of several decades. The paper does not specify a size but quotes the Project Cyclops study which proposed a "bogey system of 3.16 km clear aperture".*


Artist's impression of the complete antennae array proposed for the Project Cyclops Study (NASA).

Antennae array proposed for the Project Cyclops Study (NASA) from the JBIS paper.

Credit: Lawton/Wright/NASA

3.2 Cerf's interplanetary internet

If present thinking in interstellar studies leads to a near-term launch of chipsat-scale probes within a few decades then the vision of Internet veteran Vinton G Cerf of a mature interplanetary internet** is unlikely to have been achieved by that time.

But delay-tolerant protocols developed to help fulfil that vision have already been defined and used. The Bundle Protocol Specification is an Internet Engineering Task Force Experimental Protocol, RFC 5050 (tools.ietf.org/html/rfc5050) which has already been the basis for some implementations.

RFC 5050 includes a timestamp measuring seconds from the year 2000 and is a Self-Delimiting Numeric Value - meaning that it can be arbitrary long (lesson learned from the original 32 bit IP address and the major software engineering effort required to overcome it!). There are 32 megaseconds in a year so 25 bits required and 32 bits is therefore enough to specify 128 years. An interstellar internet would be a strange beast but we should not rule it out in the long term.

Vint Cerf addressing the Royal Institution London, 9 March 2020. Credit: RIGB

* Page 74 of *Project Cyclops: A design study of a system for detecting extraterrestrial intelligent life*, NASA/Stanford 1971

See also *Project Cyclops: The Greatest Radio Telescope Never Built*, Robert Dixon - in - *Searching for Extraterrestrial Intelligence: SETI Past, Present, and Future*, Springer, 2011.

** *The Interplanetary Internet: A Communications Infrastructure for Mars Exploration*, 53rd International Astronautical Congress 2002 https://trs.jpl.nasa.gov/bitstream/handle/2014/9399/02-1611.pdf

See also - *Google's Chief Internet Evangelist on Creating the Interplanetary Internet*, Wired 2013 - www.wired.com/2013/05/vint-cerf-interplanetary-internet/.

4 Current Work

A useful starting place in understanding the thinking of the Breakthrough Starshot team is their published papers. This section includes references to them, a brief analysis of the implications of each and a discussion of them including some comments on the possible advantages of a space based infrastructure. It is by no means a thorough analysis of the work. The papers themselves are available as open publications and are largely comprehensible even by your reporter, who has not worked in this field professionally for almost 50 years!

4.1 The Breakthrough Starshot System Model

The Breakthrough Starshot System Model, Kevin L G Parkin, Acta Astronautica, Volume 152, 18 pages. November 2018, open publication - arxiv.org/abs/1805.01306

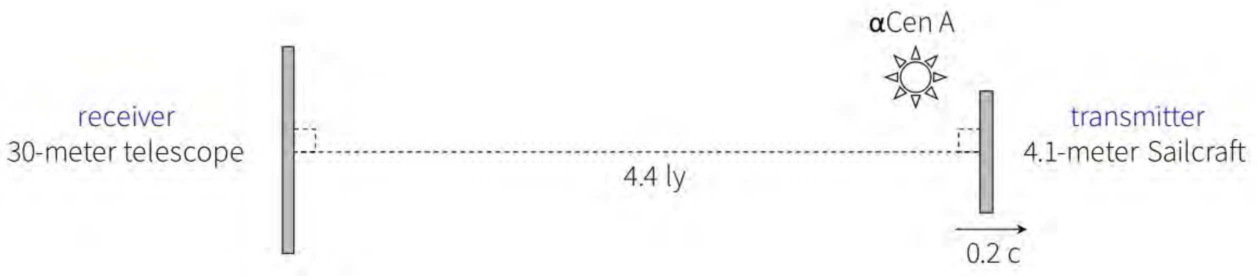
Part of the Starshot systems engineering work, Parkin's paper presents a system model and describes how it computes cost-optimal point designs including interstellar mission, a precursor to the outer solar system and a ground based test facility. The results for the interstellar case show costs of \$0.01/W lasers, \$500/m^2 optics, and \$50/kWh energy storage resulting in an \$8 billion capital cost for the ground-based beam source but a challenging \$6 million energy cost to accelerate each sail. However it also shows that Starshot could scale to achieve double the planned 20% c at an extra cost of \$29 billion and ultimately 90% of light speed - given a beamer the size of Greater London! Parkin looks in detail at the robustness of the systems engineering conclusions.

