The Icarus Firefly Downlink

John I Davies

In our last issue we outlined ***The downlink from swarming micro-probes: the "light brigade" of feasible interstellar probes***. This piece considers the "heavy brigade": communications from large fusion propelled probes. It is mainly based on the downlink envisaged from Project Icarus, the Firefly design. Comparisons with its predecessor, the downlink envisaged by the BIS Daedalus study are instructive.
John Davies looks at the Project Icarus work by Milne et al, 38 years later, on downlink communications for the "heavy brigade", fusion propelled probes.
Peter Milne made some very useful comments on a draft of this article. However any errors or omissions remain the responsibility of the author.

1 Introduction

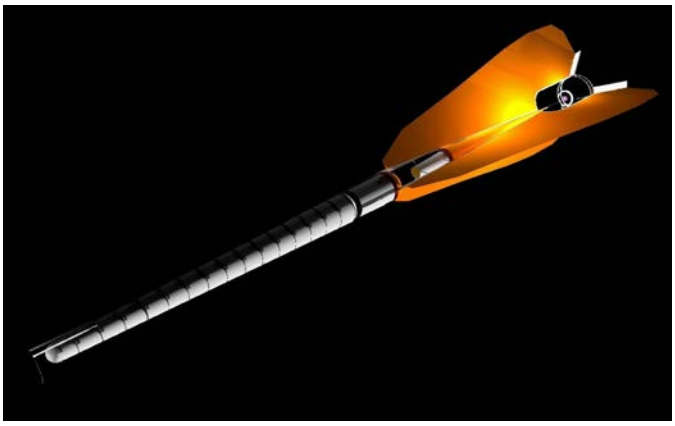
The downlink from an interstellar probe is the other most challenging issue alongside the propulsion required to achieve reasonable travel times. Earlier articles in Principium have mainly considered this challenge for the very small probes envisaged for laser-push propulsion - including early studies by Philip Lubin (UCSD) and i4is teams (projects Dragonfly and Andromeda). Here we consider the challenge for probes using the other reasonably feasible means of propulsion - a fusion rocket. This is mainly based on the 2016 paper *Project Icarus: Communications Data Link Designs between Icarus and Earth and between Icarus spacecraft* by Peter Milne, Michel Lamontagne and Robert M Freeland II [1].

The different probes and downlinks are directly compared below in *Table: The probes* and *Table: The downlinks*.

2 Daedalus and Icarus - The Downlinks

There is a long gap between the 1978 paper by Tony Lawton and Penny Wright on communications from the Daedalus probe, propelled by inertial confinement fusion [2] and the 2016 paper by Peter Milne, Robert M Freeland II and Michel Lamontagne on communications from their envisaged Icarus Firefly Z-pinch fusion propelled probe [3].

These are the "heavy brigade" of proposed interstellar probes and the communications downlink technology they have suggested to their designers differ very substantially from those proposed for the chipsats and chipsat swarms envisaged by Breakthrough Starshot.



Firefly Icarus, perspective view at main engine shutdown.
Michel Lamontagne, 2015

[1] Milne et al, JBIS, Vol. 69, pp.278-288, 2016

[2] *Project Daedalus: The Vehicle Communications Systems*, A T Lawton and P P Wright, Project Daedalus — Final Report, pp. S163-8171, 1978. in *Project Daedalus: Demonstrating the Engineering Feasibility of Interstellar Travel*, bis-space.com/shop/product/project-daedalus-demonstrating-the-engineering-feasibility-of-interstellar-travel/

[3] *Firefly Icarus: An Unmanned Interstellar Probe using Z-Pinch Fusion Propulsion*, R M Freeland II & M Lamontagne, JBIS, 68, pp.68-80, 2015 see also *Reaching the Stars in a Century using Fusion Propulsion - A Review Paper based on the 'Firefly Icarus' Design,* Patrick J Mahon, Principium 22 August 2018 i4is.org/reaching-the-stars-in-a-century-using-fusion-propulsion/

The tables below compare the two "heavy" studies with the Icarus Firefly study being the most explicit of the three sources. The rest of this article summarises its results, comparing the Daedalus study where there are clear similarities and differences. It's worth noting that Project Icarus spawned a number of studies, all based on fusion propulsion and requiring rendezvous at the target system.

