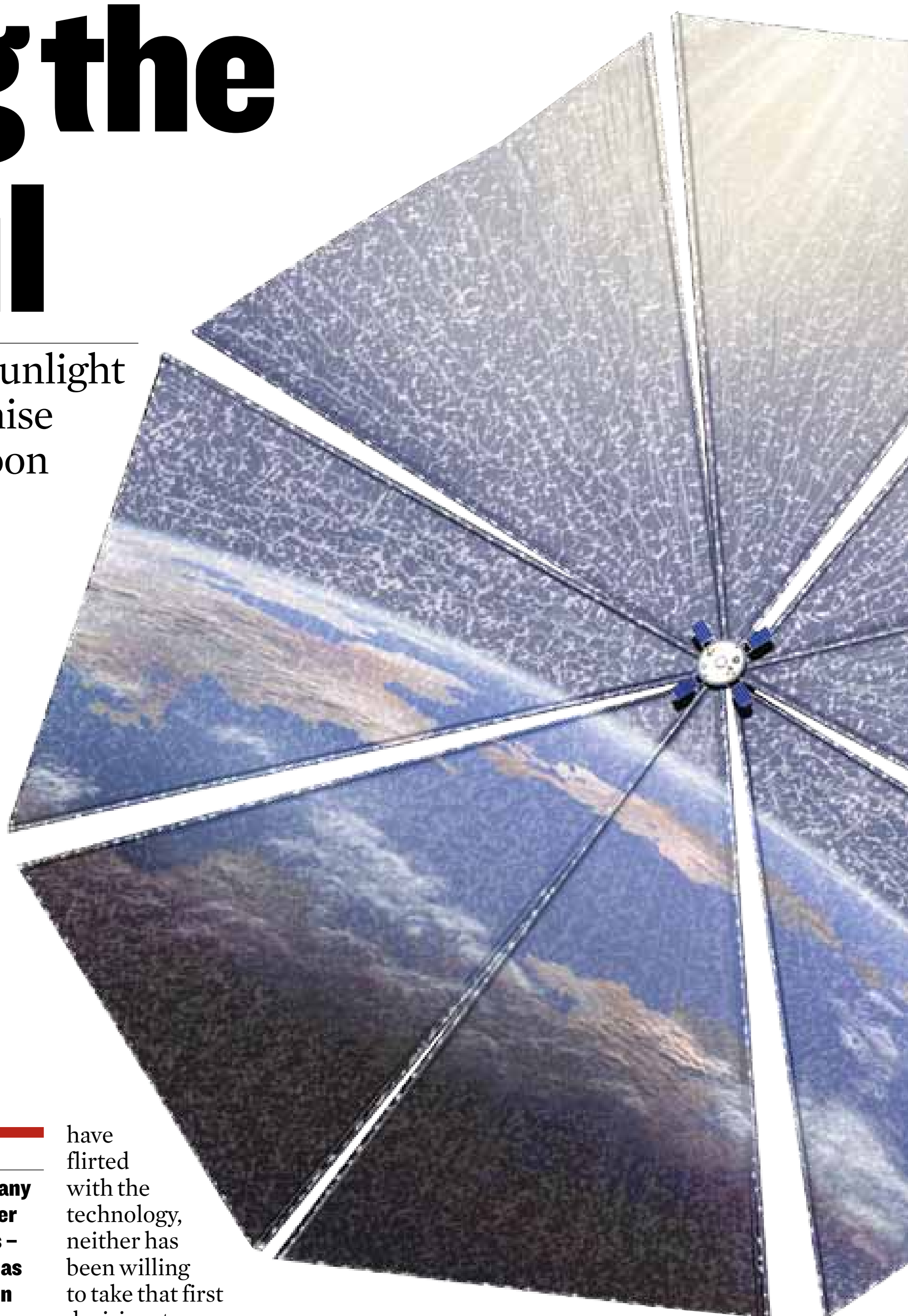
Hoisting the solar sail

Flying through space by catching sunlight on ultra-thin sails could revolutionise space travel – and the idea could soon take off, says Ned Stafford



Just one demonstration mission. That is the goal of frustrated solar sailing advocates around the world, who have endured years of minimal funding from national space agencies – and more than their share of bad luck. But if they can prove that a spacecraft fitted with reflective solar sails can be flown through space by the force of sunlight alone, then they believe that NASA and the European Space Agency (ESA) would finally commit serious money for solar sail research and space missions.

