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HOW WE BEAT 2019 PDC TO NYC
BY 2 YEARS, WITHIN 2 YEARS, 2 YEARS AGO

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ABSTRACT

For the Planetary Defense Conference *Exercise* 2019, we set out to find ways to obtain the earliest possible characterization of the incoming (*fictitious!*) asteroid, 2019 PDC. After a partially successful deflection, a ‘small’ fragment was still bound for impact. The location was only known two weeks before impact – the time left for the evacuation of the larger New York City metropolitan region. With experience in Near-Earth Object (NEO) exploration mission design, solar sail and solar-electric propulsion (SEP) technology for small spacecraft, agile responsive design and integration, and from previous PDC Exercises, the importance of earliest possible information on impact location and energy was obvious. NEO in-situ exploration can provide invaluable information not just for deflection actions but also for planetary science and resource utilization. This is only possible with space missions closely approaching the asteroid. Expecting a solar sail mission flying in the 2020s could be re-directed, a unique feature of solar sailing, we searched for multiple rendezvous missions at initial sail technology characteristic accelerations of $\leq 0.10 \text{ mm/s}^2$. We found numerous options of up to three NEO encounters in the launch window 2019-2027 but none could divert to 2019 PDC in time. In addition, we explored very steerable and throttleable low-thrust solar-electric propulsion (SEP) rendezvous to a particular group of NEOs, the Taurid swarm which was expected to become observable in the summer of 2019, with a possible impact threat in the early 2030s. An acceleration of 0.23 mm/s^2 would suffice for a rendezvous in ≈ 2000 days. Shorter transfers are available at higher acceleration. Finally, we found two low-thrust options to 2019 PDC, one sail and one SEP, both arriving about 2 years before impact at the fragment, SEP requiring 0.3 mm/s^2 acceleration – about the performance limit we estimate for “now-term” technology. They require launch within less than 2 years of discovery of 2019 PDC, which we consider feasible provided that

the basic technology has been flown. This is the case for SEP but not yet for solar sails of which only a few demonstrators were flown. SEP has become a mainstream propulsion method. Soon, the majority of all spacecraft ever launched will be small SEP spacecraft. DLR GOSSAMER solar sails use a strategy for controlled deployment of large membranes based on a combination of zig-zag folding and coiling of triangular sail segments spanned between crossed booms, all unfolded by dedicated deployment units. To reduce the complexity of this system for fast-tracked initial solar sail flights an adaptation of that deployment strategy was developed that allows deployment actuation from a central bus. The mass of such a sailcraft will be slightly increased but its performance is still reasonable for first solar sail missions. This design was breadboarded to demonstrate feasibility of the deployment strategy and its performance analyzed. On this background we developed two preliminary spacecraft designs by taking SEP off-the-shelf and getting solar sails into space soonest. We present how we beat 2019 PDC to NYC by >2 years, within <2 years, 2 years ago – and didn't tell anyone.

INTRODUCTION

The PDC 2019 provided an exercise scenario that in many ways was a 'middle of the road' situation if any such exist for incoming asteroids: a 100 to 300 m diameter Potentially Hazardous Asteroid (PHA), discovered some 8 years before impact, mostly difficult to track by telescope, and just barely out of reach for planetary radar which is the only means to quickly ascertain the impact risk during the discovery opposition period. The orbit of 2019 PDC (note the impossible three-letter provisional designation – it's an exercise!) is of average eccentricity and inclination for Near-Earth Objects (NEO). Only the relatively brief lead time till impact and its particular phasing with Earth makes it a somewhat challenging target for the exercise (Chodas et al., 2019) and an interesting one by our standards. (Pelsoni et al., 2016, 2018)

Our asteroid related background is in small spacecraft based solutions including flight missions, hardware projects, and studies. The part of getting to the target asteroid is covered by deployment demonstrators for solar sails (GOSSAMER-1, Seefeldt et al., 2017a,b) and large lightweight photovoltaic arrays (GO SOLAR, Sprowitz et al., 2020) for solar-electric propulsion, among other things. Once arrived, our asteroid nanolandings spring into action like MASCOT flown aboard HAYABUSA2 to PHA (162173) Ryugu. (Ho et al., 2016, 2021a,b) Its successors such as MASCOT2 intended to fly on AIM to the moonlet of the (65803) Didymos binary NEA system as part of the AIDA mission with DART are long-lived derivatives; many were studied for the particular needs of other missions. (Lange et al., 2018a,b, 2020, 2021) And since the asteroid in question first has to be found, we can look back on our NEO survey satellite design of ASTEROIDFINDER/SSB. (Findlay et al., 2011a,b, 2013) When combined, these technologies match hand in glove to mutually enhance their capabilities and cover their weaknesses (Grundmann et al., 2015, 2017, 2019a,b) and pack even more punch together (Grundmann et al., 2011).

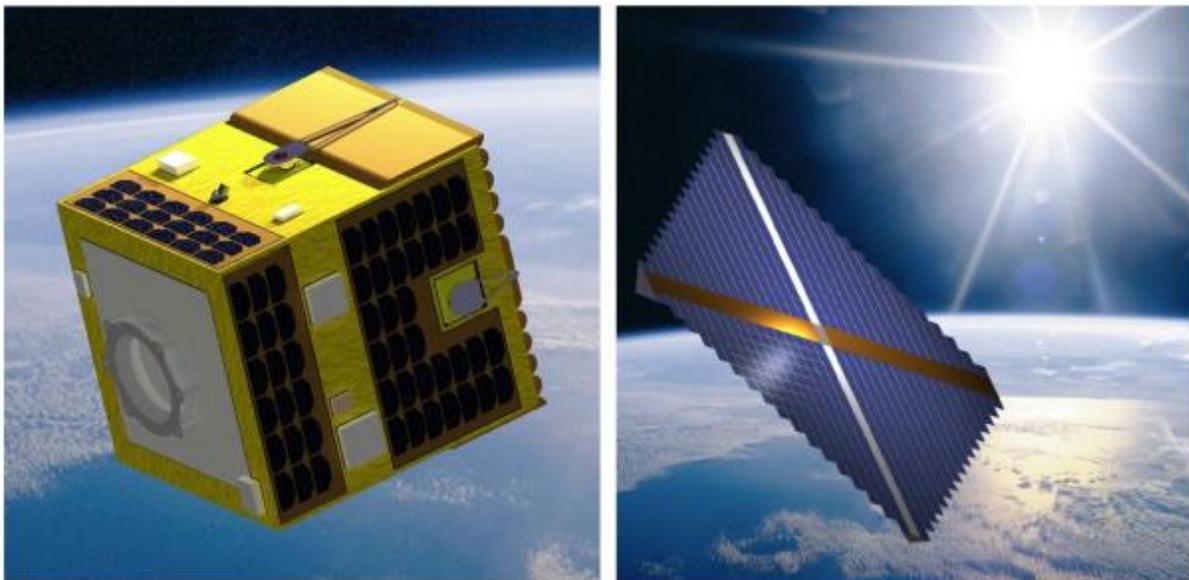
OUT HERE IN THE FIELDS: THE QUIET JOURNEY OF GoLUNAR

Unbeknownst to each other, while some of us (CL, JTG) were itching to give the then-planned advanced bus avionics technology test satellite, S2TEP, of DLR Bremen

(Dannemann et al., 2018) a slightly more exciting mission than endless laps in low-Earth orbit (LEO) by going for that pie in the sky that we would call a planet if it wasn't already our Moon, a fresh new-space start-up including one of our former students (LK) was gearing up at the FH Aachen university to pave the way for future lunar miners by designing a responsive and fast-built Earth-Moon conveyor bus, Levity Space System's¹ ESCI.

Levity Space was looking around the commercial space market for large lightweight photovoltaic panels to power their RIT2X SEP engine while we were considering the large photovoltaic (PV) membrane deployer demonstrator GoSOLAR as the most likely major tech-dem payload of S2TEP. The power of such a (5 m)² membrane photovoltaic array has to be dumped somewhere to demonstrate its capability. Although it was to be fully equipped with a fancy foldable power and instrumentation harness for an all-in credible deployment demo, most of the usable area of some 20 m² was limited to carrying purely mechanical PV dummies because of the limited power-taking capability of the slim and efficient S2TEP bus, a (60 cm)³ cube packed with advanced avionics. In the ensuing trade between adding a large deployable dump radiator, a bank of car headlights, on-membrane power shunting, and other similarly creative solutions, one in particular solution for efficient power wasting stuck out: SEP engines when seen as power dump radiators are incredibly efficient in terms of mass and volume.

Then, one thing that future lunar explorers, prospectors, miners, and photovoltaic cells have in common is some degree of sensitivity to ionizing radiation. Both, GoSOLAR and Levity Space, had compiled their own radiation monitoring payloads; the former with extensive background from a previous selection of small radiation instruments for GOSSAMER-1, the latter proceeding along the lines laid out by crewed spaceflight focused studies. These two radiation payloads, when put together consisted of almost the same set of instruments that were the catalog of candidates considered independently in yet another study for a Lunar Gateway Radiation Platform (LGRP) proposal – overall, a very nice case of convergent evolution that we thought we might as well add up in synergy for the PDC 2019.



GoSOLAR/S2TEP in launch configuration (left) and with GoSOLAR deployed (right)

¹ <https://levityspacesystems.eu/>

Before we get much older: Responsive Small-Space

We also figured that a – for the purpose of the exercise fictitious – start-up spearheading a market and venturing into lunar resources by responsively obtaining hardware commercially off-the-shelf (COTS) with an eye on the long run might just as well consider diversification in entering a game that's sometimes easier reached than our nearest nighttime illumination in terms of ΔV : asteroids. Such a company might like to accept a very well tested MASCOT Flight Spare (FS) in near-mint condition, refurbished with a shiny new photovoltaic finish, for the purpose of looking after newfangled membrane-based thin-film photovoltaics as a [Membrane Ageing Studies Concurrent Observations Technology package](#) by conveniently repurposing (Grundmann et al., 2015) all its science instruments (Bibring et al., 2017; Grott et al., 2016; Herčík et al., 2016; Jaumann et al., 2016) and bus sensors (Ho et al., 2016, 2021a,b). There are examples of similarly agile and fast-paced projects achieving flight. (Day et al., 1998; Grimm et al., 2019, and references therein; Hall, 1977; McDonald, 1997; Peebles, 1997)

...and at this point in time and with a subtle change in typography, we left the real thing and entered the PDC 2019 Exercise with a few [fictitious press releases](#) tucked up our sleeves just in case the exercise would turn out to be not so rigidly scripted (as it was, in the end).

+++ FROM OUR CORRESPONDENT ABROAD, APRIL 29TH, 2019 (UT)
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GoLunAr Ltd, an international consortium of small and medium enterprises, semiconductor research and space technology institutes reported today that it raised additional funds to continue and complete the development of a small spacecraft to test new propulsion, solar cell and space structures technologies for future lunar outposts and their commercial supply missions. The GoLunAr mission is planned to launch in late 2020 or early 2021, sharing the ride with a large commercial communication satellite into a geostationary transfer orbit. From there, it will proceed under its own solar-electric propulsion to the Moon, paving the way for future space tugs to deliver cargo and astronaut supplies into lunar orbit for research and in-situ resources utilization. The GoLunAr consortium opened an announcement of opportunity for experimental lunar, planetary science and communication payloads of up to a few kg, each. In a move of transparency following the recent criticism of reclusive space billionaires, GoLunAr encouraged private individuals, radio amateurs and publicly funded research institutions to submit their proposals. "We learned a lot from the solar sailing, renewable energy, plasma physics, and nanolander communities in the last five years," said GoLunAr CTO Yvonne Yarborough, "Peer-reviewed science is the greatest thing people ever invented. We just had to pay our journal subscriptions, pick up the papers and turn them

into a system. This is our way of giving back." Asked about the company's aggressive schedule she added, "Oh, they've been there, done that. To go from preliminary design to Flight Model in 2 years is space qualified, TRL9. Since the late 50's, actually. Has a lot of heritage. It's very much fun and rewarding, mutually, to work with a bunch of nice ol' guys in their late 70's to 90's. And we don't have all those funding authorities and review boards to keep happy. It's just us and them and the stakeholders."