This system model thinking sets the scene for the detail work on downlink communications. There are three papers focussed on this so far and a further one looking at methods of relaying the downlink through a number of probes which will be the subject of a later Principium article.

4.2 A Starshot Communication Downlink

A Starshot Communication Downlink, Kevin L G Parkin, May 2020, arxiv.org/abs/2005.08940 (6 pages)

In this paper Parkin derives a raw data rate of 260 bits per second assuming a 1.02 μm wavelength 100 Watt laser using 4.1 m diameter "antenna" on the probe received at 1.25 μm by a 30-meter telescope on Earth. The telescope would receive 288 signal photons per second.



Arrangement of the transmitter relative to the receiver for data downlink following transit of αCentauri A. Credit (image and caption): Parkin

For comparison the New Horizons probe data rate from Pluto was about 1,000 bits per second. (pluto.jhuapl.edu/Mission/Spacecraft.php).

Parkin uses a link budget (as explained in section 2.3 *Link Budget* above) - Parkin's table cells **bold** -

<table>
<tr><th>Link Budget item</th><th>In dB terms</th><th>Equivalent to -</th></tr>
<tr><td>Transmitter input power (Pᴛ)</td><td>+50 dBm 100 W at 1.02 µm</td><td>100 W</td></tr>
<tr><td colspan="3">A dBm is a decibel milliwatt, as explained in 2.3 above. Imagine a decimal point, one to the left, in any value of dB you see, so 50 dBm in milliwatts is $10^{5.0}$ milliwatts which is 100,000 milliwatts or 100 watts - about the same as an old-fashioned incandescent light bulb.</td></tr>
<tr><td>Transmitter gain (Gᴛ)</td><td>+140 dBi 4.1 m diameter circular primary, 70% aperture efficiency</td><td>100,000 billion</td></tr>
<tr><td colspan="3">dBi is the ratio of gain of an antenna compared to one which radiates equal power in all directions, so the 4.1 m antenna on the probe concentrates the signal in the required direction, back to the Solar System, so that the laser light appears to be $10^{14.0}$ times brighter.</td></tr>
<tr><td>Receiver gain G<subscript R</td><td>+156 dBi 30 m diameter circular primary, 70% aperture efficiency</td><td>400,000 billion</td></tr>
<tr><td colspan="3">Again dBi is the ratio of gain of an antenna. In this case compared to one which receives from all directions equally. So the 30 m antenna concentrates the signal from the direction of Alpha Cent so that the light received appears $10^{15.6}$ times brighter.</td></tr>
<tr><td>Path loss</td><td>-476 dB free-space path loss over 4.367 ly, 80% atmospheric transmittance, 3 dB link margin</td><td>About 10 followed by 46 zeros - too big to fit!</td></tr>
<tr><td colspan="3">Path loss is conventional losses, including path loss, atmospheric transmission losses and link margin, but not relativistic loss.
Note how the inverse square law loss over 4 light years makes the rest of the losses look trivial!</td></tr>
<tr><td>Relativistic loss L_β</td><td>-3.5 dB transmitter recedes from receiver at 0.2 c; Doppler effect, headlight effect</td><td>about 2.</td></tr>
<tr><td colspan="3">The probe is travelling at 20% of light speed, c. The effect is small $10^{0.35}$ is about 2</td></tr>
<tr><td>Received signal power, S</td><td>-133 dBm 288 photons/second at 1.25 µm</td><td>1/20,000,000,000,000 of a milliwatt</td></tr>
<tr><td colspan="3">Again dBm is decibel milliwatts. -133 dBm is $10^{-13.3}$ milliwatts. In more practical terms the signal from New Horizons, out beyond Pluto, is -220 dBm ($10^{-22.0}$ milliwatts) at the NASA Deep Space Network dishes in Goldstone (California), Madrid and Canberra (Australia). But the signal from Alpha Cent would be at a much shorter wavelength, 1.25 µm infrared light, than the microwave signal from New Horizons.</td></tr>
</table>