Advocates argue that, unlike traditional rocket-powered craft, spacecraft propelled and navigated using ultra-thin solar sails will never run out of fuel, and are capable of reaching much higher speeds. They say solar sails are also particularly well suited to certain types of orbits, such as being positioned over the north pole or between the sun and Earth. But while NASA and the ESA have flirted with the technology, neither has been willing to take that first decisive step.

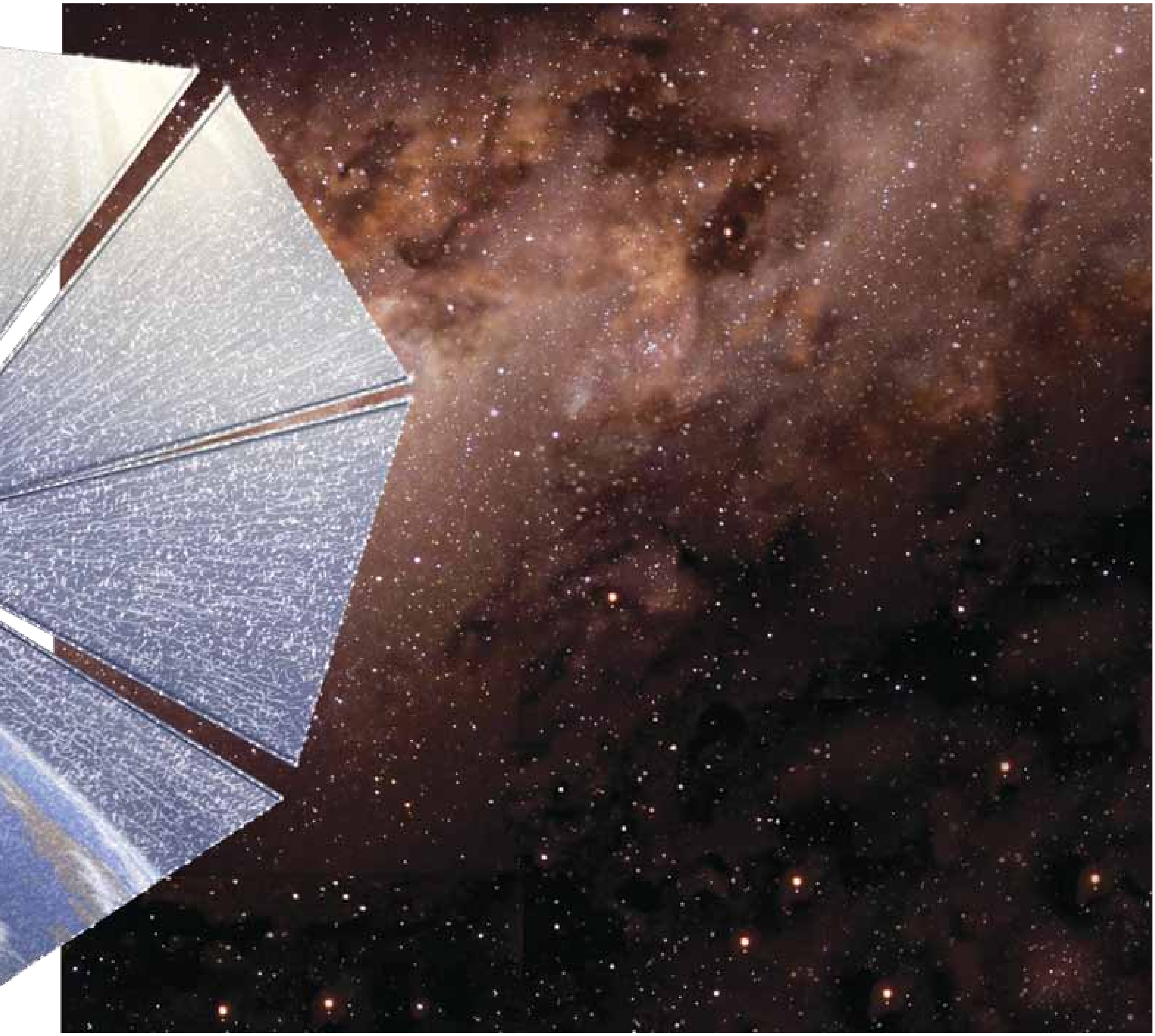
In short

- **Solar sails offer many potential benefits over conventional rockets – but serious funding has never been invested in the technology to prove the idea**
- **Plenty of evidence exists to support the idea of solar sailing, but a dedicated test flight is yet to be achieved**
- **For sail-powered spacecraft to reach useful speeds, they must be made of ultra-light yet tough materials**

Solar sail advocate Louis Friedman, former NASA scientist and cofounder and executive director of the Pasadena, California-based Planetary Society, explains: 'NASA and ESA have discontinued their programmes because they are caught between not wanting to use solar sail technology because it is not proven, and not proving the technology because it hasn't been used.'

So unless NASA or ESA change their minds, someone else is going to have to be first to prove the technology. In 2005, the Planetary Society's Cosmos 1, a low-budget solar sail built in Russia, was launched from a Russian submarine. But the Russian rocket malfunctioned and Cosmos 1 never reached orbit for testing (see box p44). Friedman is aching for a second chance with a Cosmos 2, but is struggling to raise money.

In Europe, a dozen or so German solar sail dreamers, most affiliated with the German Aerospace Centre (DLR), also would like to be first to fly. They spent a day together in April in Berlin to plot their solar sail strategy, and hope to convince DLR to fund an orbital solar sail demonstration. Bernd Dachwald, a former DLR aerospace engineer now at Aachen University of Applied