There is a more detailed summary of the Starshot studies in *The Interstellar Downlink - Principles and Current Work* in Principium 31, November 2020 [1].

3 Three Downlinks compared - Daedalus, Icarus Firefly and Starshot .

3.1 Table: The probes

	Daedalus[2]	**Icarus Firefly[3]**	**Starshot[4]**
Study date	1978	2016	2020
Destination	Barnard's Star	Centauri System	Centauri System
Destination distance, light-years	7	4	4
Approximate journey time, years	40	100	20
Probe mass (metric)			
at launch	50,000 tons	23,550 tons	1 gram
at encounter	450 tons	2,200 tons	1 gram
Number of probes	1 (+subprobes)	1 (+subprobes)	thousands
Probe speed	12.2%c	4.7%c	20%c
Probe propulsion	Electron beam fusion	Z-pinch fusion	Laser-driven sail
Speed at destination	12.2%c	0	20%c
Approximate encounter duration*	8,197 seconds = 2 hours 17 minutes	indefinite	5,000 seconds = 1 hour 23 minutes

* For flyby missions I assume the useful encounter distance to be one Earth orbit diameter (2 AU) - so at speed of light, c, this is about 1,000 seconds.

Both Daedalus and Starshot are "flyby" probes with encounter duration in hours or days and there is therefore little benefit from a possible uplink to the probe since the link round-trip time is 8 to 12 years. The Daedalus study did not rule out an uplink but any useful traffic would need to have been sent during the decades of transit to the target system.

The Icarus studies require a deceleration to rendezvous and a usable encounter time limited only by reliability and availability of power. The Icarus Firefly study therefore included an uplink capability not discussed in this article but there are obvious advantages including target selection based on discoveries reported, software refinement and even instructions for hardware repair. The encounter duration would, of course, need to significantly exceed the minimum round trip communcations delay of about 8 years.

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

[2] *Project Daedalus: Demonstrating the Engineering Feasibility of Interstellar Travel,* Alan Bond, Anthony R Martin et al, 1978, available in book form from the BIS website (http://www.bis-space.com/eshop/products-page/merchandise/books/)

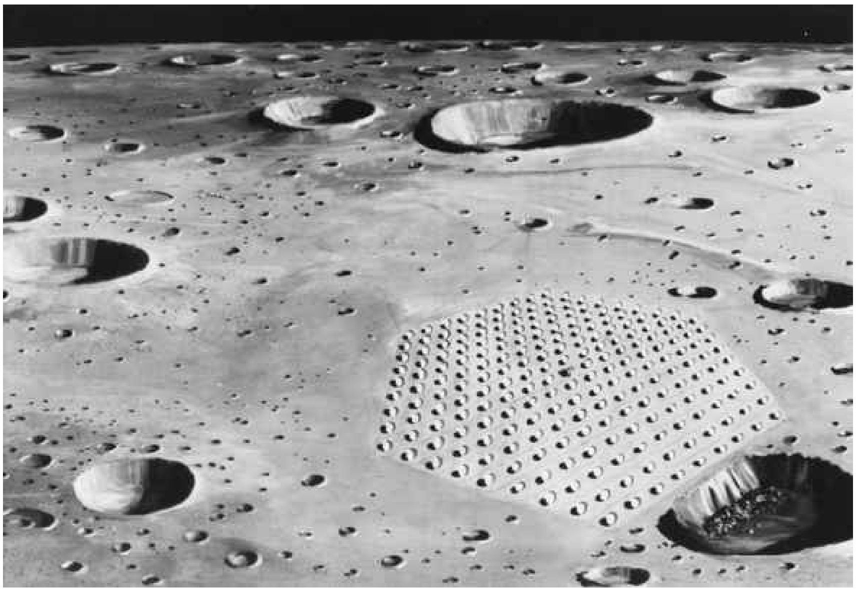
[3] *Firefly Icarus: An Unmanned Interstellar Probe using Z-Pinch Fusion Propulsion*, R M Freeland II & M Lamontagne, JBIS vol 68 2015 see also *Reaching the Stars in a Century using Fusion Propulsion, A Review Paper based on the 'Firefly Icarus' Design*, Patrick J Mahon in P22, August 2018 - also - https://i4is.org/reaching-the-stars-in-a-century-using-fusion-propulsion/