Parkin uses numbers derived in his System Model paper (see 4.3 above). The transmit antenna aperture is set by using the laser sail. The sail diameter is 4.1 m - minimising capital expenditure on the Earth-based "beamer" (200 GW laser array). Based on this the assumption is that "cruising at 0.2c, the interstellar medium manifests as a 0.7 kW monoenergetic hydrogen beam" (see Parkin's System model paper, section 7. *Conclusions*, as referenced in 4.3 above). So the "battering" that all probes travelling at these high speeds is used as a power source and his earlier paper asks "A key question for future research is, what fraction of this power can be harvested?". His communication paper assumes 100 W will be available at the transmitter, which is 14% of the 700 W raw energy from the ISM "beam", which looks like a reasonable round figure starting point at this early stage of thinking. The major factors degrading the signal on its long journey are noise, including radiation from the Earth's sky, from the dust disc around Alpha Cent and light scatter within the receiving telescope. Radiation from Alpha Cent itself could be minimised by use of a coronagraph (en.wikipedia.org/wiki/Coronagraph).

Parkin concludes that since each Starshot sailcraft is generating 8-50 Gbit per year this is "more than enough to look for signs of life by imaging planets and gathering other scientific data". With a flyby rate of one sailcraft per week "the cumulative pipeline of data will be vast indeed". Finally he suggests briefly that a mesh network of cooperating sailcraft would allow later craft to be re-targeted to objects of interest, given sufficient cross-range capability*.

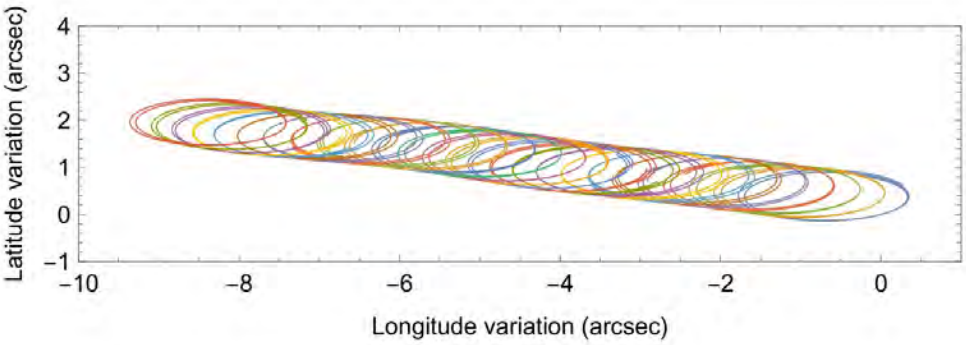
4.3 Technological Challenges in Low-mass Interstellar Probe Communication

Messerschmitt D G, Lubin P and Morrison I, *Technological Challenges in Low-mass Interstellar Probe Communication*, accepted by the Journal of the British Interplanetary Society, June 2020, arxiv.org/abs/2001.09987 (10 pages).

In this paper Messerschmitt, Lubin and Morrison examine the effect of swarm of probes, contrasting single probe performance. In this context, swarming does not imply cooperative or additive effects but is simply the effect of the large number of probes implied by the scale economics of the Starshot proposal. The single probe case is not intended for implementation. The scale economies offered by the relatively low cost of each sailcraft make this attractive - though the beam power cost "per shot" quoted in Parkin's System Model reduces this advantage (see 4.1 *The Breakthrough Starshot System Model* above - and 4.5 *Observations* below). Some of the assumed parameters, such as the transmit antenna aperture, differ from those in the Parkin paper above but this is foundation work - and engineers may not even agree with themselves in this sort of early scenario study!