THE PLANETARY SOCIETY

Sciences who helped organise the meeting, believes Germany already has the know-how to succeed. 'I am quite confident we could do it with the current technology,' he says.

Catching rays

The roots of the current quest to fly solar sails in space go back four centuries to German astronomer Johannes Kepler. He noticed that tails of comets did not form in the direction of motion, but in the direction opposite from incoming sunbeams. He hypothesised that the tails were being blown by a solar 'breeze' and suggested that 'ships and sails proper for heavenly air should be fashioned' to glide through space.

We now know that solar wind exists in the form of a stream of charged particles, or plasma, ejected from the upper atmosphere of the sun to form the heliosphere, a vast bubble surrounding our solar system. However, the force of solar wind is less than 1 per cent of light pressure. Current solar sail spacecraft concepts would rely on sunlight.

Scottish theoretical physicist and mathematician James Clark Maxwell demonstrated in a work published in 1873 (while at the University of Cambridge) that sunlight exerts minute amounts of pressure. In the case of solar sails, a photon reflecting off a reflective sail delivers a double kick. The first push comes from the sail stopping the photon. The second shove, compliments of Newton's third law of motion that for every action there is an equal and opposite reaction, occurs as the reflected photon accelerates away,

Sail-based spacecraft could reach far higher speeds than rockets

Friedman explains that although sunlight force is slight, it is continuous, unlike rocket thrust that ends when the fuel tank is

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empty. This continuous force would enable a solar sail spacecraft in the void of space to reach high speeds. Navigation is controlled by the angle of the sail toward the sun, adding to or subtracting from the orbital velocity, he says. When velocity is added, the sail flies away from the sun and when subtracted the orbit spirals inward.