Don't need to be forgiven: Venture Commercial

We imagineered us a small company with the freedom to make a difference *after* they got the money, without bureaucracy in the way non-institutional venture capital is run at the best of times based on trust in the capabilities of the techie folks and on a personal investor – solution provider relationship. So, let's assume a few days after the discovery of 2019 PDC a few engineers gave their investor a call with a crazy idea about this asteroid that stubbornly kept the center of its scatterplot on the B-plane aligned with the planetary home of everyone attending. Looking at our reporter's notes it seems they got the word to get up and 'Go!'. And so they did.

+++ LAUNCH PRESS KIT, OCTOBER 03RD, 2020 (UT) +++

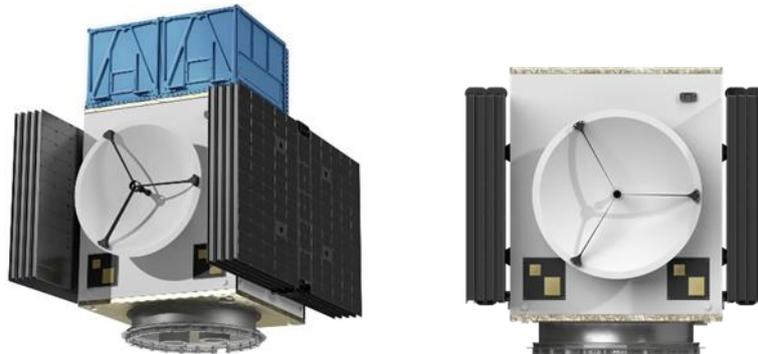
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13.) Secondary Passenger: GoLunAr

The GoLunAr small spacecraft has been advanced from the originally manifested launch in February due to a combination of primary payload schedule requirements and residual launch vehicle capabilities. The small spacecraft was designed to accommodate launch vehicle changes easily by a rugged structure and strictly adhering to our standardized secondary payload 'micro' envelope. GoLunAr was completed and acceptance-tested nearly half a year ahead of schedule. It will be the last payload separated just prior to upper stage passivation and safe disposal. GoLunAr Ltd CTO Yvonne Yarborough thanked the consortium members for their support of responsive space operations: "There are few people in the solar system stuff business, and even fewer in the southern hemisphere. One of the two of them involved in local planetary development companies contacted a generous collector of aerospace hardware up there who provided not just a qualified spare Xenon tank from his museum collection which allowed us to resolve the concerns voiced by the primary payloads, and thus to make this launch well ahead of our own planning, but also a full load of Xenon. Also, we thank our launch provider for offering us to tag along during the upward disposal of the upper stage after payloads delivery to geostationary orbit. This will give us a head start to the Moon, and the seismometers there a well calibrated bang to listen to while we watch that stage diving in.

With the full propellant tank, we hope to operate our propulsion system for several years to come.”

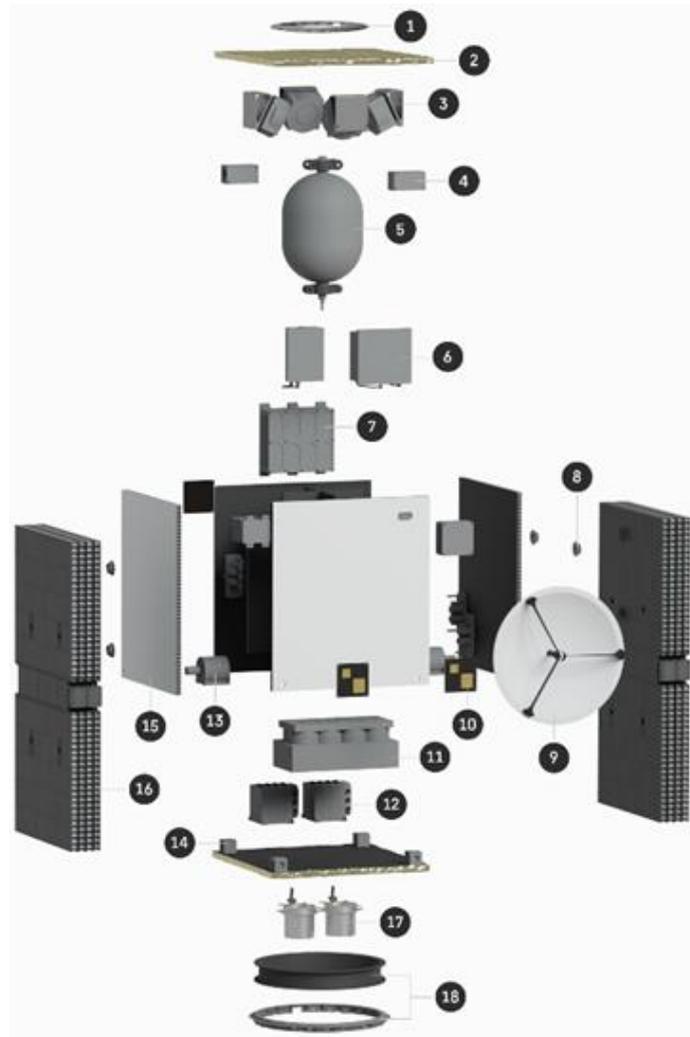
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Launch configuration of ESCI – blue: payload box example

Don't look past my shoulder: Changing a Lunar Resources Mission

A SEP universal satellite platform currently in development made a viable baseline for the 2019 PDC encounter of [GoLunAr Ltd.](#) The [STEIGER-ESCI](#) as developed by German new-space start-up [Levity Space Systems](#) for [GoLunAr Ltd.](#) is a satellite platform in washing machine format of 325 kg wet mass at 125 kg dry mass including a 50 kg payload. Not only in the context of the PDC 2019 exercise it offers a universal payload deck, up to 2500 W of electrical power, a low thrust propulsion system actually available on the market in 2021 (RIT2X by Arianespace, 88 mN thrust and 3400 s specific impulse), a communications system for deep space applications (up to 50 Mbps), a closed-loop ADCS system with an accuracy of up to 10 arcseconds, and a lifetime of more than than 5 years in deep space. The platform is designed as a deep-space SEP kickstage to substantially extend the reach of mission concepts beyond the capabilities of the launcher. To this end, flexible payload and “cargo” interfaces are employed, to be able to not only transport dedicated payloads, but also smaller satellites like CubeSats and even other microsats, i.e., spacecraft of a similar size as the ESCI bus itself. By using an electric RIT propulsion system and large solar panels, ESCI is capable of sustained maneuverability as well as providing very high electrical power to payloads and cargo when not thrusting. The power consumption of typical microsat payloads can be covered while thrusting.



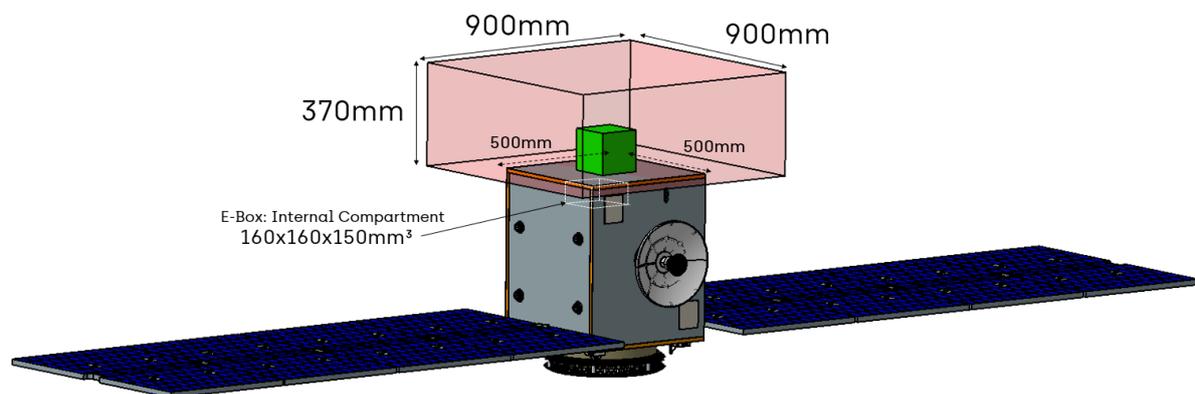
Exploded view of ESCI

With this, it allows to accommodate and operate high-fidelity and power-hungry payloads on its payload deck and to supply ride-share to nano-spacecraft or cubesats until they reach their respective target trajectories, where they would be separated. Multiple missions, all based on multiple ESCI platforms can be employed to encounter 2019 PDC (although we envisaged only one launched for our scenario at the time) or 2021 PDC, covering various purposes like imagery, spectroscopy, carrying swarm-spacecraft to be set free around 2019 PDC, carrying impactors to 2021 PDC (Grundmann et al., 2021), etc., using currently available launch solutions. As low-thrust simulations show, the platform reaches the necessary accelerations for optimized trajectories to 2019 PDC by Ceriotti et al. (2020), allowing a low-thrust encounter well in time to extend the precise impact warning substantially. With this, a flexible plug-and-play-platform approach employing fast-paced launches in early and late-stage is possible.

Liberated from the fold: Payloads with a Cause Go Beyond Lunar

The 50 kg payload assumed in the [STEIGER](#)-ESCI design (designated by ‘mission’-‘bus’ or ‘payload’-‘bus’) is well sufficient to carry the *entire* combined catalog of radiation platform instrument candidates (we assume for the original lunar mining environment scouting mission), a fancy navigation tele camera (we suggest adapted

from the ASTEROIDFINDER/SSB instrument sensor and processing technology for pure position astronomy going after a tiny PHA; Findlay et al., 2011a,b, 2013, Grundmann et al., 2013), and a MASCOT nanolander of nearly any kind studied so far. Options for the latter include the refurbished MASCOT FS (Grundmann et al., 2015) which could actually have been made available in time, a design further upgraded to approximate MASCOT2 with maximum physical MASCOT FS reuse (Lange et al., 2018a,b, 2020, 2021), or a further upgrade with self-transfer propulsion and navigation capability (Chand, 2020). The latter could have been on the map of GoSOLAR as well as GoLunAr already, primarily for GoSOLAR membrane inspection with the option of either *one final* fly-around (no re-docking capability) or an optional post-lunar extended mission to a NEO. The options for this range far, from a rendezvous as we envisaged for GOSSAMER-3 + MASCOT FS earlier (Grundmann et al., 2015, 2017, 2019a,b) to a fast fly-by as was performed in December 2012 by Chang'e-2 to (4179) Toutatis. In the latter, a smartly spun-up or self-transfer capable nanolander could have imaged the far side of the target asteroid in whizzing by to be lost forever in the interplanetary abyss. A short end for a long-lived MASCOT (as all future ones will be) but maybe worth the other sights of a 'poster asteroid' of the early PD years if a rendezvous can't be achieved.