[4] *The Breakthrough Starshot system model*, Kevin L G Parkin, Acta Astronautica Vol 152 November 2018 (https://parkinresearch.com/wp-content/uploads/2018/07/starshotmodel.pdf)

◀ 3.2 Table: The downlinks

	Daedalus[1,4]	Icarus Firefly[2]	Starshot[3]
technology	microwave	microwave	laser
frequency/wavelength	2.60 GHz / 0.115 m	32 GHz / 0.0094 m	293,914 GHz / 1.02 µm
power source	fusion 2.6 MW	fusion 2 MW	radioisotope (RTG) ?
transmit power	1.00 MW	2.00 MW (2*1 MW)	100 W
dbm	90	93	50
tx antenna diameter m	5.0	1,000	4.1
tx antenna area m²	19.6	785,500	3.46
gain dbi	45	107.50	140
path loss db[5]	378.4 [4]	394.9	476
relativistic loss db[6]	negligible	negligible	3.5
rx antenna location	terrestrial/space	Earth-Moon L4/L5	terrestrial
rx antenna diameter m	3,160	15,000	30
rx antenna area m² [7]	$9.98*10^4$	$1.77*10^8$	707
gain dbi	98.7	131	156
rx power dbm [8]	not given	-257.4	-133
rx antenna noise loss db	3.1 [4]	3.1	complex analysis, no single figure
bit rate	864 Kbps	20 Gbps (2*10 Gbps)	260 - 1.5 Kbps

NOTE: db is log base 10 - ratio expressed as tenths - so 3 db is $10^{0.3}$ approximately 2.
dbm is milliwatts in the same log 10 form so 80 dbm = $10^{8.0}$ milliwatts = 100,000,000 milliwatts = 100 kW
dbi is db isotropic showing the ratio of power to/from a directional antenna versus a theoretical isotropic antenna which treats all directions as equal.



artist's rendering of a Project Cyclops hexagonal array on the far side of the Moon

NASA Report: https://ntrs.nasa.gov/api/citations/19730010095/

Image Credit:: fossilhunters.xyz

[1] Encounter phase values from - *Project Daedalus: The Vehicle Communications Systems*, A T Lawton and P P Wright in *Project Daedalus — Final Report*, pp. S163-8171, 1978. bis-space.com/shop/product/project-daedalus-demonstrating-the-engineering-feasibility-of-interstellar-travel/
[2] See especially tables 2 and 3 in *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, pp278-288, 2016
[3] *A Starshot Communication Downlink*, Kevin L G Parkin, May 2020, arxiv.org/abs/2005.08940) - also Parkin, The Breakthrough Starshot system model, cited above
[4] Where the Daedalus study is silent I have used the Icarus Firefly values where they seem appropriate.
[5] Free space path loss = $(4*\Pi*distance*frequency/c)^2$
[6] Neither the Daedalus nor the Icarus Firefly studies include relativistic loss and I have assumed they are negligible within the much less challenging link budget for these very large probes - and at the lower encounter speeds.
[7] The Daedalus study assumes a Project Cyclops-based receiver. The NASA design study quotes "effective clear aperture diameter of 3.16 km." = $3.16*10^2$ m == area $9.98*10^4$ m²; gain assumes 100% efficiency. Quote source: NASA Technical Report CR-114445 - Project Cyclops: A design study of a system for detecting extraterrestrial intelligent life.
[8] This appears to be the main omission from the Daedalus study. Corrections and comments would be very welcome.