With the current level of technology, Friedman says acceleration from sunlight would be approximately five ten-thousandths of a metre per second, depending on the size of the sail and total spacecraft weight. This would be equal to a velocity increase after one day of about 45 metres per second or 160km per hour. Friedman says that such a sail in 100 days could reach a speed of 16 000 kph and in a year 58 000 kph. In three years, it would be sailing at 160 000 kph.

That might seem fast, but he notes that 160 000 kph is only 0.00015 the speed of light. It would take about 1000 years for a solar sail to reach one-tenth the speed of light, even with continuous light, which, if relying on sunlight, would not be possible.

But sunlight would suffice for missions within the solar system. 'Solar sailing is ideal for interplanetary monitoring stations – observing solar weather, sitting above the Earth's pole, looking for near-earth comets and asteroids,' Friedman says. 'Also for round-trip missions such as sample return missions.'

Louis Friedman, standing left, at the 1980 founding of the Planetary Society, with (left to right) cofounders Bruce Murray and the late Carl Sagan, and adviser Harry Ashmore

Going about

The basic structure of a solar sail is as simple as a sailing boat, with three prime components. The first two are the reflective sails, and the booms that hold the sails in place. Both of these emanate from the third component, the central payload, which could house radio, photographic and other scientific equipment. Most current solar sail concepts would use a polyimide film for the sail, and for the boom either a carbon base or inflatable tubes containing, for example, nitrogen, which would then freeze solid in space. The sails and booms, packed tightly for rocket launch, need a deployment mechanism to unfurl the booms and sails after attaining orbit.

But what on paper seems a fairly simple contraption is actually not simple at all, thanks to one major issue – weight. Even in deep space, solar sail spacecraft must be extremely light in order to reach high speeds.

Larger sails, being pummelled by more photons, can compensate for a heavy payload. But increasing sail size also requires longer booms, which all adds to spacecraft weight and increases the risk of sail tearing and boom breakage – a vicious circle, because trying to reduce weight with thinner sails and booms also increases risk of tearing and breakage.

Building a solar sail able to perform space missions will require contributions from a varied team of specialists, from materials scientists to nanotech experts. Joachim Block, an engineer at DLR's Institute of composite structures and adaptive systems in Braunschweig, has helped developed potential solar sail boom systems of carbon fibre reinforced plastics. He knows first-hand that success would take serious effort. 'If developing solar sails was not so difficult, NASA would have already done it,' he says.

Weighty issues

The key specification for solar sail design is weight per square metre of sail, which can also be broken down between the sail-boom system and the payload, giving the solar sail designer flexibility with the payload weight. For example, for a 10 × 10m sail and boom system weighing 50kg and the payload 50kg, the square metre weight of the sail/boom would be 0.5kg.

But this example would be much too heavy to be practical, and would probably gain only enough speed to get past Mars within a lifetime. Solar sail designers speak in terms of grams per square metre of sail.

Dachwald, the former DLR aerospace engineer now at Aachen University of Applied Sciences, says current materials technology

Testing times

NASA

While a spacecraft with solar sails as primary propulsion has yet to be flown in space, the underlying concepts have been tested on conventional spacecraft. In 1974 the Mariner 10 probe, heading toward Mercury, was running low on attitude control gas. In a bid to control the craft, NASA mission controllers angled its solar panels to receive direct hits of solar radiation – and it worked.

India already uses solar sails on some of its communications satellites – but to offset solar pressure on the solar panels, rather than for propulsion.

In early 1993, Znamya 2, a 20 metre diameter mirror similar to a solar sail, was unfurled from Russia's Mir space station as a test to beam solar power to earth. The reflection produced a 5km wide spot on the ground in Europe with luminosity equivalent to a full moon. Its successor, Znamya 2.5, with a 25m diameter, was deployed in 1999, but caught on a Mir antenna and ripped. The planned 60–70m wide Znamya 3 was scrapped.