Much of the paper is concerned with the difficulties arising from receiving signals from multiple probes - as illustrated by the diagram from the paper - Longitude variation (arcsec) versus Latitude variation (arcsec).

Longitude variation versus Latitude variation - relative effects of Earth motion and target star motion on reception of transmissions



Relative angle of probe trajectories as seen from a terrestrial receiver. Shown in different colors are the trajectories over 2.12 years of downlink operation for each of 26 probes launched at 30 day intervals. The oval shape for each probe's trajectory is due to the parallax effect as the probe as viewed from different locations on the earth's orbit. The general drift in the trajectories is due to the proper motion of the target star Proxima Centauri, which requires the launch angle of the probes to change so as to track the target.

Credit (image and caption): Messerschmitt et al

The effect of the motion of the Earth around the Sun in each year produces about two elliptical shapes in roughly two years of receiving data from each probe. The motion of the target star Proxima Centauri has a larger effect and is secular, meaning it does not repeat, and is the result of the different trajectories of the star and our Solar System through the galaxy. Messerschmitt et al suggest that the optimum transmit time would be 10% of the transit time to Proxima Centauri. It takes 20 years at 0.2c to transit 4 light years. Launching probes 30 days apart with each transmitting for 2.1 years means that 26 of them of them will be transmitting at any one time (2.1*365/30= about 26).

In addition to the single versus swarm comparison Messerschmitt et al consider a number of difficulties to be encountered in receiving the very weak signals arriving on Earth. Among these are -

- Impracticability of receiving during terrestrial daylight due to atmospheric scattering of sunlight - the blue sky!
- "Dark counts" caused by thermal and quantum events in both receiving "antennas" (since this is optical these will likely be mirrors).

Data storage and Transmission Rate implications

The time to cross the Proxima Centauri system would be much less than 2.1 years. Taking the example of the Solar System and delay of signals from New Horizons at Pluto of about 5 hours that's 5/0.2=25 hours for a Starshot probe from Pluto to Earth. Taking this as a rough order of magnitude means that about 25 hours of real-time data would be transmitted over about 2 years.

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* A quick calculation based on 1 astronomical unit being about 8 light-minutes shows that the sailcraft would transit the Earth-Sun distance, one astronomical unit (AU), in 8/0.2=40 minutes and that in one day (24*60=1,440 minutes) the sailcraft would travel 1,440/40=36 AU about the distance to Pluto. So a week would leave successive sailcraft about 3.5 solar system diameters apart.

- Practical issues concerned with gathering incoming to a very large number of receivers.
- Very high data reliability requirement - the paper suggests no more than one error in 1-10 megabits with 83% of transmitted data being redundant information providing error-correction coding (ECC).

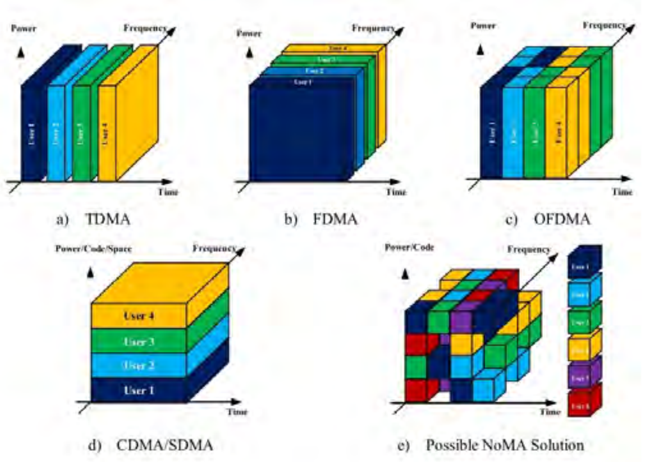
One issue which is raised but left largely for future study is the inevitable multiplexing of simultaneous signals from multiple probes - 26 of them at any one time in the example scenario above. The study identifies four possible approaches "separation of signals by angle, by frequency, by time, or by code". Respectively, these are

- space-division multiple access (SDMA)
- frequency-division multiple access (FDMA)
- time-division multiple access (TDMA)
- code-division multiple access (CDMA)

All are used in mobile telecommunications systems but your mobile phone has an easy job by comparison with a Starshot sailcraft at Alpha Centauri!

