your window to space

CAPCOM

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NASA + SPACEX + ASTRONAUTS READY TO LAUNCH

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Global Space News

American Astronauts to Fly from American Soil Once Again

A new era of human spaceflight is set to begin as American astronauts once again launch on an American rocket from American soil to the International Space Station as part of NASA's Commercial Crew Program. NASA astronauts Robert Behnken and Douglas Hurley will fly on SpaceX's Crew Dragon spacecraft, lifting off on a Falcon 9 rocket at 4:32 p.m. EDT on 27 May, from Launch Complex 39A in Florida, for an extended stay at the space station for the Demo-2 mission. The specific duration of the mission is to be determined.

As the final flight test for SpaceX, this mission will validate the company's crew transportation system, including the launch pad, rocket, spacecraft, and operational capabilities. This also will be the first time NASA astronauts will test the spacecraft systems in orbit.

Behnken and Hurley were among the first astronauts to begin working and training on SpaceX's next-generation human space vehicle and were selected for their extensive test pilot and flight experience, including several missions on the space shuttle.

Behnken will be the joint operations commander for the mission, responsible for activities such as rendezvous, docking and undocking, as well as Demo-2 activities while the spacecraft is docked to the space station. He was selected as a NASA astronaut in 2000 and has completed two space shuttle flights. Behnken flew STS-123 in March 2008 and STS-130 in February 2010, and he performed three spacewalks during each mission. Born in St. Anne, Missouri, he has bachelor's degrees in physics and mechanical engineering from Washington University and earned a master's and doctorate in mechanical engineering from California Institute of Technology. Before joining NASA, Behnken was a flight test engineer with the U.S. Air Force.

Hurley will be the spacecraft commander for Demo-2, responsible for activities such as launch, landing and recovery. He was selected as an astronaut in 2000 and has completed two spaceflights. Hurley served as pilot and lead robotics operator for both STS-127 in July 2009 and STS-135, the final space shuttle mission, in July 2011. The New York native was born in Endicott but considers Apalachin his hometown. He holds a Bachelor of Science degree in Civil Engineering from Tulane University in Louisiana and graduated from the U.S. Naval Test Pilot School in Maryland. Before joining NASA, he was a fighter pilot and test pilot in the U.S. Marine Corps.

Lifting off from Launch Pad 39A atop a specially instrumented Falcon 9 rocket, Crew Dragon will accelerate its two passengers to approximately 17,000 mph and put it on an intercept course with the International Space Station. Once in orbit, the crew and SpaceX mission control will verify the spacecraft is performing as intended by testing the environmental control system, the displays and control system and the maneuvering thrusters, among other things. In about 24 hours, Crew Dragon will be in position to rendezvous and dock with the space station. The spacecraft is designed to do this autonomously but astronauts aboard the spacecraft and the station will be diligently monitoring approach and docking and can take control of the spacecraft if necessary.';

After successfully docking, Behnken and Hurley will be welcomed aboard station and will become members of the Expedition 63 crew. They will perform tests on Crew Dragon in addition to conducting research and other tasks with the space station crew.

Although the Crew Dragon being used for this flight test can stay in orbit about 110 days, the specific mission duration will be determined once on station based on the readiness of the next commercial crew launch. The operational Crew Dragon spacecraft will be capable of staying in orbit for at least 210 days as a NASA requirement.

Upon conclusion of the mission, Crew Dragon will autonomously undock with the two astronauts on board, depart the space station and re-enter the Earth's atmosphere. Upon splashdown just off Florida's Atlantic Coast, the crew will be picked up at sea by SpaceX's Go Navigator recovery vessel and return to Cape Canaveral.

The Demo-2 mission will be the final major step before NASA's Commercial Crew Program certifies Crew Dragon for operational, long-duration missions to the space station. This certification and regular operation of Crew Dragon will enable NASA to continue the important research and technology investigations taking place onboard the station, which benefits people on Earth and lays the groundwork for future exploration of the Moon and Mars starting with the agency's Artemis program, which will land the first woman and the next man on the lunar surface in 2024.