The only successful solar sail demonstrations thus far have been sub-orbital. As well as the DLR and NASA ground-based tests, in 2004 Japanese researchers sub-orbitally deployed two prototype solar sails from a sounding rocket, but only to test the deployment mechanisms, not propulsion. Similarly, in February 2009 the DLR tested deployment mechanisms onboard an A300 Zero-G test aircraft.

Mariner 10, the first spacecraft to be propelled by sunlight

NASA

NASA has successfully deployed a solar sail – but only on the ground

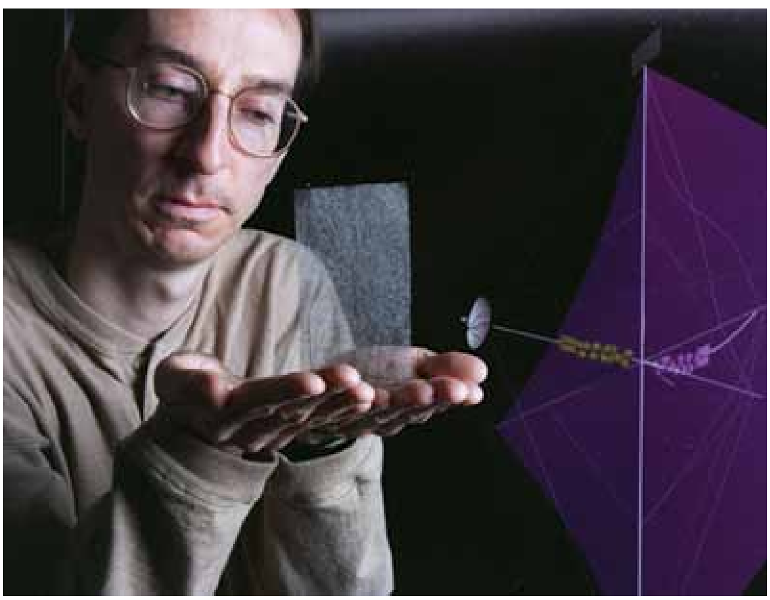
is capable of producing first-generation solar sail spacecraft of between 30 to 50 grams per square metre, depending on payload size.

That compares with the 87 grams per square metre of a 20 × 20m solar sail that in 1999 was deployed in a ground demonstration in a DLR testing facility. After the ground demonstration, Dachwald helped develop potential plans for solar sail missions to near earth asteroids – the least ambitious a four year mission to asteroid 1996FG3, involving a 148kg spacecraft with a $50m^2$ sail – but the plans remain on the drawing board.

NASA has also conducted initial tests, in 2004 deploying two 20 × 20m sails on the ground in vacuum conditions. But the same year, the then President George W Bush vowed to return Americans to the moon by 2020, and NASA's limited resources were focused on that goal. In August 2008 the US agency did launch the NanoSail-D, a 4.5kg, $10m^2$ solar sail mainly designed to test sail deployment technology in low orbit. But like Planetary Society's Cosmos 1, NanoSail-D's rocket suffered launch failure and it did not achieve orbit.

One of NASA's most vocal solar sail cheerleaders, Les Johnson, deputy manager in NASA's Advanced concepts office at the George C Marshall space flight center in Huntsville, Alabama, says: 'It is priorities. I am frustrated, yes. Not bitter.'

NASA



NASA's Les Johnson holds a polyimide film so thin it is almost transparent

'If developing solar sails was not so difficult, NASA would have already done it'

The ESA a few years ago funded a study to assess GeoSail, whose primary purpose would have been as a solar sail technical demonstration to pave the way for more complex missions. At a heavy 79 grams per square metre, GeoSail would have been a low performance solar sail even by current standards, and ESA hasn't progressed the project further.

Colin McInnes, research director of the mechanical engineering department at the University of Strathclyde in Glasgow and involved in the GeoSail study, still believes it would be an ideal first orbital demonstration. Money, not technology, is the only barrier, he says, adding, 'I think it is at the stage now, it is just putting it together and doing a demonstration mission in orbit.'