4 The Icarus Firefly Downlink

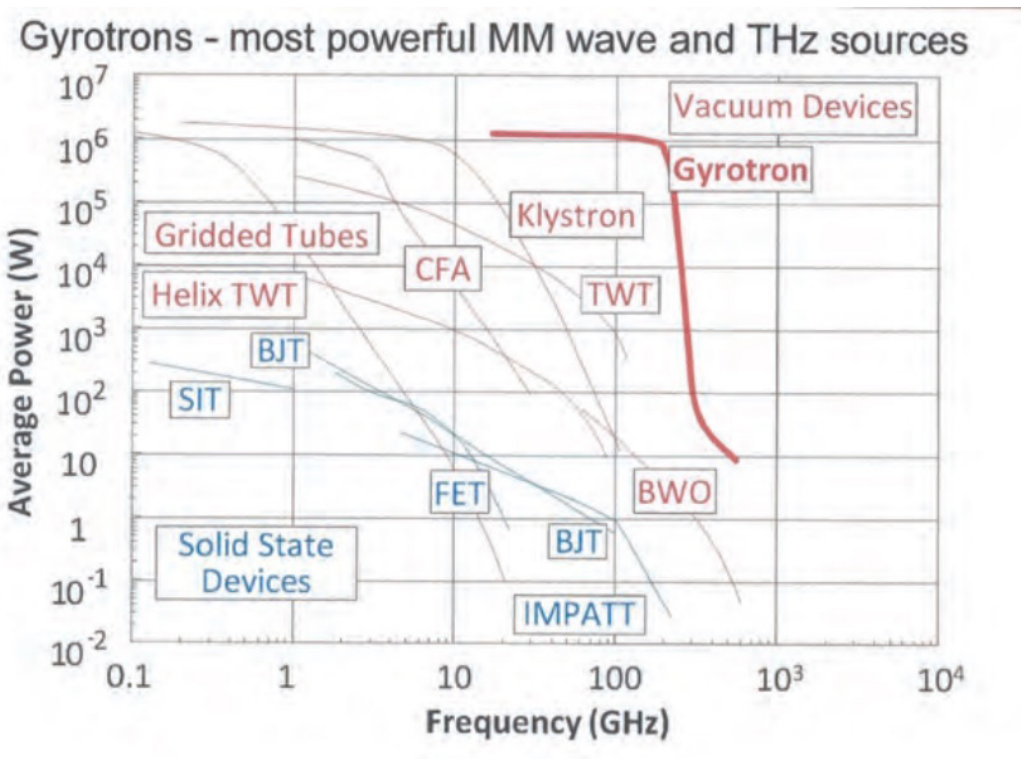
Here we deal mainly with the downlink from the probe to the receiving station (referred to as Gateway in the Milne et al paper) after arrival. This is the rendezvous phase. Milne et al set the rendezvous downlink requirement: "target 20 Gbps data rate between the Icarus probe and Earth, is the equivalent of 13 high definition TV channels (at 1.5 Gbps each)".

The paper also covers Gateway to Earth communication, boost phase and cruise phase communication, intercommunication with a variety of subprobes while exploring the target system and uplink communication (for example for software updates to the probe) during all phases of probe operation.

If and when we develop the capability to send large probes to the stars then the downlink challenge can be addressed using a correspondingly large transmit antenna. Daedalus proposed to use the second stage reaction chamber as a hemispherical reflector but the Icarus mission profile, intended to rendezvous with the target star system, would have time to deploy a larger, dedicated purpose, antenna. The Icarus Firefly team considered both a radio frequency (RF) and an optical downlink.

One thing which does not change whether the mission uses small probes (as in the Breakthrough Starshot studies and early i4is work) or large probes (as for the Daedalus and Icarus studies) or whether the target system encounter is flyby (as in Daedalus and Starshot) or rendezvous (as in the Icarus studies) is the enormous losses resulting for the inverse square law applied over multiple light year distances.

The Firefly study considered a number of RF transmitter options and settled on a developed version of a current technology, the Gyrotron [1]. The target device would yield an output power of 1 MW at 32 GHz over a bandwidth of 3 GHz.