Boeing to Fly Second Uncrewed Orbital Flight Test for NASA

Boeing has decided to fly a second uncrewed flight test as a part of NASA's Commercial Crew Program. Although no new launch date has been set, NASA has accepted the proposal to fly the mission again and will work side-by-side with Boeing to resume flight tests to the International Space Station on the company's CST-100 Starliner system.

Although many of the objectives of Boeing's first uncrewed flight test in December 2019 were accomplished, Boeing decided the best approach to meeting the agency's requirements would be to fly the mission again, including docking with the space station. However, as completing a second uncrewed flight test was not in the timeline for returning U.S. human spaceflight on Starliner, NASA fully supports Boeing's commitment to flying astronauts as safely as possible.

NASA
http://www.nasa.gov

Black Arrow: Return To Flight

On the 50th Anniversary of the first successful British rocket launch, the Black Arrow name is reinvigorated as Black Arrow Space Technologies starts up in business. Black Arrow Space Technologies is a new British company developing spaceflight technologies designed to launch satellites into orbit.

Black Arrow Space Technologies Launch Services

Black Arrow Space Technologies will launch payloads of up to 500Kg into Polar Low Earth Orbit, or 300Kg into Sun Synchronous Orbit, or smaller multiple payloads on the same mission. Our system is designed to scale up so that, after initial demonstration, we will be able to increase our payload and performance capabilities.

Our launch programme will be flexible, frequent, reliable and responsive. We will plan our schedule to meet the specific needs of our launch customers – and this includes responding to short notice, urgent requests to launch. We will be able to prioritise and fast track launches without adversely impacting on previously agreed schedules.

BLACK ARROW
SPACE TECHNOLOGIES

Launches will take place from the optimal location to achieve the required orbit for the payload – from our seaborne spaceport.

Terrestrial Spaceports are usually sited in the most ideal place for space operations. Sometimes, geography may limit these locations, by restricting the ability to achieve the orbit required for a particular mission; adding environmental implications for the local environment (not least the noise impact on the neighbours); and placing limitations on the trajectory (or line-of-sight) due to populations or national infrastructure below the preferred flight path, or disruption of commercial airway corridors.

Launching from a stabilised sea platform enables the launch to take place from the optimal location to achieve the required orbit, with significant reductions on the fuel required to achieve that orbit (no mid-course adjustments); minimises the concerns about environmental and noise impact on local populations, protected sites and wildlife; and enables more safety in trajectory planning without overflying populated areas.

It offers great savings without having the costs of creating a land-based infrastructure, lowers insurance costs, and provides increased cost and time efficiencies through unrestricted campaigns. In some cases, we could even beat the weather!

Our fleet will be based in South Wales, where final payload preparation will take place prior to boarding the vessel and sailing to the launch site. Ultimately, we aim to have ships based in key locations across the world so that we can offer a truly global launch service.

Black Arrow Space Technologies
https://blackarrow-space.uk

50 years since Black Arrow launched the UK into space

The 4th March 2020 marks 50 years since the Black Arrow rocket conducted its first successful flight, launching the UK into the space age. In the years since Black Arrow, the UK has become one of the world's leading satellite manufacturers, providing technology that helps the world communicate, keeps people safe and monitors the environment.

The government wants to establish a new UK launch capability on a commercial footing, with a number of potential spaceports across the country and new launch operators developing the capability to take small satellites into orbit from UK soil.

Black Arrow is an important part of the UK's space heritage, and it is great to be able to recognise the achievements of the past, as we look to the future.

The UK Space Agency is partnering with Farnborough Air Sciences Trust (FAST) and British rocket launch provider Skyrora to celebrate the 50th anniversary of the Black Arrow launch and the current success of the UK space sector. Skyrora brought the first stage of Black Arrow R3 back to the UK from Australia two years ago and has lent it to the FAST Museum where it will be on display for the next three years.

About Black Arrow

Black Arrow is of great historical and technical importance playing a pioneering role during the late 1960s and early 1970s in placing the first British designed and built space satellite into Earth orbit. The programme grew from earlier UK space research and development programmes undertaken by the Royal Aircraft Establishment (RAE) at Farnborough, which included designing and building in conjunction with industry, a series of launch vehicles and their rocket engines, along with all the associated ground-based infrastructure, including assembly and test facilities in the UK and a launch complex with control and range facilities at Woomera, Australia.