300l Payload Volume

3.85l Internal Compartment

ESCI payload volumes

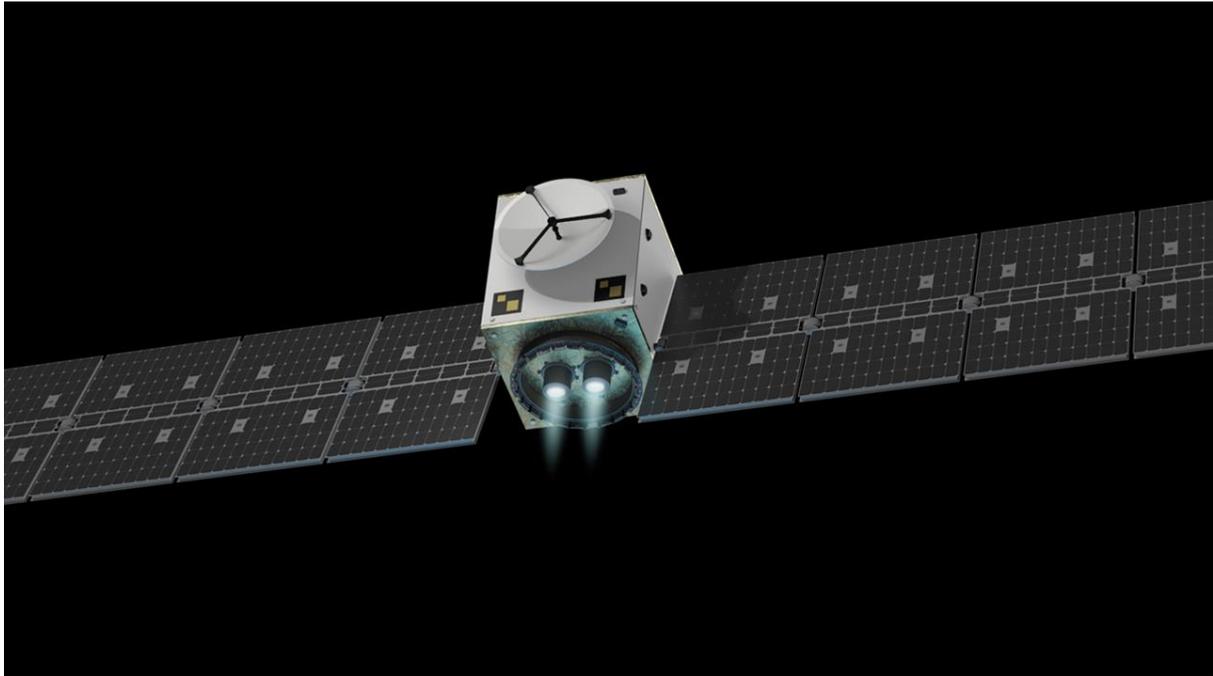
Who spurred us on: Digging Deep

Where humans travel they are mining. Mining is the search for and recovery of specific mineral resources. On Earth we do it since the very beginning of the Stone Age (by definition, kind of). On the Moon, the Surveyors, Apollo astronauts, and Luna landers shoveled, pick-hammered (if not -axed) and drilled into the local rock. One that didn't but went to look at the mineralogy from above with the fresh eyes of new instrument technology was named after a miner's song, Clementine. Venera landers used several of their precious few minutes of life to drill into the faintly glowing 500°C hot surface on Venus. On Mars, the Vikings picked their shovels of dirt (for a change, in search of life – exobiologists in pursuit of habitability parameters, biosignatures & biotracers please forgive the use of the four-letter word here) and pretty much every lander that followed at least took a peek at the dust, dirt, soil or rocks churned up by their landing, wheels, or highly specialized geotechnical tools. Asteroid mining is on our radar, too, (Grundmann et al., 2016, 2018) and in another case of converging evolution, the first

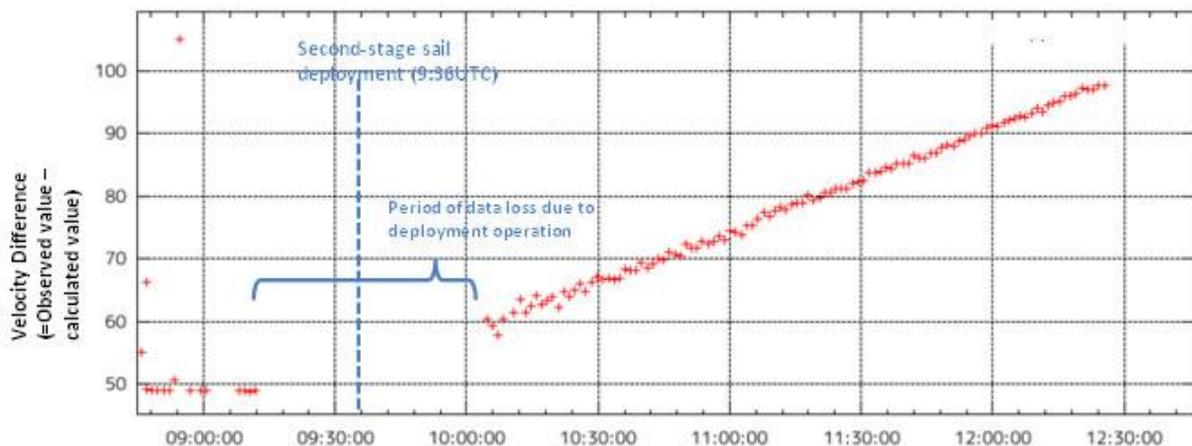
steps towards the ESCI platform by Levity Space Systems were done in pursuit of a long-term sustainable structural change initiative for mining regions in the state of North-Rhine Westphalia in Germany.

+++ ADVANCED TECH BIZ FLASH - OCTOBER 29TH, 2020 +++

The recently launched STEIGER-ESCI spacecraft of GoLunAr Ltd. seems to perform nominally after first check-outs. STEIGER stands for its mission, 'Solar-electric Transfer from Earth to Interplanetary space using Gossamer solar array for the Exploration of lunar Resources'. ESCI is the spacecraft bus procured from Levity Space Systems, a new-space start-up based in Germany. The cruise engine was already started. Independent experts note that this is unusually early in its flight, but only one of the mysteries of this mission that its owner company has recently become unusually tight-lipped about. At the confirmation of ignition and nominal operation of the solar-electric drive, there were none of the usual cheers and hugs familiar from webcasts of NASA or ESA operations, but a rather tense atmosphere seems to have prevailed. The Ops Lead of the German company operating the spacecraft for GoLunAr Ltd., followed the upturn of the velocity tracking graph, rose, and began a confidently solemn traditional German miner's song. Within seconds, the whole team in the control center got up and sang all stanzas, some with tears in their eyes. They shook hands one by one, there seemed to be much talk in confidential terms, as one outside observer commented "as if they share a dark unspoken fear". Accidentally, the Lousberg-Sands Foundation Observatory's telescope independently confirmed the successful ignition when a few hours later a strange brightening in the many series of dots in their images, at first thought to be a tiny asteroid rotating, were correlated with the trajectory and timeline of events of the mission. At this point of brightening, STEIGER had already lit up its engine in the dark of space.



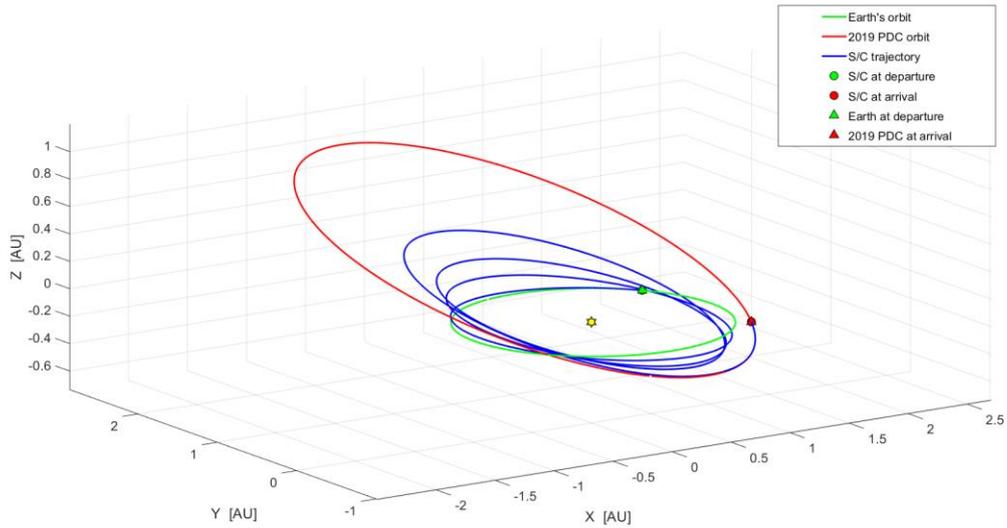
A moving moment: ESCI under SEP power ventures into the great black yonder



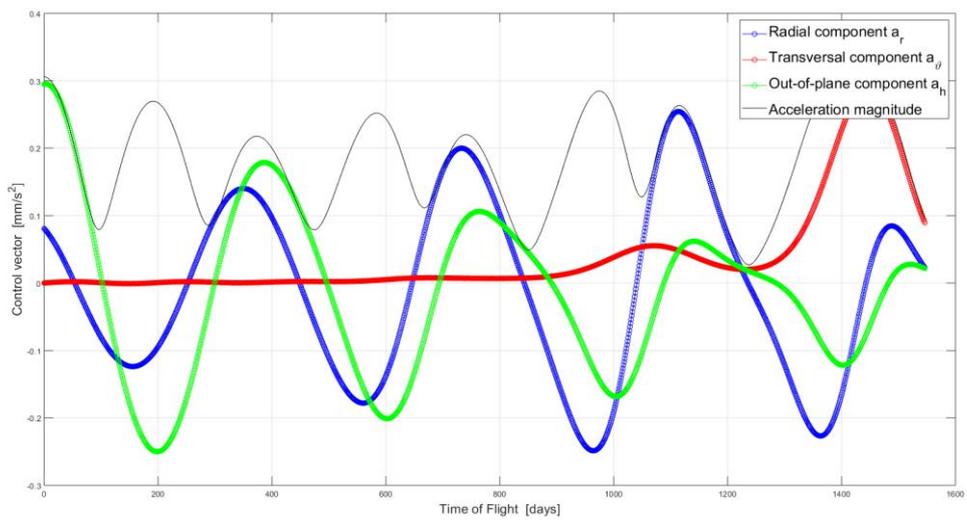
Another moving moment: solar sail acceleration of IKAROS confirmed by Doppler tracking on June 6th, 2010 UT (JAXA, 2010)

The exodus is here: For the Whole Ride

Riding all the way in to impact for two years from achieving rendezvous, [GoLunAr](#)'s trajectory enables constant tracking and monitoring of the asteroid fragment. Ceriotti et al. (2020) extensively described the development of the trajectory and specified a specific impulse of $I_{sp} = 3000$ s and a mass ratio of $m_1/m_0 = 0.342$ for the successful SEP rendezvous trajectory. This would lead to a wet mass of 366 kg for a dry mass of no more than 125 kg. The configuration studied as [STEIGER-ESCI](#) can take advantage of the somewhat higher I_{sp} of the RIT2X engine, 3400 s. This results in a wet mass of 325 kg, very close to 300 kg configurations previously studied, and a ΔV of ~ 31.6 km/s.



For the long run: GoLunAr (blue) catching up with 2019 PDC (red) after departing from Earth (green) - from Ceriotti et al. 2020



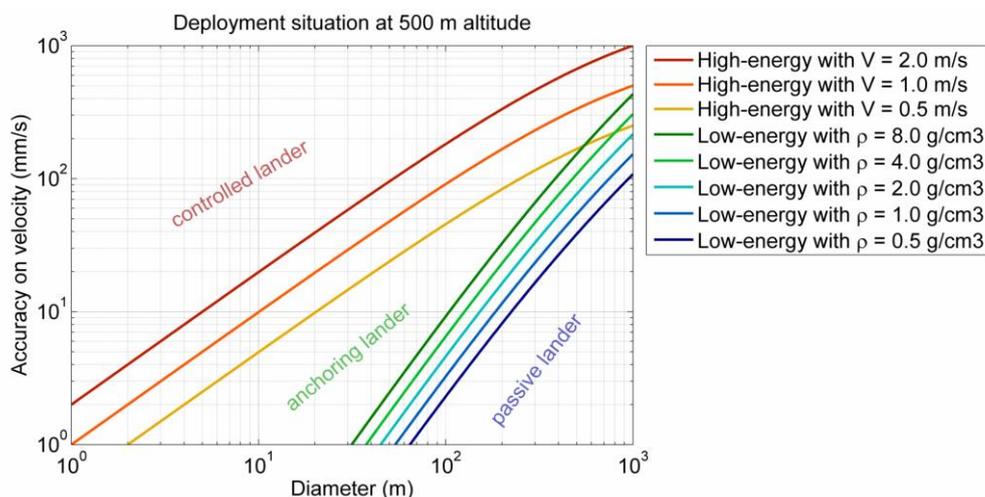
Er läuft und läuft und läuft: skidmarks after launch and when closing in, and not a day without thrusting for ESCI but plenty of performance margin most of the times - from Ceriotti et al. 2020

maximum acceleration, a_{\max}	0.3 mm/s ²
departure (launch) date	2020-OCT-27
Earth departure velocity, v_{∞}	0
arrival date	2025-JAN-22
total time of flight	1546 days (4.23 years)
relative distance at arrival	<1000 km
relative velocity at arrival	0
specific impulse	3000 s (29420 m/s)
propellant mass ratio	0.342 (<0.4)

Parameters of the SEP trajectory from Ceriotti et al. 2020

'Cross land: Hopping Over at the Brink

Landing on a very small asteroid can be difficult for a ballistic lander like MASCOT. Indeed, the 'surviving' fragment of 2019 PDC is borderline-small for an unassisted asteroid landing, as we described in Grundmann et al., 2019. MASCOT's separation velocity was 4.5 cm/s. At the 60 m diameter fragment of 2019 PDC the separation of a MASCOT from [STEIGER-ESCI](#) would have to be delivered with better than 2 mm/s accuracy at a fairly conservative altitude of 500 m, to allow a MASCOT to free-fall to the surface and be captured by bouncing away its kinetic energy collected long the way. This accuracy requirement applies to the sum of the pre-set separation spring of MASCOT (Grimm et al., 2020) and the velocity of the spacecraft passing very close to the asteroid that together place the nanolander into the asteroid's gravity well slower than local escape velocity.