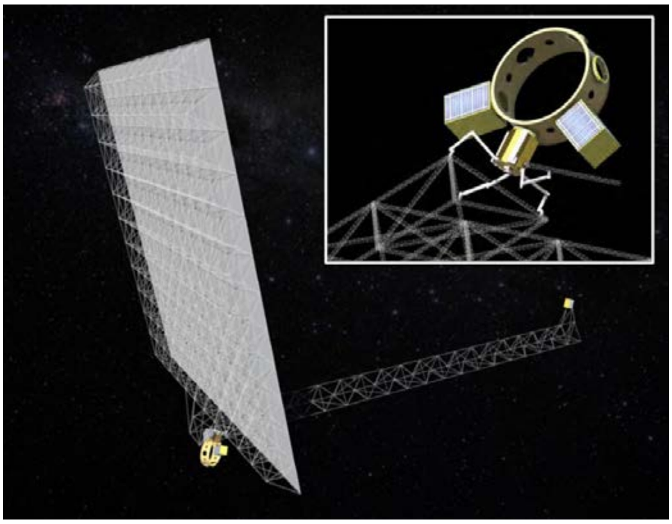
Transmitter Technologies - from *High Frequency Gyrotrons and Their Applications*, R Temkin, Plasma Physics Colloquium, Columbia University 28 February 2014 [2]. Updated from Granatstein et al. Proc. IEEE 1999 [3]

Credit:, image and caption: Milne et al Fig. 1

[1] A type of free-electron maser (microwave equivalent of a laser) which generates high-frequency electromagnetic radiation by stimulated cyclotron resonance of electrons moving through a strong magnetic field. It can produce high power at millimetre wavelengths because its dimensions can be much larger than the wavelength of the radiation. This is unlike conventional microwave vacuum devices such as klystrons and magnetrons. More at en.wikipedia.org/wiki/Gyrotron

[2] Available as High Frequency Gyrotrons and Their Applications to tokamak plasma heating, K E Kreischer, January 1981, Journal of Magnetism and Magnetic Materials, Volume 11, Issues 1–3, April 1979, dspace.mit.edu/bitstream/handle/1721.1/93407/81rr001_full.pdf.

[3] Vacuum electronics at the dawn of the twenty-first century, V L Granatstein, R K Parker and C M Armstrong, in Proceedings of the IEEE, vol. 87, no. 5, pp. 702-716, May 1999, doi: 10.1109/5.757251.(No public version found).



Concept for demonstration of SpiderFab construction of a large RF aperture as a payload on an ESPA platform. SpiderFab technology can be validated on affordable secondary payload platforms prior to use in operational missions.

Credit: (image and caption) Hoyt et al, Figure 57

A deployable antenna is selected. This is a natural choice for a mission which decelerates. It need not operate at the cruise velocity of the mission, 4.7%c, with the accompanying hazard from the impact of high velocity interstellar dust particles. Both downlink and uplink are envisaged for the cruise phase but the requirements are restricted to telemetry and limited science data.

A 1 km diameter antenna could be fabricated using "spiderfab" robots [1]. The paper estimates that such a 1 km antenna would have mass 40 tons (40,000 kg). This is a fairly small fraction of the intended probe mass at encounter of 2,200 tons.

One or more receivers would be located at Earth-Moon L4 and L5 stable positions. The advantage in scale and power availability for such very much larger probes means that pointing accuracy of transmit and receive antennas can be enhanced by the downlink transmitter including a tracking signal which the downlink receiver can use to point its antenna more accurately using monopulse tracking (via multiple antennas or subarrays of an active electrically scanned antenna or phased array). Note also that the uplink can also include a tracking signal with similar enhancements of pointing accuracy for the antenna on the probe.

The paper includes a detailed link budget and a tradeoff analysis of the effects of different antenna diameters and transmit powers at both probe and receiving station. One striking result of this is that doubling transmitter power results in a 23% improvement in data rate (8.995 to 11.716 Gbps) while doubling the transmit antenna diameter (0.5 km to 1 km) results in a 58% improvement in data rate.

The paper addresses a number of other detailed issues including downlink implications of a possible Proxima Centauri Flyby. Proxima Centauri is not on the flight path between Earth and Alpha Centauri but the Icarus project objectives include the possibility of a subprobe to visit it without decelerating.