He does believe at some point someone will conduct a successful demonstration mission and that solar sails in coming decades will be used for increasingly complex missions, even in the far reaches of the solar system. 'I am a strong believer that if you get a bunch of engineers and enough funding you can achieve anything,' he says.

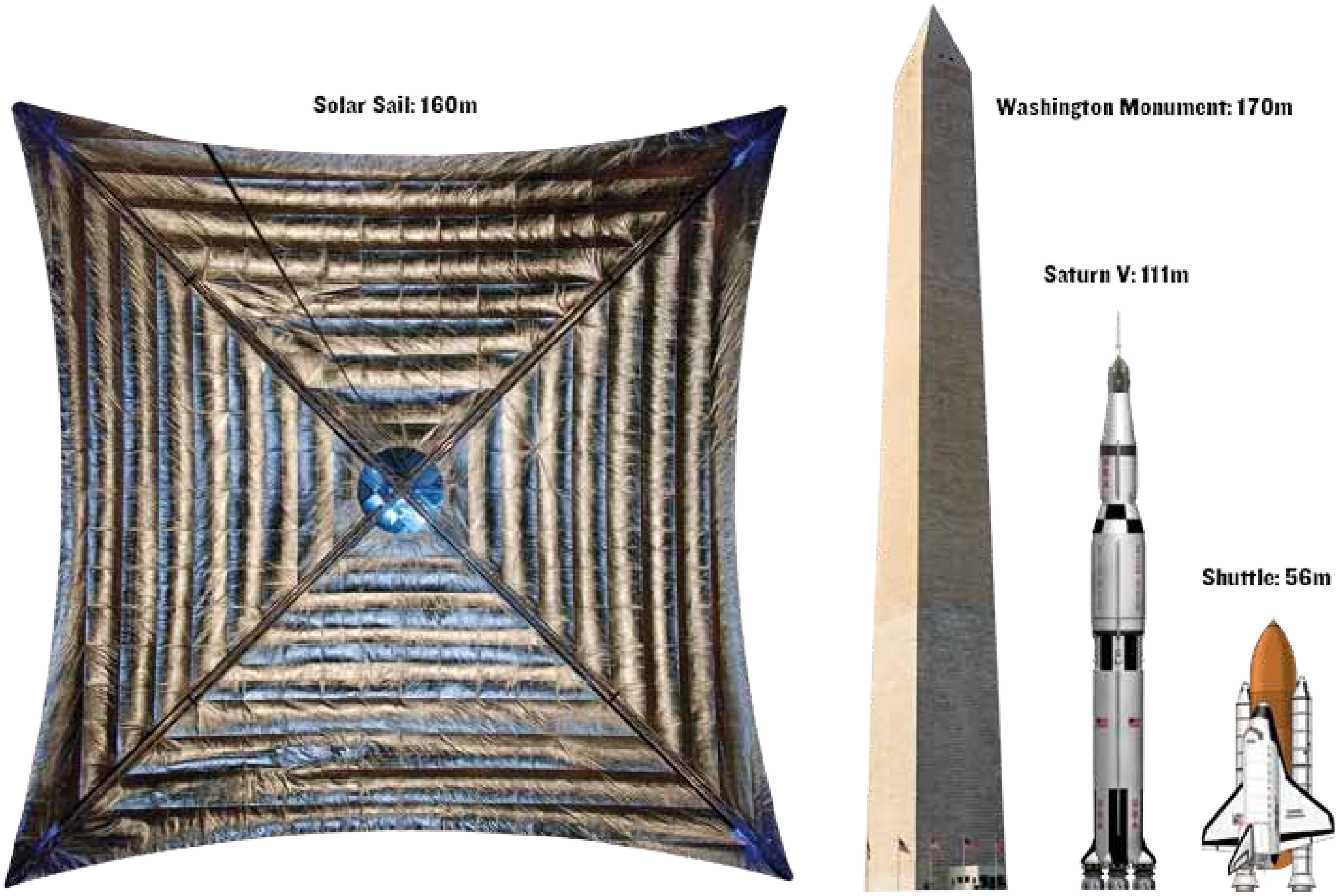
Making a film

Two polyimide films appear to be leading candidates as sail material for initial demonstration missions. One is Kapton, made by DuPont. The other is LaRCT-CP1, developed by NASA's Langley research center but licensed to the NeXolve Corporation, Huntsville, Alabama.

Dachwald and other German solar sail advocates say they probably would use Kapton as the base of their sail material. Justin Blount, DuPont global business manager of high performance films, says Kapton is well suited for solar sails. 'The material's robust physical properties over a wide range of temperatures allow it to be used in the temperature extremes of space,' he says. 'Also, these robust properties are important for folding/packing and then unfurling in any application.' Blount declined to name previous or current solar sail customers or to reveal specifications.

Johnson, of NASA, prefers the CP1 of NeXolve. The sail of NASA's NanoSail-D was made of CP1. Johnson says Kapton degrades too rapidly: 'I do not recommend Kapton,' he says.

Blount counters that, like CP1, Kapton can be tailored for space missions. 'Kapton films have



NASA's proposed 160 x 160m sail would dwarf previous spacecraft

been used successfully in space applications for most of their 40-plus year history and can be selected or tailored to have the desired balance of properties for a particular application.'

Garrett Poe, the director of advanced materials at NeXolve Corporation, says that LaRCT-CP1 has several advantages over traditional polyimides. CP1 is essentially colourless, while traditional polyimides are orange or yellow. Also, CP1 can be cured at lower temperatures than traditional polyimides, which allows it to be applied to substrates with a lower thermal budget.

In using CP1 for prototype solar sails, Garrett says: 'We were able to fabricate CP1 in a much thinner gauge than off-the-shelf polyimides such as commercially available Kapton or Upilex.' Poe notes that NeXolve's sails end up about 2–3 microns thick, which translates into 4–5 grams per square metre.