In the Conclusions the authors say "There are a considerable number of obstacles to achieving the downlink objectives with a focus on a large multiple probe swarm. We have outlined the most troublesome ones identified to date, suggesting considerable need and opportunity for R&D efforts directed at overcoming these obstacles. Readers with relevant expertise are encouraged to tackle these challenges."

There is a lot of engineering talent in commercial areas such as satellite communications and mobile telecommunications. The interstellar downlink could benefit greatly from their attention.



Illustrative example of different multiple access schemes - from *Toward the Standardization of Non-Orthogonal Multiple Access for Next Generation Wireless Networks*, Chen et al, IEEE Communications Magazine • February 2018, (www.researchgate.net/profile/Xiaolin_Hou4/publication/323141497_Toward_the_Standardization_of_Non-Orthogonal_Multiple_Access_for_Next_Generation_Wireless_Networks/links/5c947420a6fdccd460312299/Toward-the-Standardization-of-Non-Orthogonal-Multiple-Access-for-Next-Generation-Wireless-Networks.pdf) Credit: Chen et al / IEEE

4.4 Challenges in Scientific Data Communication from Low-Mass Interstellar Probes

Messerschmitt D G, Lubin P and Morrison I, *Challenges in Scientific Data Communication from Low-Mass Interstellar Probes*, accepted by The Astrophysical Journal, Jan 2018 - May 2020, arxiv.org/abs/1801.07778 (arxiv 43 pages), published in The Astrophysical Journal Supplement Series, Volume 249, Number 2, August 2020, (ApJS 39 pages). The arxiv version differs significantly from the definitive ApJS version but it is available as an open publication and has the merit of verbose rather than terse references.

This is an earlier and much more detailed paper by the same authors as discussed in 4.3 *Technological Challenges* above. Nevertheless these are early days in the design process and the authors emphasise this in 1.1. *Goals*, "The goal of this paper is not to propose a concrete and fully specified design for such a communication downlink, as there are too many uncertainties, interactions between launch and downlink communication, and questions about the technologies that may be available in the timeframe of the first operational downlink" (both arxiv and ApJS versions).

The paper remarks that first launch is unlikely for at least two decades and the first reception of data adds the transit time of 20 years.

The paper devotes four pages to the receiver (ApJS page 4) and about two thirds of a page to the transmitter (ApJS 3). There are clearly many more unknowns for the probe. This brief review concentrates on the probe end and inevitably simply gives a flavour of the paper, which has about 130 numbered sections.

Where both versions of the paper are referenced, for example (arxiv 2.5.2, ApJS 4.2) this is abbreviated to (2.5.2/4.2).

4.4.1 Power sources

The entire link budget is obviously constrained by the power available to the probe transmitter. The paper is cautious about this, making "... no prior assumption about transmit power, but rather characterize the minimum transmit power necessary subject to the other constraints" (arxiv 2.5.2, ApJS 4.2).

Three power sources are suggested - a radio-isotope thermoelectric generator (RTG), photovoltaic power (PV) from the target star during the encounter and forward-edge ISM proton-impact conversion during the cruise phase (before and after encounter). Contrast the Parkin paper discussed in 4.2 A Starshot Communication Downlink above which suggests the ISM source "0.7 kW monoenergetic hydrogen beam" delivering 100 W to the transmitter.

An RTG is the "traditional" power source for deep space probes - from the Pioneers and Voyagers to New Horizons and most if not all future proposals. For a twenty year mission the exponential decay of the standard Plutonium 238 (see *Assessment of Plutonium-238 Production Alternatives*, www.energy.gov/sites/prod/files/NEGTN0NEAC_PU-238_042108.pdf) may be not be a problem given the 40 year duration of the still-functioning Voyagers.