The intention was to see if a rocket, capable of launching satellites into space, could be developed from existing technologies, for example HTP/kerosene powered engines developed in experimental British submarines and torpedoes.

The Black Arrow programme developed four rockets between 1969 and 1971. Black Arrow was a three-stage rocket, thirteen metres tall, with a single eight-chambered engine in its first stage. The third stage for Black Arrow was a solid rocket motor manufactured by RPE Westcott. The first stage of Black Arrow R3, the surviving launcher that was used to place the Prospero satellite into orbit in 1971, has been brought back to the UK by Skyrora and is now on public display at the Farnborough Air Sciences Trust Museum, close to the original programme birthplace, the RAE Space Department.

UK Space Agency
https://www.gov.uk/government/organisations/uk-space-agency

NASA Outlines Lunar Surface Sustainability Concept

When NASA sends astronauts to the surface of the Moon in 2024, it will be the first time outside of watching historical footage most people witness humans walking on another planetary body. Building on these footsteps, future robotic and human explorers will put in place infrastructure for a long-term sustainable presence on the Moon.

NASA recently proposed a plan to go from limited, short-term Apollo-era exploration of the 1960s, to a 21st Century plan in a report to the National Space Council. With the Artemis program, we will explore more of the Moon than ever before to make the next giant leap – sending astronauts to Mars.

"After 20 years of continuously living in low-Earth orbit, we're now ready for the next great challenge of space exploration – the development of a sustained presence on and around the Moon," said NASA Administrator Jim Bridenstine. "For years to come, Artemis will serve as our North Star as we continue to work toward even greater exploration of the Moon, where we will demonstrate key elements needed for the first human mission to Mars."

On the surface, the core elements for a sustained presence would include an emphasis on mobility to allow astronauts to explore more of the Moon and conduct more science:

- A lunar terrain vehicle or LTV, would transport crew around the landing zone
- The habitable mobility platform would enable crews to take trips across the Moon lasting up to 45 days
- A lunar foundation surface habitat would house as many as four crew members on shorter surface stays

Astronauts working on the lunar surface also could test advanced robotics, as well as a wide set of new technologies identified in the Lunar Surface Innovation Initiative, focusing on tech development in the areas such as of in-situ resource utilization (ISRU) and power systems. Rovers will carry a variety of instruments including ISRU experiments that will generate information on the availability and extraction of usable resources (e.g., oxygen and water). Advancing these technologies could enable the production of fuel, water, and/or oxygen from local materials, enabling sustainable surface operations with decreasing supply needs from Earth.

Another key difference from Apollo and Artemis will be use of the Gateway in lunar orbit, built with commercial and international partners. The lunar outpost will serve as a command and control module for surface expeditions and an office and home for astronauts away from Earth. Operating autonomously when crew is not present, it also will be a platform for new science and technology demonstrations around the Moon.

Over time, NASA and its partners will enhance the lunar Gateway's habitation capabilities and related life support systems. Adding a large-volume deep space habitation element would allow astronauts to test capabilities around the Moon for long-duration deep space missions.

While the goal of Apollo was to land the first humans on the Moon, the Artemis program will use the Moon as a testbed for crewed exploration farther into the solar system, beginning with Mars. This is America's Moon to Mars space exploration approach. A proposed multi-month split-crew operation at the Gateway and on the lunar surface would test the agency's concept for a human mission to the Red Planet.

For such a mission, NASA envisions a four-person crew traveling to the Gateway and living aboard the outpost for a multi-month stay to simulate the outbound trip to Mars. Later, two crew members would travel to the lunar surface and explore with the habitable mobility platform, while the remaining two astronauts stay aboard Gateway. The four crew members are later reunited aboard the lunar outpost for another multi-month stay, simulating the return trip to Earth. This mission would be the longest duration human deep space mission in history and would be the first operational test of the readiness of our deep-space systems.