5 Possible Laser downlink

The proposed Starshot probes would use a (very small) laser as their downlink transmitter. Milne et al consider laser technology as an alternative to microwave. The basic physics and thus link budget is similar see - *Table: The downlinks* - above. The antenna accuracy requirements are inversely related to the wavelength - the difference is millimetres versus µm so the antenna needs to be around 1,000 times more accurate in shape. The paper gives a rendezvous phase link budget suggesting a 1 KW laser pulsing to 1 GW at 0.532 µm wavelength with a 10 m diameter transmit reflector. It would use pulse position modulation and achieve a 1 Kbps data rate. The data rate depends on the rate at which the laser source can be pulsed. The duty cycle sees a high power during the "on" period and then sufficient time for the device to cool before the next duty cycle begins. The need to dispose of waste heat limits the possible duty cycle of laser. An alternative downlink design utilising spread spectrum modulation (as in 3G mobile) was also considered, but although it could achieve a 12 Gbps data rate it would require a very large mirror with very high surface accuracy and synchronisation of multiple laser sources so that their outputs could be combined coherently. Those drawbacks were considered too difficult to overcome. Milne et al conclude that an RF link is preferable based on current technology but that in the likely timescales for such a heavyweight probe laser technology may have advanced to achieve comparable or better performance.

[1] *Spiderfab: Process for On-orbit Construction of Kilometer Scale Apertures*, R P Hoyt, J I Cushing and J T Slostad, "Tethers Unlimited Inc, NASA Innovative Advanced Concepts. ntrs.nasa.gov/api/citations/20140000422/downloads/20140000422.pdf

6 Citations

The Milne et al JBIS paper has been cited in these subsequent papers-

Interstellar communication. I. Maximized data rate for lightweight space-probes, Michael Hippke, International Journal of Astrobiology, Volume 18, Issue 3, June 2019, pp. 267 - 279, Open access: arxiv.org/abs/1706.03795.

Direct Exoplanet Investigation Using Interstellar Space Probes, Ian A Crawford, in *Handbook of Exoplanets*, ISBN 978-3-319-55332-0. Springer International Publishing AG, 2018, Open access: arxiv.org/abs/1707.01174.

See also *Communications vs isolation*, in *Worldship and self replicating systems*, Michel Lamontagne, Principium 32 February 2021, i4is.org/wp-content/uploads/2021/06/Worldship-and-self-replicating-systems-Principium32-print-2102221659-opt.pdf.

7 Other studies since Daedalus

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

Technological Challenges in Low-mass Interstellar Probe Communication, Messerschmitt D G, Lubin P and Morrison I, JBIS v73 #12 December 2020, Open access: arxiv.org/abs/2001.09987.

See also -

The Interstellar Downlink Principles and Current Work, J I Davies, Principium 31 November 2020, i4is.org/wp-content/uploads/2021/02/jid_20210201_principium.pdf - notably the final section - *6 References: Starshot and other related sources*.

8 Future work

The following are my own thoughts on where studies might usefully take us -

- A long duration rendezvous makes it feasible to consider retransmission if an error is detected in downlink data - remembering of course that means a round-trip delay of around eight years even for our nearest stellar neighbour.
- The assumption of a space based downlink receiver and continued use of constructor robots such as Spiderfab for the Gateway antenna means that it can be enlarged during all mission phases. In principle this would allow reduction of the error correction overhead for downlink data and thus a higher useful downlink data rate as the probe explores the target system.
- The massive $100m investment by Yuri Milner in the Breakthrough Starshot study programme includes a continuing effort to address downlink issues. While much of this aims to overcome the difficulties of downlink communication from gram scale probes, some of the results are likely to be applicable more widely.
- The transmit antenna could use three obvious sources of materials - purpose-designed components as in the Milne et al study, cannibalised elements of the probe and materials found in the target system - in-situ resource utilisation (ISRU).
- The life and capabilities of the probe may be extended by ISRU in other ways. Obvious applications include fusion fuel and powersat construction. ■

THE POSSIBLE OBJECTIVE?

Proxima b 3D Model - snapshot

Credit: NASA Visualization Technology Applications and Development (VTAD) exoplanets.nasa.gov/resources/2211/proxima-b-3d-model/