Accuracy requirements on the delivery velocity of ballistic landers delineating the regions of feasibility for passive, anchoring (semi-active), and fully controlled (active) landers, from calculations by S. Tardivel in Grundmann et al., 2019

This result was one of the motivations to investigate self-transfer variants of MASCOT which can navigate and thrust themselves over to the asteroid surface. The capability for a bouncing landing and mobility on the surface typical of MASCOTs enable a very efficient solution and at the same time de-risk the carrier spacecraft mission which does not need to approach closer than several km to the asteroid surface. (Chand, 2020)

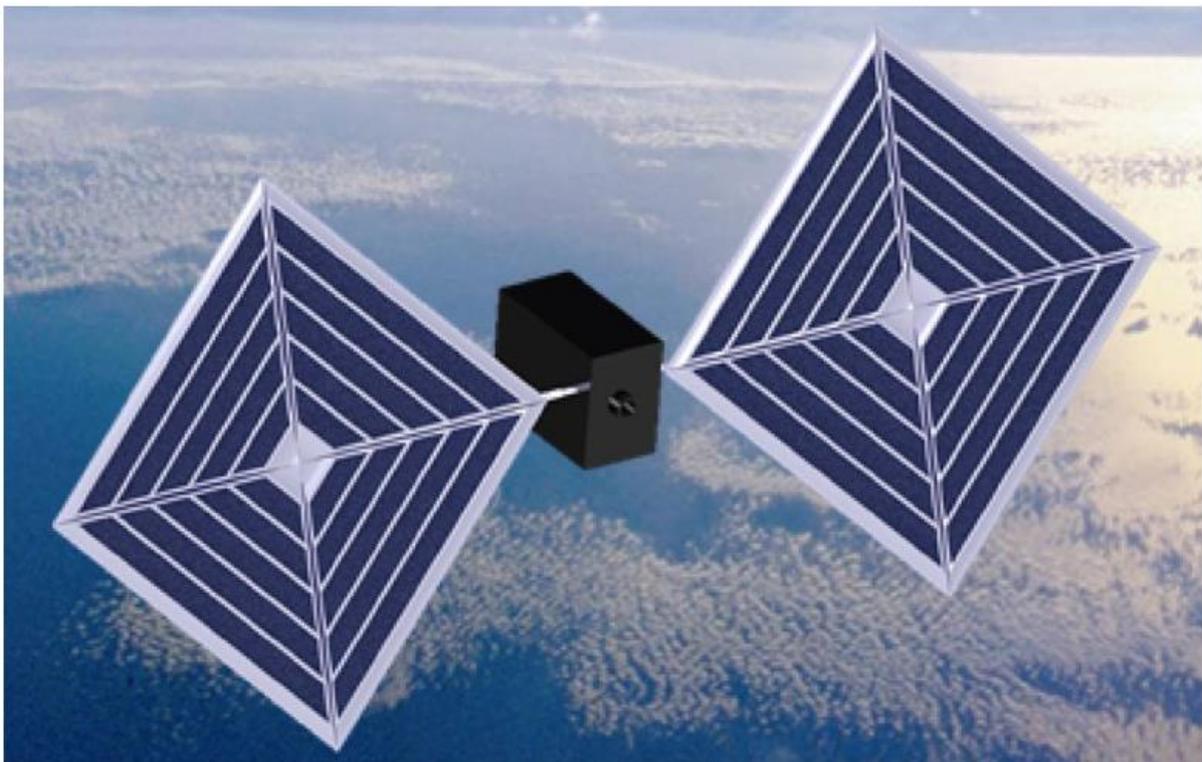
Whether by a most delicate drop from 500 m, by going in really close, or by self-transfer, it seems from the local news that the shoebox-sized [Membrane Ageing Studies Concurrent Observations Technology](#) package aboard [GoLunAr's STEIGER-ESCI](#) not just made it to the surface but stayed around in the asteroid's extremely weak field of gravity, and – somewhat unusually for a lunar resources endeavour as well as a very quickly re-used MASCOT FS – was fitted with a low frequency radio link reminiscent of the Low Frequency Radar (LFR, Hérique et al. 2018, 2019) of MASCOT2 (Lange et al., 2018a,b, 2020, 2021) perhaps suggesting that the [MicrOmega](#) (Bibring et al., 2017) FS, however most welcome aboard, was still busy in the HAYABUSA2 curation facility. Or LFR was just too handy a plot device to peg the asteroid to the by this point in time surely 'round the clock Deep Space Network tracking of [GoLunAr's](#) trajectory while doing some tomography of that rock and trying mass estimates to constrain the impact energy and air burst altitude.

SIDENOTE - THE EXTRA MILE

April 27th, 2027 - Bermuda

While the largest dedicated coordinated geophysical observation network deployed since the International Geophysical Year of 1957/58 and the atmospheric nuclear testing of the 1950's and 60's, and most of the horrified 8 billion inhabitants of Earth, and even astronauts in space, watched live the stupendous obliteration of the empty remains of New York City, a modest telescope and a small antenna pointed serenely into the sky above our beautiful island. Just seconds after midnight, New York time, and on time to the millisecond, a pinpoint of light appeared in the sky, not unlike Venus, quickly grew, exploded into sparkling fireworks, and faded away forever. The mission of [GoLunAr](#) had ended. It was this unlikely spacecraft that, instead of going to the Moon for business, had quietly flown past its original target almost to the day six and a half years ago, to vanish into deep space for a four-year journey to a rendezvous with the object of fear itself. Alone for months at a time, and when in communication accessible only at the pace of Morse telegraphs of the Wild West and through the largest radio telescope on Earth until recently, it weathered solar eruptions, fixed glitches, endured the cold of the asteroid belt and the unknown unknowns of an asteroid recently blasted to bits, and kept its tiny engine running all the way until it arrived there in January two years ago, missing the fly-by of NEOWOG only by a whisker. A few months later, in a most delicate manoeuvre it dropped its [Membrane Ageing Studies Concurrent Observations Technology](#) package towards the largest Earth-bound fragment of 2019 PDC. The shoebox-sized instrument package after much bouncing settled on the rocky surface fractured by the deflection attempt of September 2024 and transmitted most valuable data to predict the burst height at the day of impact. Using a

mechanism intended to excite controlled vibrations in the experimental photovoltaic membrane of GoLunAr for mechanical studies, it even managed to move around on the asteroid fragment. The high bandwidth, low frequency radio link between these two modules of GoLunAr enabled precision tracking of the asteroid all the way in, through ground stations and radio telescopes on Earth. The last signals collected here indicate that the instruments package was blown off the asteroid by the atmosphere just seconds before its signals ceased in the terminal flash. From its vantage point some 750 miles off to the side and trailing the asteroid, GoLunAr provided coarse one thousand frames per second movies of the explosion as well as high resolution pictures at almost movie frame rate, transmitted live to listening posts along the East Coast. A few days ago, it took a last look at the Moon as when it first left Earth, to calibrate its cameras on the same object after seven years in deep space. In between, it did not just walk the extra mile. It flew billions and billions. GoLunAr Ltd.'s shares currently follow.



A small spacecraft equipped with GoSOLAR photovoltaic arrays

THE CHANGE, IT HAD TO COME: NEOW0G, FOR SAILING OUT LOUD

On the background of two preceding PDCs in a row with contributions on the advantages of solar sailing in getting to wayward asteroids among many other publications to that effect, you may safely bet that we first tried to get 2019 PDC without

spending on tanks full of rare and precious noble gases, by solar photons only and directly.

Somewhere the Sun is shining: Stuck in no projects

Solar sailing understood as the concept of a propulsive force of sunlight celebrated its 400th anniversary around the PDC 2019, by Kepler's observations and remarks published in 1619 on the directionality of comets' tails. In the early 20th century, pressure due to radiation was experimentally demonstrated by Lebedev, and by Nichols and Hull. Oberth, Tsiolkovsky and Tsander proposed it as propulsion for space flight applications in the 1920s. The term 'solar sailing' was introduced by Garwin in 1958, at the beginning of the space age. Although the development of complete concepts and designs of sailcraft was occasionally carried through to the stage of hardware production and full-scale ground testing, and despite the – in terms of technology development research programmes – substantial effort invested in these projects, only simplified and/or sub-scale demonstrators were flown before the single exception, IKAROS. Their hardware development however started slowly. First deployment tests only occurred in the 1990's on the ground, and in suborbital flight in the following decade.

The flight of the Interplanetary Kite-craft Accelerated by Radiation Of the Sun (IKAROS) launched in 2010 piggy-back with JAXA's probe Akatsuki to Venus became the first attempt and success of a spacecraft propelled directly by sunlight. It has so far remained the only one in deep space. The IKAROS first demonstrated solar sail effect in space, as predicted, and performed the first gravity-assist of a solar sail on December 8th, 2010, at Venus. (Mori et al., 2009, 2012)



Sailing past another island in deep space: IKAROS flyby image of Venus
©IKAROS/ISAS/JAXA

After the primary mission was completed at the end of 2010, telemetry was received again in 2012, 2013, 2014, and 2015 when it entered hibernation as expected and in good health. With a sail loading of 1821 g/m² and assuming 90% efficiency, a characteristic acceleration of only 0.0045 mm/s² is achieved – and yet, it keeps

moving, accelerating off the ballistic path: By August 2013, IKAROS had already accumulated a sail-generated velocity change of 400 m/s. It also had taken photos of itself by means of two deployable cameras (DCAM, Matunaga et al., 2011)

IKAROS demonstrated solar sail effect even though it was a very heavy spacecraft with a mass of 315 kg and a net sail area of 173 m², a fill factor of 88% at its (14 m)² size. The very high mass is a consequence of its unique rideshare launch opportunity: the main payload, the Venus Climate Orbiter, AKATSUKI, was too light for the very large H-IIA rocket. A very substantial total trim/damping weight of 700 kg was needed of which IKAROS had to come in between 300 and 315 kg. The development time was limited to 2½ years, requiring an accelerated testing schedule. The project relied heavily on re-use of already existing components of the suspended LUNAR-A mission and copy-built units from AKATSUKI and HAYABUSA. (Matsuura, 2010)

With our children at our feet: Citizen Sailing

Considering the history of IKAROS which was made possible by a few individuals at ISAS recognizing the opportunity of a massive trim weight for what it could become for solar sailing, and our own experience with the sudden death of membrane deployment related projects (Spietz et al., 2021), we found encouraging perspectives in citizen science, crowd funding, and crowd sourcing – so why not crowd sailing?

We knew it all along: Solar Sailing D.I.Y.

“Give me ten million bucks and leave me alone for five years. Then you’ll have solar sailing.”
– *Sailors, Anonymous*

Any brief history of solar sailing reveals who is currently leading the field in terms of flight hardware: small institutional and privately funded projects. The Planetary Society started this new millennium with a suborbital deployment test unfortunately lost in a launch vehicle failure. Leading up to IKAROS, ISAS performed two deployment tests on a sounding rocket in 2004. In 2005, the Cosmos-1 sail of the Planetary Society was lost in a launch failing to achieve orbit. One more ISAS deployment test followed as a stage-attached orbital payload in 2006. Two years later, Nanosail-D by teams at NASA MSFC and Ames was lost in a launch failure. Only months after IKAROS in 2010, Nanosail-D2 achieved orbit and was deployed in early 2011. In 2015, the Planetary Society’s Lightsail-1 deployed successfully in a low orbit that soon decayed to re-entry. Lightsail-2 was launched between the PDC 2019 and the International Symposium on Solar Sailing (ISSS) 2019 and managed to raise its orbit by a few km just in time for the latter, although it was just barely able to overcome atmospheric drag with the limited means of attitude control of its cubesat bus. (Nye, 2019)



D.I.Y. solar sails? - Been there, done that. ... Well, as far as getting really efficient deployers and some more nice stuff space-qualified.