The 2016 i4is Andromeda study by i4is for Breakthrough Starshot, *The Andromeda Study: A Femto-Spacecraft Mission to Alpha Centauri* (arxiv.org/abs/1708.03556) in 2.10 *Power Supply for the Probe* also considered Americium-241 which has a much longer radioactive half-life but with a reduced power density. The same study examined and rejected RTG (too heavy), Alphavoltaics (too heavy) Betavoltaics (too heavy), Microbal battery (stability, temperature) and suggested a CubeSat Nuclear D-cell battery, a thermophotovoltaic source. But the assumed probe mass for Andromeda was much greater, with the beamer in space and a total mission duration of 50 years travelling at a cruise speed of 10% c.

4.4.2 Burst pulse-position modulation (BPPM)

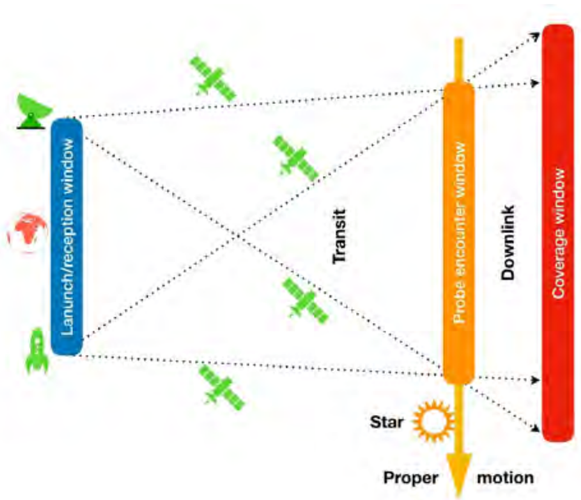
The paper proposes a "novel burst pulse-position modulation (BPPM) [which] beneficially expands the optical bandwidth and ameliorates receiver dark counts". The paper suggests a semiconductor laser generating pulses with duration of the order of 0.1–1 μs, with a repetition rate of about 1–2 Hz. This is a duty cycle of 0.00001 to 0.0000005 so average powers of 1-100 mW become peak powers in kilowatts. The paper points out, however, that this scaling of peak power is difficult to achieve in practice. Good conversion efficiency is also hard to achieve and compromising on that very short duty cycle in turn means that parameters like receiver aperture (telescope mirror size) have to increase and that interference from moonlight for the terrestrial receivers becomes more significant.

4.4.3 Receiver Aperture

Messerschmitt et al calculate the coverage required to receive the signal from concurrently transmitting probes and the antenna gain required to pick up the tiny, single photon, signals. These are in conflict if a single receive antenna is used. This is similar to the situation for your modern TV satellite dish versus the backyard monsters, yards across, that were common in more rural areas when I first visited the USA in the late 1980s. Big antennas need to point very accurately, usually at just one satellite, small antennas are much less directional but not as good with weak signals.

The scope of the problem is well illustrated by Figure 1 in the paper. So the paper proposes an array of smaller receivers (telescopes) with signals combined to achieve the necessary photon detection rate and a sophisticated mixture of combining optical paths with combining the electronic signals produced by the photon detectors.

The four most extreme probe trajectories as viewed from Earth



"Figure 1. 2D schematic representation of the four most extreme probe trajectories as viewed from Earth. The launch/reception window captures the seasonal variation in Earth's position, and the probe encounter window captures the proper motion of the target star. As shown, all encounters are assumed to fall on the same side of the target star, which moves away from the encounter positions. Downlink operation follows encounter. Receiver coverage is assumed to cover all concurrently transmitting probes, and a coronagraph function takes advantage of spatial separation to reject a portion of the target star's radiation."

Credit: Messerschmitt et al

4.4.4 Choice of optical frequency

The paper considers only optical frequencies for the downlink. It does not rule out the option of radio but suggests that optical link has an advantage of 10^4 to 10^5 in the link budget.