The report also highlights a robotic return to the surface beginning next year for scientific discovery. The Moon is a natural laboratory to study planetary processes and evolution, and a platform from which to observe the universe. NASA will send dozens of new science instruments and technology demonstrations to the Moon with its Commercial Lunar Payload Services initiative. Some of these robotic precursors, including the Volatiles Investigating Polar Exploration Rover or VIPER, will study the terrain, and metal and ice resources at the lunar South Pole.

The Space Launch System rocket, Orion spacecraft, human landing systems and modern spacesuits will round out the agency's deep space systems. As part of the Artemis III mission, the first human expedition back on the Moon will last approximately seven days. NASA plans to send Artemis Generation astronauts on increasingly longer missions about once per year thereafter.

With strong support in NASA, America and its partners will test new technologies and reduce exploration costs over time. Supporting infrastructure including power, radiation shielding, a landing pad, as well as waste disposal and storage could be built up in the coming decades, too.

"The U.S. is still the only nation to have successfully landed humans on the Moon and spacecraft on the surface of Mars," the report states. "As other nations increasingly move out into space, American leadership is now called for to lead the next phase of humanity's quest to open up the future to endless discovery and growth."

Read the full report at:

https://www.nasa.gov/sites/default/files/atoms/files/a_sustained_lunar_presence_nspc_report4220final.pdf

NASA

http://www.nasa.gov

The Clearest View

by Nicholas Booth

Mars never quite leaves you. So said one of the first scientists to ever send a mission there and look for microbes -- and it is so true. Dr. Gerry Soffen spent the best part of twenty years thinking about life on the Red Planet – and years later, I count myself very lucky to have spoken to him at length. He was the NASA project scientist for the Viking missions and, as he told me, it was the greatest experience of his life.

How, he wondered, could you ever pay back the taxpayer for searching for life on another world?

The great tragedy was that Viking found no microbes. But – as has become increasingly clear in recent years – that may have been a premature conclusion. Organics, the biochemical backbone for life, have been found on many occasions on the Red Planet. Gerry – who died in 2000 – is one of many people who we spoke to for our new book. It's the story of the greatest scientific detective story, not just of the space age, but of all time.

Now, in the summer of 2020, the next American mission due for launch to Mars will look for signs of ancient life for the first time since the seventies. The Red Planet is back where it should be. Centre stage.

And, the best is yet to come.

I have wanted to go to Mars for many years. Soon somebody really will – possibly within the next twenty years. It promises to be the defining moment for this century.

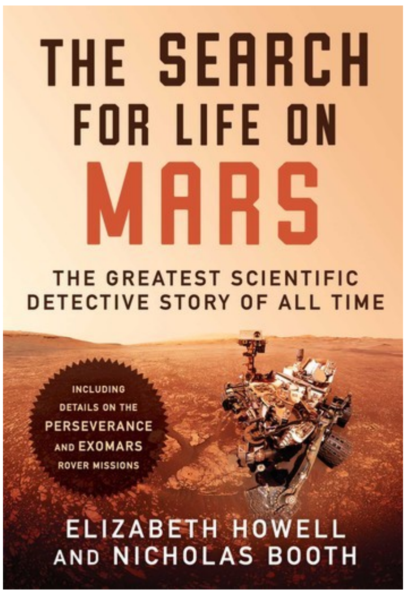
I have been very lucky to settle for a ringside seat for many of the adventures to date. As a teenager, I used to write to JPL for all the latest information. In 1988, I worked on a book about sending humans to Mars. It all seemed so very far off.

Now it really is only a matter of time. Somebody who reads this might actually go to Mars.

And in the nineties, I was a regular visitor to JPL and NASA. I was a technology editor on a national newspaper and found any excuse to go. And probably the greatest evening of my career was when rumours about life turned to a flood wave in August 1996. That was when the suspected fossilized microbes inside the Allan Hills meteorite were announced. Even now, nearly twenty five years later, those findings still make little sense. The jury is still out.

Dr Gerry Soffen

NASA
www.nasa.gov



But it was – as we show – one of the many occasions where people claimed to have found life. I have a sneaking suspicion there will be many more to come in the century ahead. That, too, is the greater narrative we discuss in our book.