+++ FROM OUR CORRESPONDENT ABROAD, DEC. 24TH, 2019 (CET)
+++

The WikiMiti Foundation for Potentially Hazardous Asteroid Mitigation today celebrated the 17-millionth donation to its crowdfunding campaign for a "solar sail" to achieve the first close look at the asteroid known as "2019 PDC" which some astronomers believe could impact Earth in the near future. Volunteer spacecraft aficionados from all over Europe converge on the city of Bremen in the north-west of Germany where a grassroots industry has sprung up occupying disused industrial estates. Some recover spacecraft "spares" and "models" from museum displays and space industry storage dumps. A local space systems institute waived license fees on their "drag sail" patents, apparently another obscure space-cleaning technology. Local painters donate scaffoldings to put up vast "cleanroom tents" in gyms where schoolkids, refugees and sportsmen alike patiently glue roll after roll of silvery foil thinner than a human hair to make triangular sheets that could cover whole tennis courts. 627 kids from a school in the north of town made up the largest team when it was announced their contribution would count for the space course and work experience programs offered there. They believe that their sail will not only be the first to look at the inbound space rock but also the first to strike back at it. A young student from New Zealand won the online contest to name the spacecraft which is now called "NEOWOG", reportedly after an endangered local flightless bird.

As the tall ships do: In the Doldrums

Cerioti et al. (2020) attempted to find a previously published realistic near-term capability solar sail trajectory that could be deflected to rendezvous with or at least fly by 2019 PDC within the exercise timeframe, 2019-2027, to demonstrate the unique in-flight target change capability of solar sails. Such a trajectory would be the closest possible equivalent of an already flying solar sail in the context of this fictitious exercise scenario. Like a real sail-based MNR science mission's trajectory, an already published trajectory is not optimized for or tweaked towards the exercise scenario. Selection criteria were a publication date before the send time of the announcement email regarding the release of the PDC 2019 exercise scenario on October 31st, 2018, 17:35 UT, that the published trajectory is 'in flight' 2019-2027 or can be continued into this period by reasonable propagation e.g. in agreement with a likely extended mission, near-term sail performance, $a_c < \approx 0.3 \text{ mm/s}^2$, and data availability.

In time for the PDC 2019 deadlines, no such trajectory was found, partly due to the limited set of trajectories available at short notice, partly due to the relatively brief timeline of only 8 years within which a sail leaving Earth or its latest target NEA at $c_3=0$ first has to pump up eccentricity and inclination and to phase with the target. Under the given constraints, inward acceleration which a sail can't achieve would be required to achieve rendezvous.

This led us to search for a SEP trajectory with the result described above.

Put on my lead boots: Small ship, giant tug

However, we found a launch window for a ‘kick-started’ solar sail of near-term performance for a fast fly-by at 2019 PDC more than 2 years before the fictitious impact. The Earth departure velocity is high, at $v_{\infty} \approx 7.5$ km/s respectively $c_3 \approx 56.25$ km²/s² but still within range of the ‘kick-start’ launch options for small spacecraft which we presented in our contribution to the PDC 2017 and subsequent papers. (Grundmann et al., 2017, 2019a) It nearly matches the 500 kg payload to $c_3 = 56$ km²/s² option for a computational model of a stripped-down Ariane 5 ECA presented there. Within this payload limit and accounting for a customized dispenser, 2 to 3 small spacecraft solar sails could be launched at the same time on the same trajectory.

+++ LAUNCH PRESS KIT, MAY 01ST, 2020 (UT) +++

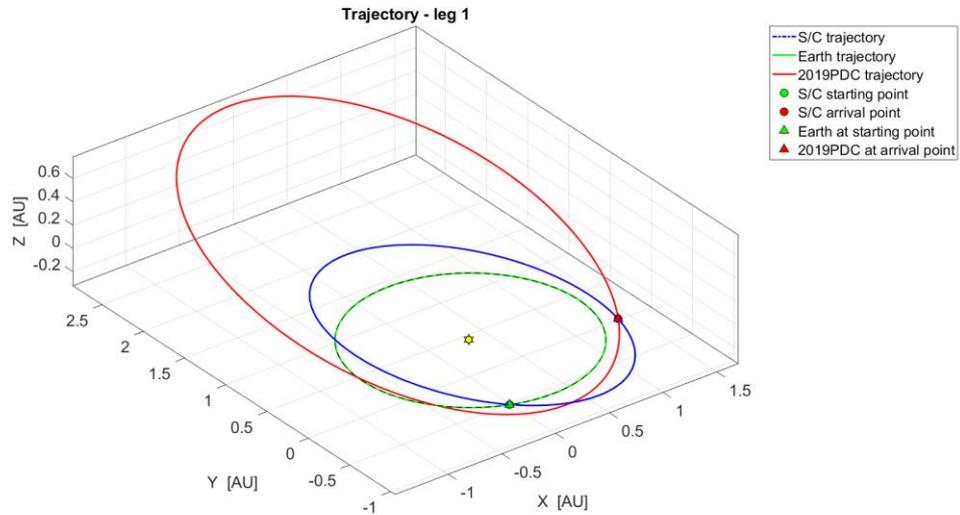
The first test launch of our new and largest launch vehicle will proceed later this month with modifications for high velocity planetary missions, in view of the predicted growth in the emerging space in-situ resources sector. Also, the possible upcoming mitigation of earthbound asteroid 2019 PDC yet to be confirmed as an impactor may benefit from this extension of our portfolio. Instead of launching an instrumented dummy, we accepted the offer by the NEOWOG community to use their recently completed small experimental spacecraft which passed our flight acceptance criteria. It has been equipped with all sensors required to record the launch environment for future commercial and institutional passengers of this launch vehicle configuration. There are no secondary payloads on this flight other than the deployable cameras on NEOWOG which will monitor its membrane deployment experiment in deep space.

Put out the fire: Stretching launchers’ legs for a point in time and space

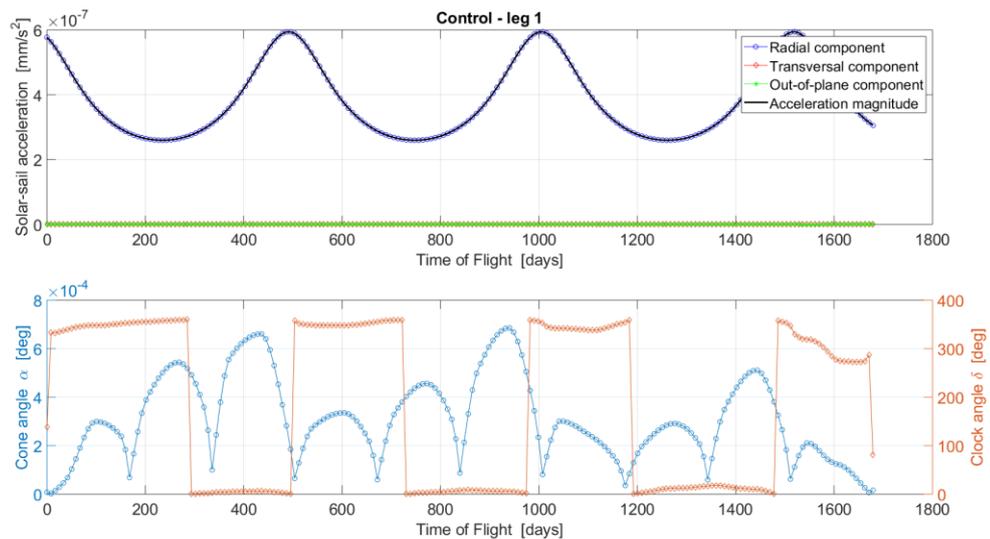
The following parameters were found for trajectories to achieve a close fast fly-by of 2019 PDC using near-term solar sail technology:

characteristic	acceleration	0.1 mm/s ²	0.2 mm/s ²
a_c			
launch date		2020-MAY-30	2020-MAY-31
Earth departure velocity, v_{∞}		≈ 7.5 km/s	≈ 7.5 km/s
arrival date		2025-JAN-03	2025-JAN-03
total time of flight		1679 days (4.6 years)	1678 days (4.6 years)
relative distance at arrival		76509 km	4696 km
relative velocity at arrival		10.45 km/s	10.44 km/s
semi-major axis, a		187714562 km (1.25 AU)	187714056 km (1.25 AU)
eccentricity, e		0.2037	0.2038
inclination, i		12°.43	12°.43

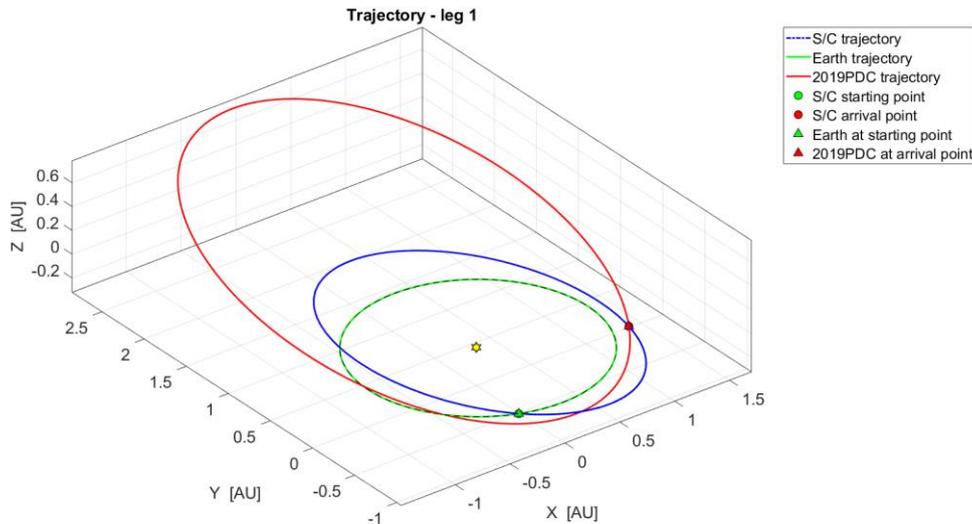
Orbital parameters of a 0th/1st generation solar sail fly-by mission at fictitious impactor 2019 PDC



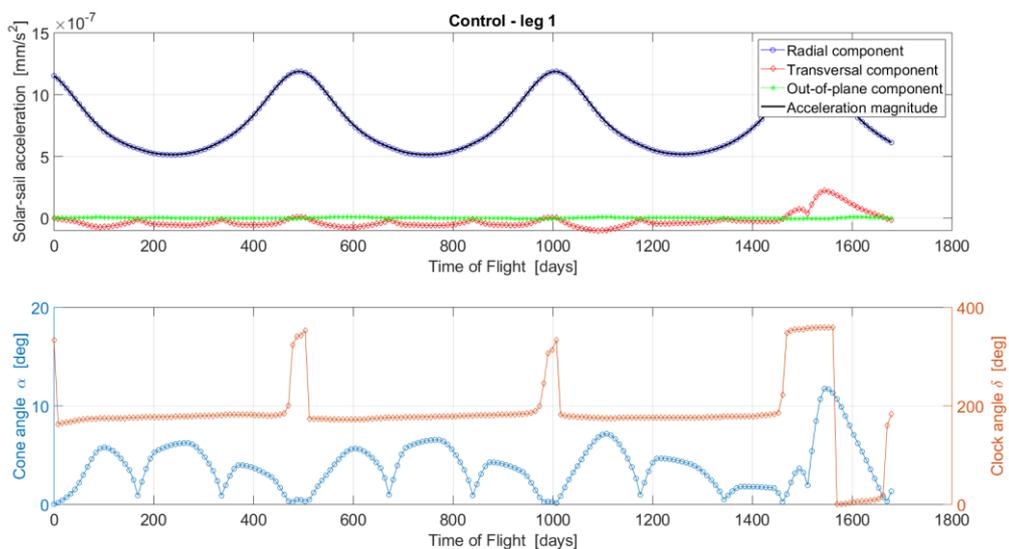
Oblique view of the 0th generation solar sail fast fly-by trajectory at fictitious impactor 2019 PDC, $a_c = 0.1 \text{ mm/s}^2$



Control history of the 0th generation solar sail fast fly-by trajectory at fictitious impactor 2019 PDC, $a_c = 0.1 \text{ mm/s}^2$



Oblique view of the 1st generation solar sail fast fly-by trajectory at fictitious impactor 2019 PDC, $a_c = 0.2 \text{ mm/s}^2$



Control history of the 1st generation solar sail fast fly-by trajectory at fictitious impactor 2019 PDC, $a_c = 0.2 \text{ mm/s}^2$

Looking at the table and figures above, it is immediately obvious that the trajectories are almost identical, despite the factor 2 difference in sail performance, $a_c = 0.1 \text{ mm/s}^2$ vs. $a_c = 0.2 \text{ mm/s}^2$. The large fly-by distance of the $a_c = 0.1 \text{ mm/s}^2$ sail is a first hint at what happens: Coincidentally, this performance is just very slightly below the minimum sail performance required to reach the target. The related control history shows that the lower performance sail is always facing the Sun with a near-zero cone angle. It has no trajectory control margin. (Its attitude control system obviously has to have a good control margin as it stays acutely pointed throughout.) All acceleration capability is put in the radial component, away from the Sun. In effect, it flies a mission profile similar to an ideal Displaced L₁ (DL₁) mission. (McInnes, et al., 2014) The sail thrust adds to the centrifugal force in the balance, allowing it to fly slower than a ballistic

object on the given trajectory, and thus phase with the asteroid to achieve the encounter.