For the chosen optical bearer, the effects of the Earth atmosphere are substantial (7/11). The paper concludes that communication with low-mass probes at optical wavelengths is not feasible given the current state of technology (4.3/8.3). The key technology advances required include -

- Daytime Sky Irradiance - ruling our reception during daylight (note that ApJ version section 11 refers to a section 11.9 which does not exist. This should probably be a reference to 10.9 *Parameter-metric Sensitivity).*
- Nighttime Sky Radiance - with the phase of the Moon having a substantial effect.
- Atmospheric turbulence - here the multiple receivers required by multi-probe coverage and single photon direction also help to mitigate turbulence effects.
- Outages - mainly from weather including water vapour, clouds, and storms (there is no mention of outages from aircraft and satellites).

4.4.5 Error correction

The interstellar downlink will test the limits of error control in communications engineering. Since the roundtrip time is around four years ARQ, as described in 2.4 *Say again?* above, is clearly ruled out and Forward Error Correction (FEC) will be required. The paper addresses error correction in the optical layer in *ECC Layer* (10.3/14.3) and FEC encoding in *Role of redundancy* (10.3.3/14.3.3) which suggests that "we have to fall back on best practices" and identifies Reed-Solomon coding as an appropriate choice.

The paper suggests a 2008 tutorial by Messerschmitt, *Some Digital Communication Fundamentals for Physicists and Others*, www2.eecs.berkeley.edu/Pubs/TechRpts/2008/EECS-2008-78.pdf.

4.4.6 Other Challenging Design Issues and Critical Technologies

The paper identifies some *Other Challenging Design Issues*(8/12) and *Critical Technologies* (9/13) notably -

- *Probe Motion Effect* (8.1/12.1) on Doppler shift of signal (Uncertainty in Probe Velocity, Earth Motion)
- *Gravitational Redshift* (8.1.3/12.1.3) produced by the target star
- *Multiplexing options* (8.2/12.2)
- *Probe Attitude Control* (8.5/12.6) especially for downlink Pointing Accuracy
- *Coronagraph Function* (8.6/12.7)
- *Transmit Light Source* (9.1/13.1) including Pulse Compression,
- *Optical Bandpass Filtering* (9.2/13.2) and *Single-photon Detection* (9.3/13.3)

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* In-Situ Resource Utilisation (ISRU) and in-space assembly are very live topics. Examples: *Adaptive In-Situ Resource Utilisation (ISRU) Systems For Long Term Space Developmen*t, Shergill & Kingston, IAC 2019 and *In-orbit Spacecraft Manufacturing: Near-term Business Cases*, Skomorohov et al, IAC 2019, www.researchgate.net/profile/Andreas_M_Hein/publication/309358565_In-orbit_Spacecraft_Manufacturing_Near-term_Business_Cases/links/580b1d6908ae74852b5401fc/In-orbit-Spacecraft-Manufacturing-Near-term-Business-Cases.pdf .

4.5 Observations

The following observations occur to this reporter. Some of them may be misunderstandings or errors - it is many decades since this was my professional area.

As explained above, the longer Messerschmitt et al paper [1] exists in two editions the open access early version on arxiv.org and the final Astrophysical Journal version. Section numbers are given in that order, for example 10.3/14.3.

4.5.1 Why not have the receiving telescope(s) in space?

The longer Messerschmitt et al paper [1] only very briefly considers a *Space-based Receiver* (4.4/8.4). Use of Earth based telescopes would require at least three instruments, like the NASA Deep Space Network [9]. Weather outages could be minimised by site selection but not eliminated. A space telescope could operate continuously by avoiding sunlight or moonlight scattering into the aperture. A ground based telescope can only be used at night and, even then, is affected by scattered moonlight.

The growing constellations of low Earth orbit (LEO) satellites are already a serious concern for terrestrial astronomers. They may be predictable but would still result in outages which could have significant effects on the link budget averaged over time.

A space telescope array might also be scalable at lower cost if most materials were provided using ISRU*.

As Messerschmitt et al [1] remark, the timescale to first data is nearly half a century and if we have not achieved this sort of capability by then there must have been significant stalls on the way to ISRU and in-space fabrication.