Converting CP1 into a solar sail was 'not an easy task,' Poe admits. 'The work consisted of the fabrication of the thin gauge film, the metallisation of this film, and the assembly of this film into a large deployable structure. There's also considerable effort in the development of the support structure and deployable booms.'

'Anytime you have a new technology there is risk'

Launch control

Although no space agency yet has committed sufficient funding for a true solar sail demonstration, research is moving forward and it now seems a question of when, not if, the first spacecraft literally sails in space. Franz Lura, head of system conditioning at DLR's Institute for space systems in Berlin, was a participant in the April meeting of German solar sail advocates. He says the group has set a goal of a solar sail spacecraft of 30 grams per square metre for the initial in-orbit demonstration at an altitude of 400km.

The goal for the next step, using solar sail propulsion to stabilise a satellite position, would be 20 grams per square metre. The third step – a spacecraft of 10 grams per square metre – will require new technologies, Lura says, adding: 'I think chemistry has a dominant role.' But of course, the team still need to persuade DLR management to pay for a solar sail in-orbit demonstration.

Johnson is facing the same issues at NASA, and notes that NASA prefers low-risk, low-cost projects. 'Anytime you have a new technology there is risk,' he says, but adds: 'The only way solar sails get over the hurdle is to fly them.'

Some solar advocates tout a future of interstellar missions to contact other intelligent life forms, using giant lasers to provide the required photons. But Dachwald believes solar sail advocates should focus on the near-term benefits of missions within our solar system. People talking up interstellar travel with solar sails the size of dozens of football fields weighing nano-fractions of what is now possible are not helping the cause, he contends. 'That makes people think we are all crazy,' he says. 'We can already do some spectacular things. We don't have to wait 100 years for new technology. We can do it now.'

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