The higher performance, $a_c = 0.2 \text{ mm/s}^2$ sail has a sufficient trajectory control margin and can provide some out-of-plane and transversal acceleration to fine-tune its trajectory. It achieves a useful fly-by distance already in this first iteration which could be further optimized beyond the task of cruise trajectory design. Still, most of its acceleration capability is invested in the radial component.

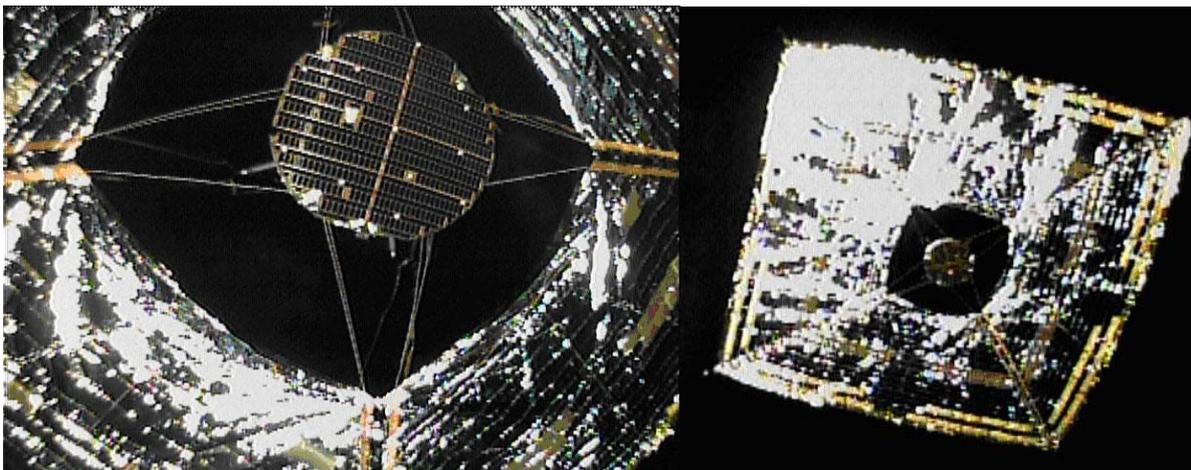
Whichever level of performance [NEOWOG](#) achieved in the infinite possibilities between $0.1 \leq a_c \leq 0.2 \text{ mm/s}^2$, according to the popular science tabloids' headlines it made it and came close enough with a little help from their friends:

+++ FROM OUR CORRESPONDENT ABROAD, JANUARY 22ND, 2025
(UT) +++

Some light at the end of the tunnel for New York City -
it's the asteroid.

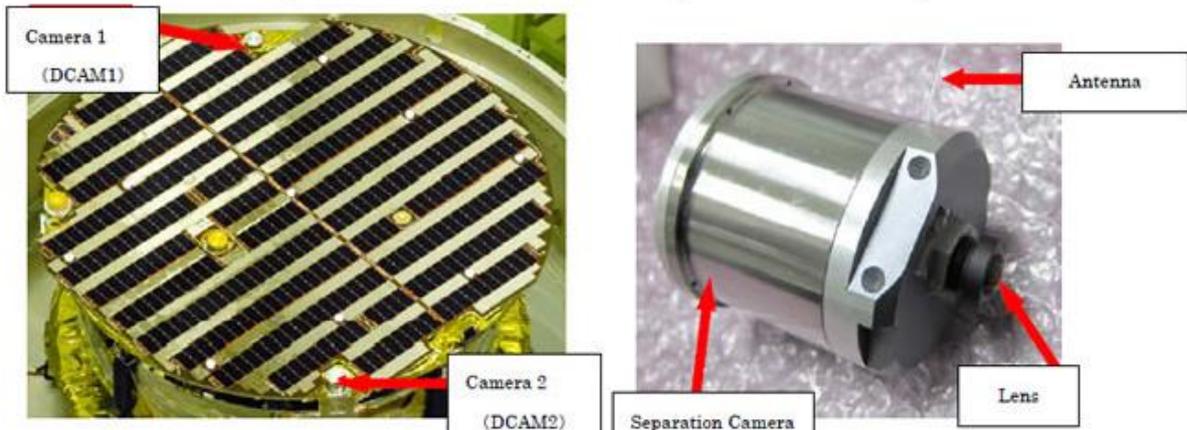
Today, the sobering results of the data returned by the gallant NEOWOG mission were presented in a joint meeting of the planetary defense advisory groups at the UN headquarters in New York City. No information whatsoever had been available for more than 100 days on the asteroid headed for Earth after the harrowing loss of the rendezvous spacecraft in a cloud of debris and rocky fragments shortly after the partially successful attempt to deflect asteroid 2019 PDC in early September last year. And no information would have been available for another two years from now until the asteroid fragments were predicted to become visible again to Earth's best telescopes. But on January 3rd this year, this tiny and flimsy-looking crowd-funded and crowd-built sailcraft flew by the remains of 2019 PDC in what appears to be a perfectly choreographed sequence of operations. The sail and a small camera ejected by it which was originally intended to image the sail deployment process passed on both sides of the asteroid. By imaging the asteroid and the fully illuminated sail against the background of stars with precise ranging of the ejected camera's distance to the sailcraft, the position and speed of the asteroid could be greatly refined. The data returned confirm the presence of one large fragment last seen through much dust and debris by the rendezvous spacecraft, which was hardly deflected at all. It is now clear beyond reasonable doubt that it is headed for impact within the New York City metropolitan area on April 27th, 2027, 12:01:38 a.m. EDT. It is a 60 m diameter rock which will release an explosion energy equivalent to 5 to 20 million tons of TNT. This is comparable to the largest nuclear weapons ever deployed, and up to 4 times stronger than the well-known Tunguska Event of 1908 over Siberia which flattened an area of forest the size of the beltway around Washington, D.C. A warning of this precision was so far only expected to be

available 10 days prior to impact. Preparations for evacuation can now focus on a much smaller area, and much more of the treasures of art and life of the city can be saved. In a final note, the team member who came up with the mission's name when still a school kid in rural New Zealand remarked, "I named it after the last organized attempt to build something to fly out there and learn much more about near-Earth asteroids than conventional spaceflight could, the Gossamer Roadmaps's NEO Working Group. The zero in there is just to say, we're not even what they thought of as a first-generation sail 20 years ago. After all the criticism of getting in the way of and diverting attention from the important stuff going on around 2019 PDC, the asteroid which shall never be named, I just want to confirm again that we never received a penny of tax money, and on behalf of the team I want to thank the science community for their generous support done in their spare time, in particular the radio and radar astronomy folks who let us talk to our baby through their babies. We'll continue to operate NEOWOG together as long as it flies."



Position of separation camera

Separation camera configuration



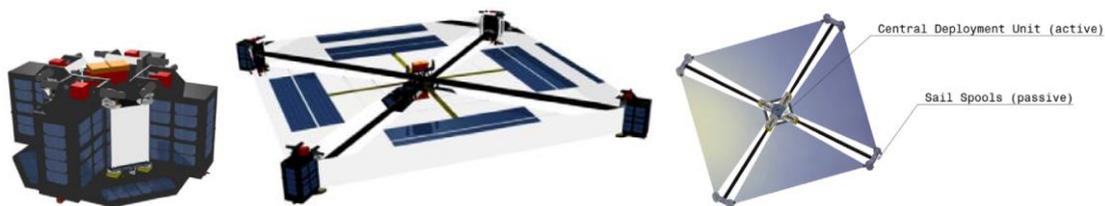
Another Space First by IKAROS: Solar Sail Selfies (top), accommodation (bottom left) and close-up of a Deployable Camera (DCAM) that took them (bottom right)

©IKAROS/ISAS/JAXA

So tired of moving slow: Design of a Now-Term Solar Sail

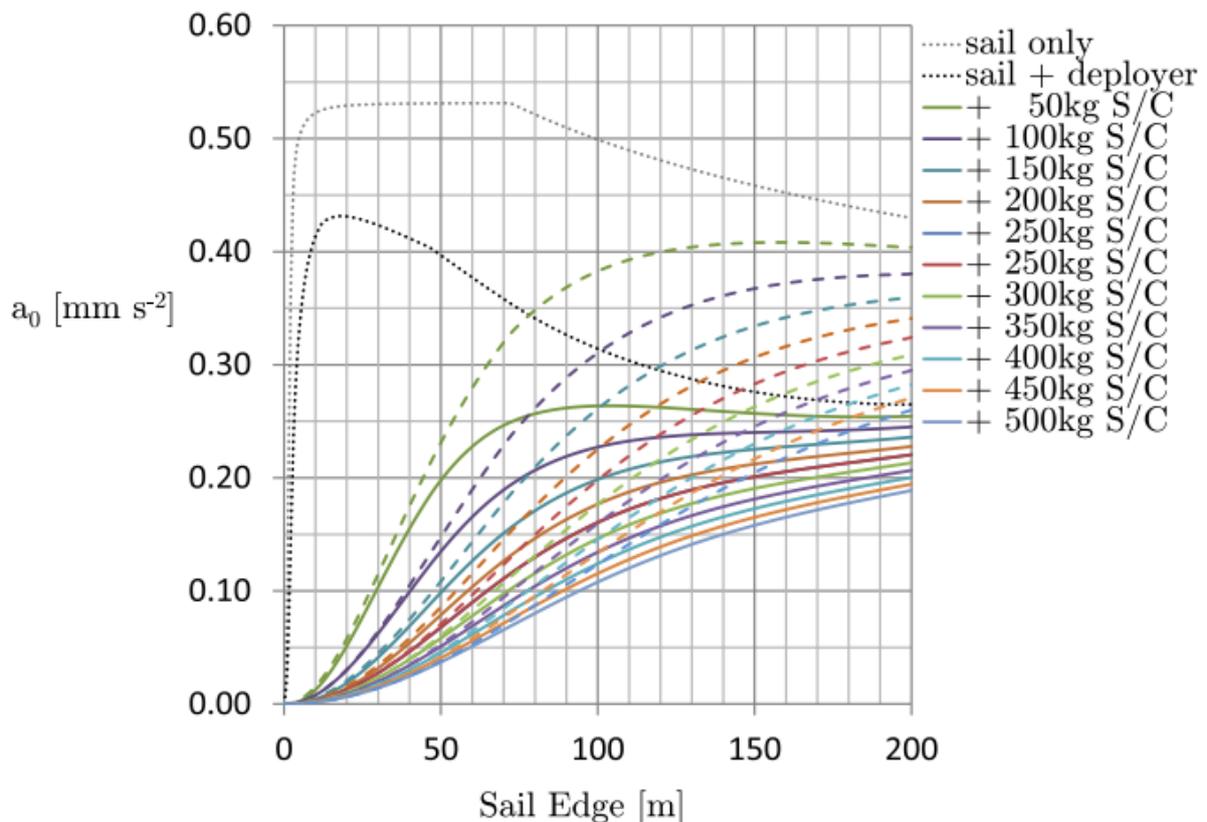
While the DLR GOSSAMER solar sail deployment strategy (Seefeldt et al., 2017a,b; Spietz et al., 2021) achieves the best performance parameters it has one disadvantage. For developments in low funded projects with very limited resources the complexity is relatively high. Each of the Boom Sail Deployment Units (BSDU) has a complexity comparable to a small CubeSat with several subsystems beside the deployment mechanisms itself. It requires power, communication, an on-board computer and data handling as well as a structural and thermal design that has to function in very different configurations, i.e., undeployed, during deployment and deployed, with all transitions in between.