So the Red Planet – and our hopes for life – will be in the news. Many of the scientists we talked to say there is little point doing anything until we get the first samples back. And that day is coming, probably ten years from now. The clock is already starting. Perseverance will earmark samples and take some onboard, leaving others on the surface. In 2028, the next American lander will ferry a European rover – probably built in Stevenage – will collect them all. There will be a total of about 500 grammes of material, but it will be enough. By then, somebody will announce that life really has been found. And for once, it will be true.

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Nicholas Booth is the co-author with Elizabeth Howell of the new book "The Search For Life On Mars – The Greatest Scientific Detective Story of All Time" (Skyhorse), out this summer. He began his career at *Astronomy Now*, then wrote about space and science for newspapers, ending up as a technology editor on *The Times*. Now he writes detective stories, this one being a kind of CSI: Red Planet. He tweets as @thievesbook.

CAPCOM Editor Michael Bryce met Nicholas Booth when he and Midlands Spaceflight Society friend the late Andy Salmon went to Kennedy Space Center to witness the launch of STS-61 in December 1993 as reporters. Nick recently re-established contact with Michael through the Twitter.com Social Media service.

How do Spacecraft get to Mars?

Adam Hibberd

Since the 1960's space faring nations have sent robotic spacecraft to the Red Planet. From Mariner 4 in 1965 to InSight in 2018, these autonomous explorers take advantage of the phenomenon known as "Orbital Mechanics", the movement of the planets relative to each other and Earth. The ultimate mission scenario taking advantage of this phenomena was dubbed "The Grand Tour" in the 1970s, eventually sending Voyager 1 and Voyager 2 on a tour of the Solar System relying predominantly on Orbital Mechanics. In those days of course computing was in its infancy and although NASA was ahead of the game in terms of New Technology, much of the calculation work would have been done by hand. These days computers are at the forefront of planetary exploration. Our new contributor Adam Hibberd looks at the mathematics and the technology behind calculating trajectories for interplanetary spacecraft.

Have you ever thought what it might be like to live on Mars? Ray Bradbury's fanciful notions in his 'Martian Chronicles' were written before Mariner 4's flyby of Mars on 15th July 1965. The deafening perpetual drumming of rain on leaves in his 'Illustrated Man' was envisaged a long time before Venera 3's crushing encounter with Venus's atmosphere prior to its impact on 1st March 1966. As is frequently the case, the reality uncovered by scientific enquiry turns out to be more prosaic than the fantasy imagined by the human mind. But this scientific reality has a beauty of its own and its language, mathematics, often has a symmetry and structure which can be compelling; a complexity which can usually reduce to an elegant simplicity when treated with respect.

Let's take two planets, say Earth and Mars, how does one find a trajectory an object, like for example a spacecraft, might take to get from one to the other? Well one possibility would be simply to guess a velocity at Earth, which when superimposed on Earth's orbital velocity around the sun would take a travelling spacecraft (s/c) along some arbitrary interplanetary path. Over the course of its journey there will be various forces influencing its motion. Firstly, and most importantly, will be the gravitational attraction of the Earth and the Sun. Indeed every celestial body in the solar system will have something to say on this - anything with mass will exert a force on anything else with mass, of a magnitude dependent on the inverse square of their relative distance from each other. So do we need to know the positions of all these bodies at all times to enable us to make an accurate prediction of the s/c's motion? Let us at this point lay down the law. We shall hereon discount every source of gravitational force on the s/c where the s/c belongs outside this object's gravitational 'Sphere of Influence' (SoI). Such an assumption is known as a 'patched conic'.

Returning to the scenario of an initial guess, with just the sun's gravitational force (when the s/c is outside of Earth's SoI), mathematically it is possible to accurately predict the s/c's position and velocity evolution with time. However, with our initial guess, it would be a question of pot luck as to whether the s/c arrived at the objective, Mars, for an intercept - the odds would literally be astronomical. So where does this leave us?