The James Webb Space Telescope (JWST) at 6.5 m aperture is less than an order of magnitude smaller than Parkin's assumed Starshot receiver [4] and terrestrial telescopes larger than the Starshot receiver are already under construction so 30 m terrestrial is conservative for such an otherwise ambitious project.

Digressing a little from downlink issues - but why not have beamer in space too, as in the i4is Andromeda study, see 2.3 *Link Budget* above? This would allow longer beaming, less demanding acceleration, free power (noting high cost of power per sailcraft noted by Parkin). It would allow scaling of both power gathering and beamers without gravitational constraints. And it would minimise dangers from a mis-directed beam. There would probably be a higher initial cost. An ISRU-based study is perhaps needed to reveal some idea of the lifetime cost.

4.5.2 Error Correcting Code

Error Correcting Code (ECC) is covered in detail, especially in the longer Messerschmitt et al paper [1] 10.3/14.3. *ECC layer* - but no application-specific error correction is discussed. In the same paper 2.2. *Scientific Objective* - an image of 1000 by 1000 is assumed compressed to one bit per pixel but "After compression, even a single bit in error often propagates across the image and thus has serious consequences". An implemented system would almost certainly compress images at source so that each pixel, after analogue to digital conversion, would have selective error correction applied so that more significant bits received greater error protection, as in typical mobile communications codec standards [10]. This achieves compression with graceful degradation as error rates increase and, for applications such as imaging, is preferable to error correction which treats all bits as equal. Adjacency of samples in space is also relevant in image data, as is time adjacency in voice, and the challenges faced in delivering images from a tiny probe at four light years are far greater even than the technology which delivered those stunning images of Pluto from the New Horizons probe.

5 Heavier Metal

Another recent study - *Project Icarus: Communications Data Link Designs between Icarus and Earth and between Icarus spacecraft*, Peter Milne, Michel Lamontagne and Robert M Freeland II (JBIS, Vol. 69, pp.278-288, 2016) is based on the massive fusion powered successor to the Daedalus design (see *Reaching the Stars in a Century using Fusion Propulsion, A Review Paper based on the 'Firefly Icarus' Design* by Patrick J Mahon in P22, August 2018).

It aims to deploy a large antenna composed of self-assembling swarms or built by "Spiderfabs" allowing for high bandwidth communication, including an uplink, to a probe orbiting the target system rather than a flyby.

The target 20 Gbps data rate between the Icarus probe and Earth, is the equivalent of 13 high definition TV channels (at 1.5 Gbps each).

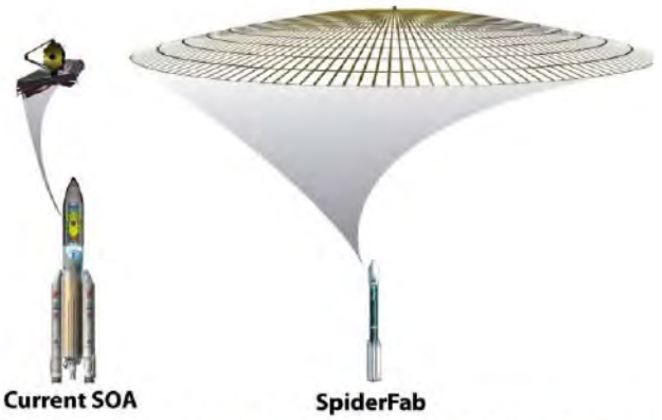

Figure 1. SpiderFab Value Proposition. *On-orbit fabrication of spacecraft components enables higher gain, sensitivity, power, and bandwidth at lower life-cycle cost*

The Spiderfab value proposition (from the report cited in Milne et al above, SpiderFab™: *Process for On-Orbit Construction of Kilometer-Scale Apertures*, Robert Hoyt, Jesse Cushing, Jeffrey Slostad, Tethers Unlimited Inc, 2013 - https://core.ac.uk/download/pdf/189598541.pdf)

But tiny sailcraft which might be launched within 20 years cannot be easily compared with a vehicle of 25,000 tons which might be launched sometime in the next century. The Milne et al paper will be the subject of an article in a later issue of Principium.

6 References: Starshot and other related sources

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