Seefeldt et al. (2021) studied an implementation of the deployment strategy without employing the independent BSDUs. Instead, the deployment is driven from a central unit and only the sail spools, which are passive elements, are mounted to the boom tips. By deploying the booms from the central unit, the spools mounted to the boom tips move away from the central unit and the sail membranes are pulled off of their spools.



The 5-in-1 DLR GOSSAMER solar sail microspacecraft concept (left) and its deployment with 4 active BSDUs moving out (center), and a simplified central deployer adaptation for early sailcraft re-using deployers developed for other applications (right).

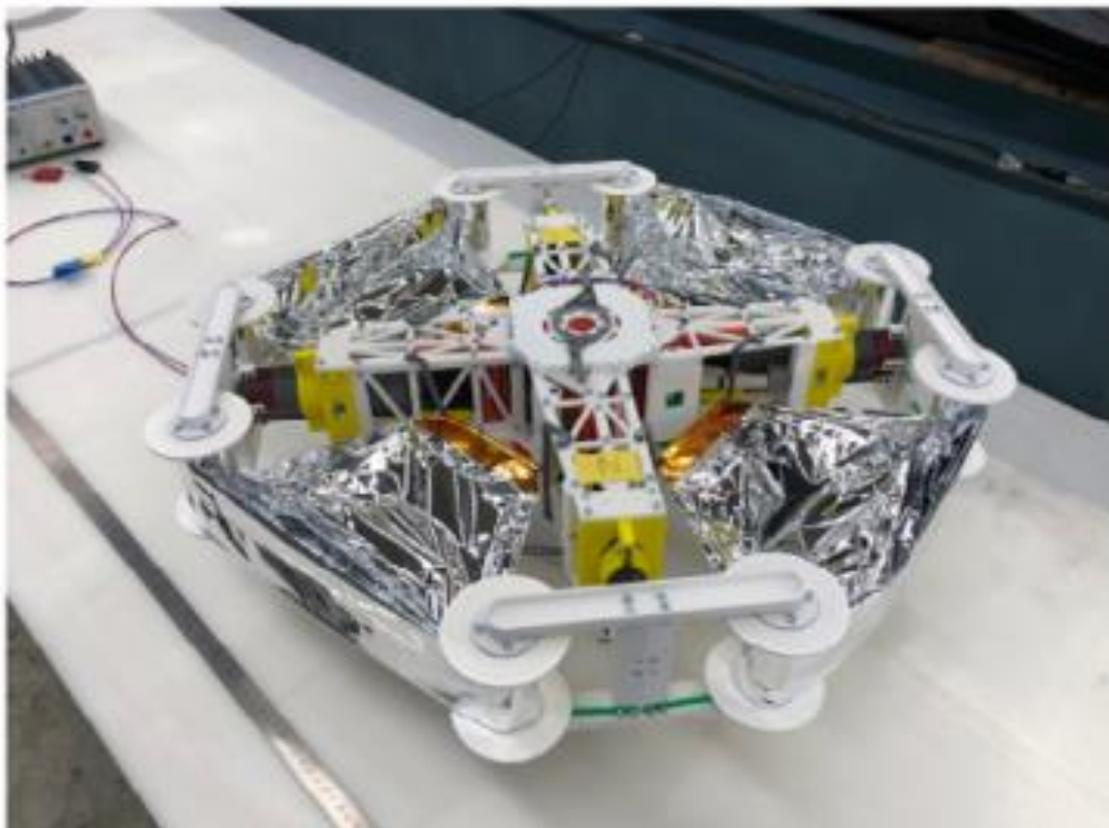
While this reduces the complexity, it comes at the expense of additional mass and thus a reduction of sail craft performance. The characteristic acceleration is evaluated for these two cases in the following figure. The first is for solar sail designs based on GOSSAMER-1 with deployment units that can be jettisoned (dashed lines). This results in a sail craft that does not include any mechanism mass. The second is for the here studied adaptation with a central deployment unit that cannot be jettisoned (solid lines). Also shown are the characteristic acceleration of the sail with booms and membrane, only (blue dotted line), and of the sail with the central deployment unit (red dotted line). In all cases a 5 μm thick sail membrane with an efficiency of $\mu = 0.9$ is considered. The radiation pressure p at 1 AU (without reflection) is 4.575 $\mu\text{N}/\text{m}^2$. Due to the consideration of the mass scaling laws, the functions for the characteristic acceleration do not approach the limit defined by the membrane density.



Characteristic acceleration for different additional space craft (S/C) mass. Dashed lines for GOSSAMER-1-like sailcraft with deployment units that can be jettisoned (no mechanism mass for the sailcraft). Solid lines show the characteristic acceleration for a system with central deployer that stays on the sailcraft after deployment.

When comparing the two designs (jettisoned deployment units or fixed central deployer), it can be seen that for sail up to 50 m side length the difference between the two designs with respect to the achievable characteristic acceleration is small, while for larger sails it becomes significant. For lighter additional spacecraft masses, this effect is more pronounced.

The design as described was implemented on breadboard level in order to verify the functional principles of the deployment mechanism as well as the deployment strategy itself. The breadboard sail segments are downscaled with an edge length of 1.4 m. The booms and the deployment drive could in principle deploy a sail area of about (10 m)².



Deployer breadboard in stowed configuration



Deployer breadboard during (left) and after (right) deployment

SMILE AT THE SKY: TRANS-SIBERIAN SIDINGS AND PASSERS-BY

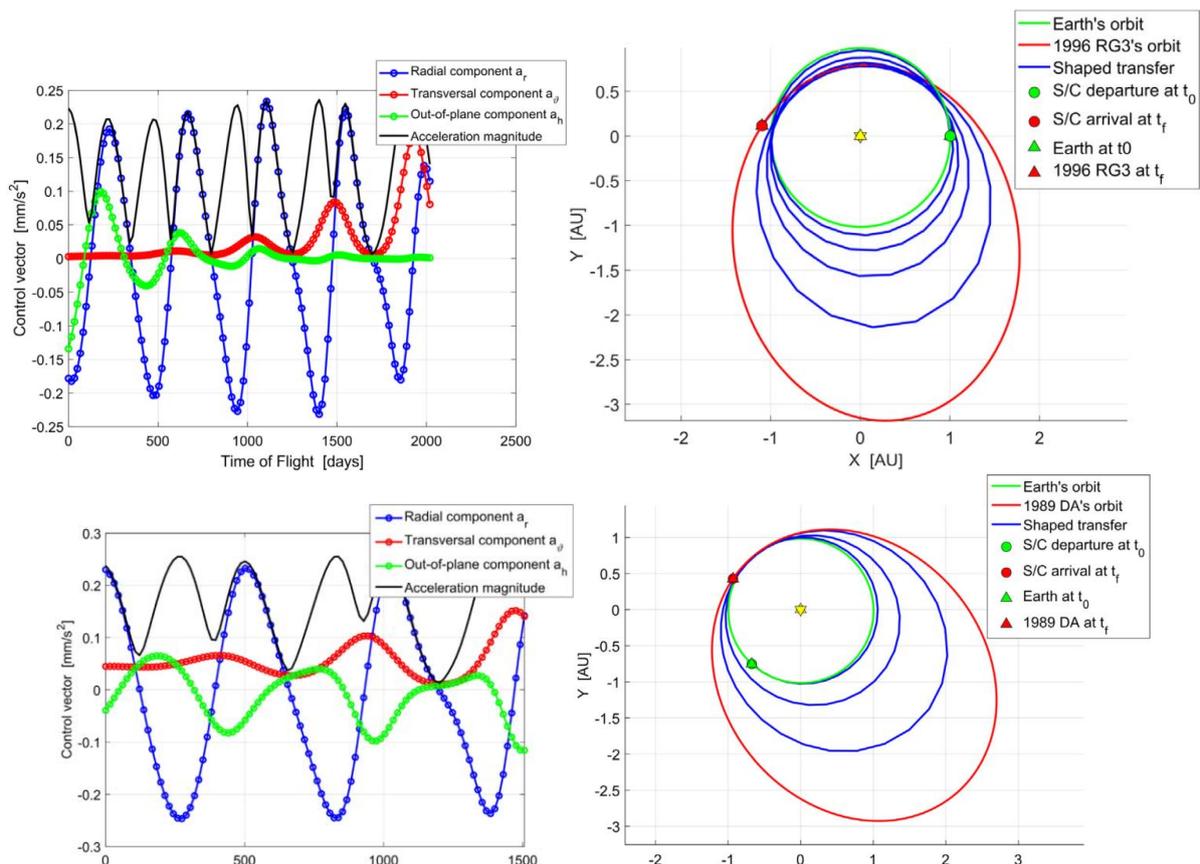
Well prepared, packed with provisions, fuelled up (if necessary), and trained in perseverance and ingenuity as we are, wouldn't it be nicer to go after some asteroids just for curiosity and 'for real' instead of imagining that one is about to fall on our heads? In that spirit, we found an opportunity or two at the PDC 2019.

Don't get fooled again: the Taurids when they come

The Taurid meteor shower is highly unusual, with its long duration (~6 months), dispersed radiant, and presence of relatively large particles. A hypothesis, although not universally accepted, exists that some large NEO impacts on Earth might be related to Taurids. (Asher and Clube, 1993; Clube and Napier, 1984) In addition, in 2019 the Earth approached the centre of the Taurid resonant swarm within 5 degrees of mean anomaly, its closest post-perihelion encounter with Earth since 1975, in good conditions for observation and tracking. If the predicted locations and trajectories are

confirmed, the Taurid swarm will come much closer to Earth in the early 2030s – so close that objects might have possible trajectories that impact the Earth in 2031 to 2036. Visible objects will be Tunguska-sized or larger, and in fact it is hypothesized that the Tunguska object itself was probably a Taurid object, too. (Clark et al., 2019) Taurids are challenging rendezvous targets, with eccentric orbits stretching between the heat limit of current sail membrane technology at perihelia of ~ 0.3 AU to near the limit of photovoltaic-powered spacecraft, with aphelia at ~ 4 AU.

We therefore envisage that a mission to further study one or more of these objects may be useful as well as a challenge worth accepting. search was performed on a number of NEO which are currently deemed to belong to the Taurid complex. The list, which was provided by Dr Auriane Egal (University of Western Ontario, Canada), comprises 55 objects, whose elements vary in semimajor axis from 1.09 to 2.55 AU, eccentricity from 0.54 to 0.88, and inclination from $1^{\circ}.94$ to $14^{\circ}.65$. The search was performed considering a launch window in the period 01/01/2020 and 30/12/2030. The maximum acceleration allowed was set to 0.3 mm/s^2 . The time of flight of the transfer was limited to a maximum of 2500 days. Feasible trajectories were found for 1996 RG₃ and 1989 DA. 1996 RG₃ can be achieved with a maximum acceleration as low as 0.23 mm/s^2 in approximately 2000 days from departure on September 23rd, 2022. 1989 DA can only be reached with a slightly higher maximum acceleration of 0.25 mm/s^2 ; however, this is compensated by a much shorter transfer time, of about 1500 days.