The Solution is to reverse engineer the problem. Instead let us assume that we have the intercept point of the s/c with Mars, M, in addition to the departure point from Earth, E. In turn, these positions E and M will be dependent on the departure time from Earth, t_E, and the arrival time at Mars, t_M. This is because Earth and Mars follow the clockwork of the heavens whose equations were laid down by scientists such as Newton, and their positions and velocities are predictable (as long as this time is of a reasonable order of magnitude, beyond which we enter the realm of chaos theory).

Generated by NASA, there is a computer file named 'de430.bsp'. This is a 'binary SPICE kernel' file, with an overall size on disc of 117Mbytes. It contains data on all the planets in our Solar System, as well as the dwarf planet Pluto. This data comprises extremely accurate positions and velocities of each body as a function of time between the dates 31st December 1549 and 25th January 2650. They can be accessed using software, also provided by NASA, called the 'NASA SPICE Toolkit'.

Now back to Earth and Mars. Given just two times, t_E and t_M, we can accurately determine their respective positions and velocities using SPICE. In addition, as long as we choose t_M to be greater than t_E, i.e. $t_M > t_E$, we also have the 'Time of Flight' of the travelling s/c which will be

$$ToF = t_M - t_E \qquad (1)$$

It turns out that given just this information, i.e. the position of the planets E and M (which in turn are only dependent on t_E and t_M respectively) and the value of ToF (also dependent on t_E and t_M), it is possible to calculate a trajectory which connects them up. The problem is known in the scientific literature as the 'Lambert Problem', the solution to this therefore constitutes a potential route our s/c could take. To be precise there are two such routes, which we shall call 'short way' (SW) and 'long way' (LW) - figures (1) & (2) show two such routes for two times t_E and t_M, chosen arbitrarily by me. It should be emphasized that 'short' and 'long' do NOT refer to the time it takes to get from E to M, because by definition, these durations are the same. Instead they refer to the angle subtended at the sun between E and M, which for SW may be say, α, and for LW would therefore be (360° - α). It also must be emphasized that these are not simply opposite directions along an identical orbit, these two solutions are actually different orbits, with different orbital parameters.

So which of these two orbits should the s/c follow? Here we bring in the notion of 'ΔV' (Delta Vee), meaning a change in velocity. To rocket engineers, ΔV is a familiar friend and can be relied upon to turn up at nearly every phase in the realization of an interplanetary mission, from preliminary mission design to the termination of mission, whether this be a dramatic plunge into Saturn's