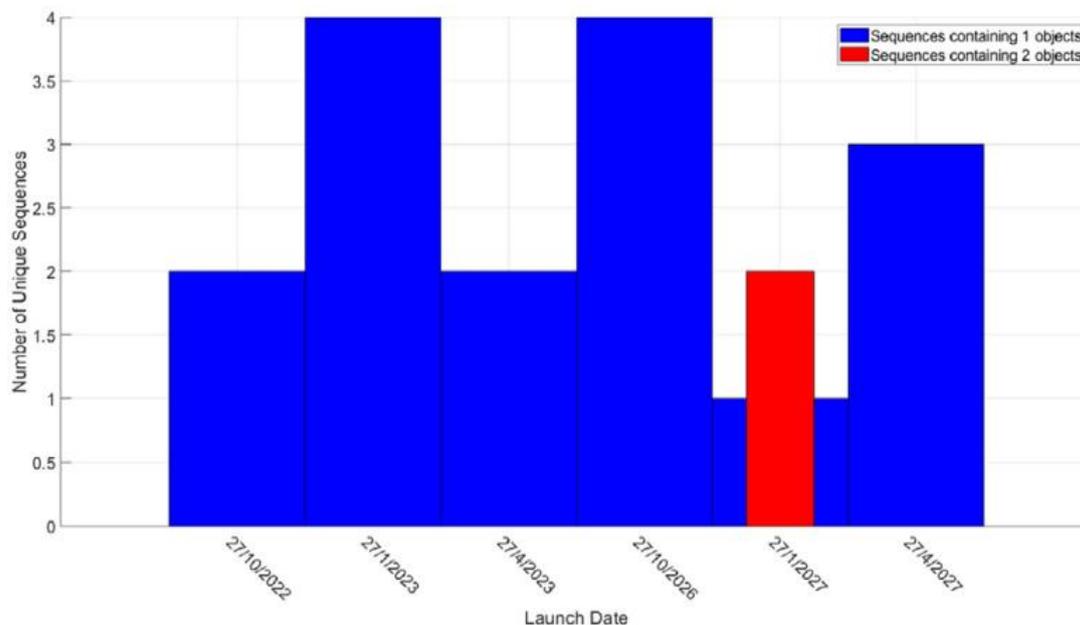


Visiting Taurids 1996 RG₃ and 1989 DA with near-term SEP spacecraft

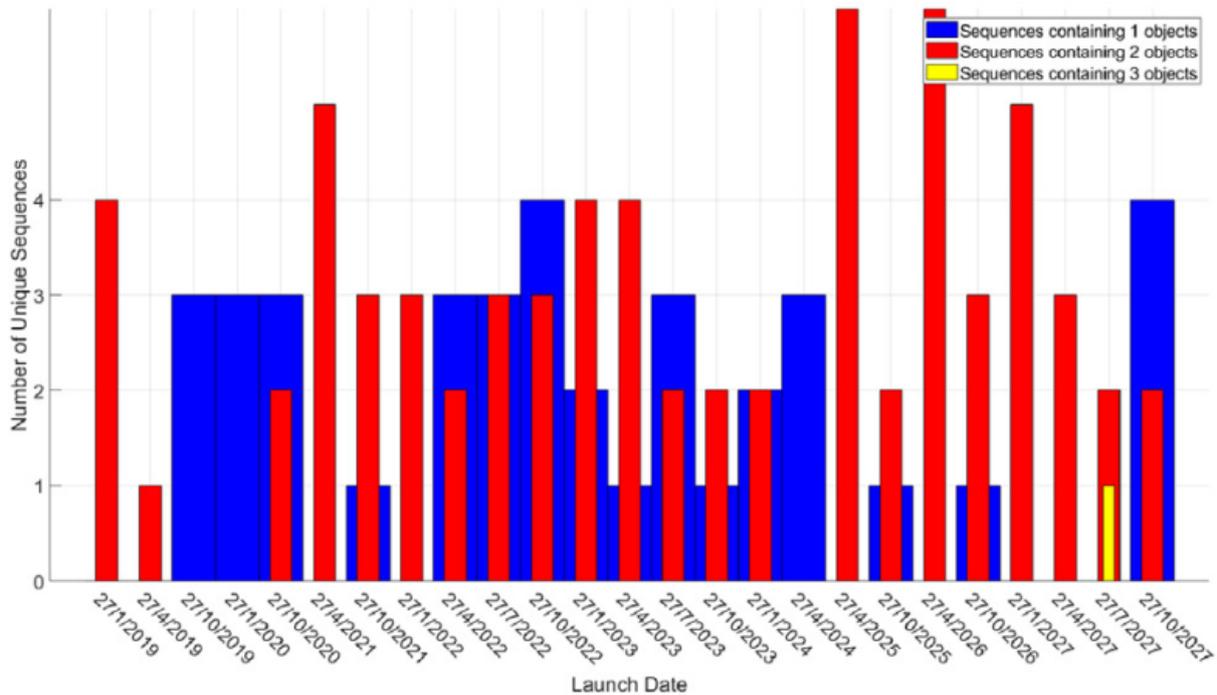
Just like yesterday: the outlook for Multiple NEA Rendezvous in the now-term

We performed a search for “slow” sail NEO rendezvous sequences with launch dates within 2019–2027, the fictitious timeframe of the PDC 2019 Exercise, to find single and multiple NEA rendezvous (SNR/MNR) trajectories to pose as “nominal” trajectories of a fictitious first scientific sail mission which is then re-targeted towards the fictitious exercise target asteroid, 2019 PDC. The performance range was limited to $a_c \leq 0.10 \text{ mm/s}^2$, and the stay time of each asteroid rendezvous is set to at least 100 days.

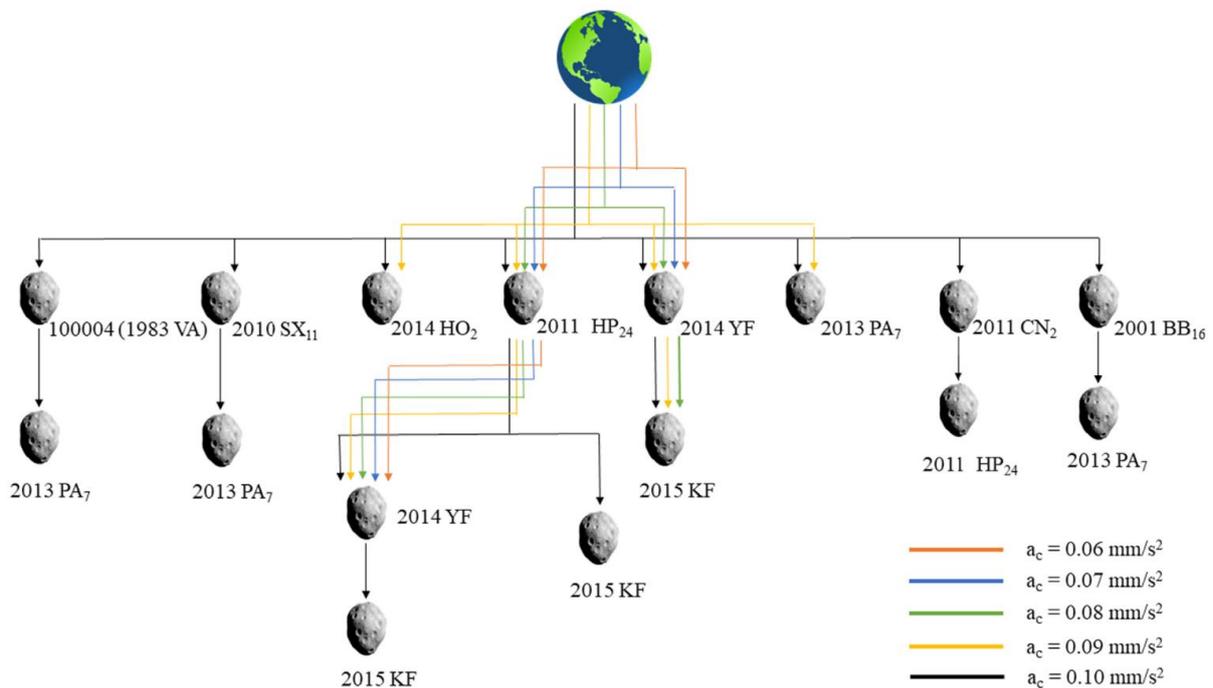
We found single rendezvous trajectories for all launch dates in the 2019 to 2027 timeframe. At the low end of a_c , some of the early part of this period did not yield trajectories, but already at $a_c = 0.06 \text{ mm/s}^2$, 2 to 3 SNR targets per launch date appear continuously throughout the later 2/3 of this period, and two 2-target MNR trajectories within one period of 4 months were found. At $a_c \geq 0.08 \text{ mm/s}^2$, the entire 2019 to 2027 timeframe offers at least 2 trajectories to choose from at any point in time, with about the same number of SNR and 2-target MNR trajectories in most time blocks. At $a_c = 0.1 \text{ mm/s}^2$, the first 3-target and thus genuine MNR trajectory appears. Sails of a_c greater than 0.1 up to about 0.2 mm/s^2 have been considered “first-generation” sails in previous MNR studies including those in which some of us participated. Thus, it appears that a “0th-generation” sail of a performance similar to that envisaged for the GOSSAMER-2 sail control technologies demonstrator (Spietz et al., 2021) can already compete with the state of the art of SEP NEO rendezvous missions.



Unique SNR/MNR sequences in the period 2019–2027 for 0th-generation sails of $a_c = 0.06 \text{ mm/s}^2$



Unique SNR/MNR sequences in the period 2019–2027 for 0th-generation sails of $a_c = 0.10 \text{ mm/s}^2$



'Family tree' of target NEAs in the unique SNR/MNR sequences for 0th-generation sails of $a_c = 0.06 \dots 0.10 \text{ mm/s}^2$ in the period 2019–2027

As may be expected, the number of unique sequences rises quickly with sail performance. On the one hand, this generates an increasing independence of the launch date if the requirement is to visit greater than 1 NEO. On the other hand, a closer look at the targets shows that some 1st targets re-appear as 2nd targets, and one 2nd target as the single 3rd target of the unique sequences found. Thus, at a given

launch date, the post-launch target flexibility uniquely feasible by solar sail propulsion already develops in this a_c range, just slightly beyond the fundamental SNR feasibility threshold.

CONCLUSION

At the end, we were left wondering. Would the kids in America let this happen if they knew 2 years ahead of impact that it would strike between sea and shining sea?

We couldn't ask them at the time. For one, due to time difference (the world is turning, and yes it matters) some of our results only came in the day after the critical day in the flow of the PDC 2019 Exercise week – in real life, with time moving at a pace of one second per second instead of 8 years in 5 days, these results and much more and better would have been on the table for the very first discussions on what to do about that asteroid. Also, even with the beneath-the-radar operation of [GoLunAr](#) or the in-other-news character of [NEOW0G](#) included just-in-case in our D.I.Y.-scripted aces up the sleeves, the 2019 Exercise was too soundly scripted and, if only by conference hotel meeting room layouts, too compartmentalized to throw in such wildcards, real life or accelerated fiction.

Whatever the price tag is on the larger New York City Metropolitan Area or well over half a state of amber waves of grain – we think *not*.

Even ignoring all the deepest feelings attached to Central Park and the Heartland, just the material loss makes every and all effort at last-ditch deflection look like a pretty good deal.

Real World Events

We didn't bother to calculate. Some 15 years ago, one of us (JTG) with the help of his forester dad estimated the loss of boreal forest and salable reindeer at Tunguska to ≥ 385 M€ if it had happened then and not in 1908. This is a lower boundary; people got killed, and as in most places in those days, the indigenous were not at all counted among them, only their lost herds were tallied up. It seems the Tunguska object was kind to us, a kind reminder; it is hard to find a cheaper target on this planet today, even discounting possible global ripple effects, within a Beltway diameter thrown anywhere on this planet.

Looking back at the PDC 2019, a different era in more than one way, there are a few more firmly rational reasons to state that the incredible can happen. Two years after the fictitious discovery of 2019 PDC, would it today come in as a poor third after covid and climate change? Would people even care to believe that an asteroid is coming?

As ridiculous as it sounds, if you're based on majority decisions or polls, in almost all countries of Earth 'the Americans' were never on the Moon on these terms. The closer your place is to authoritarian disinformation fed in a constant drip for decades, the more likely an incoming asteroid would be seen as just another sinister ploy to make something 'American' happen against 'the people', no matter how authoritative science is in that place or how much they teach it in school. Obviously, as in most conspiracy theories, the rational inverse is closer to the truth than the irrational hypothesis.

After having so much fun coming up with 101 reasons for the deflection spacecraft to fail so that the disaster management community still had something to do at the PDC

2013 Exercise in Flagstaff, Arizona, in 2015 in Frascati, Italy, we tried an inject taking Germany out of ESA in the middle of its part in the deflection effort, and with it the Ariane 5 ECA upper stage which is built in Bremen, based on 'conspiracized' public opinion that 'international' space money was better spent on creating equal wealth across Europe first. Then, it failed miserably to come across. Since then, Europe has fortunately become much more active in planetary defense creating independent institutions.

But it may still be too early to place bets on the polls if it happened today.

Not A Real World Event

You may never have heard of the crowd-built [NEOWOG](#) solar sail or the hopeful start-up [GoLunAr Ltd](#) Exploration Company. That is because they do not exist; they are as fictitious as the asteroid 2019 PDC. But like this fictitious impactor they could happen at a point in time – any point in time, starting now. Or back then, when they were first proving the principle of solar-electric propulsion or solar sailing. Here is their story, the outline of which – as for any other celestial body – is first written by their trajectories.

Acknowledgments

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