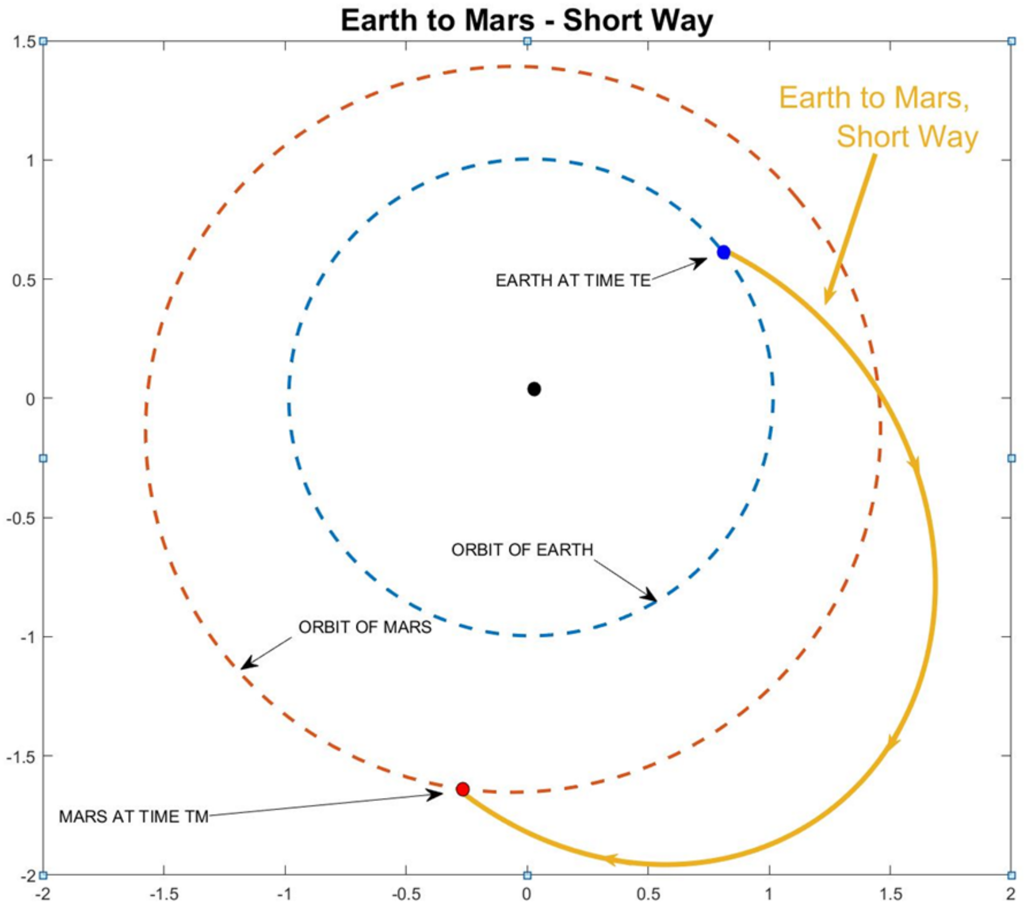
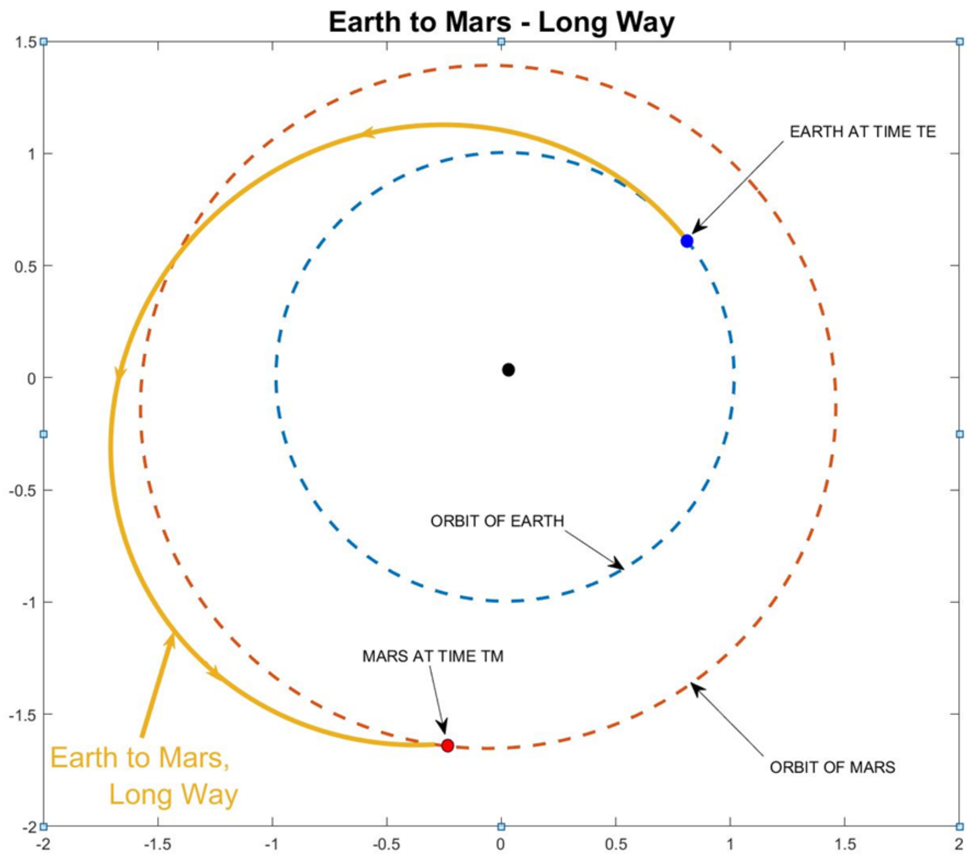


Figure 1: The "short way" to Mars

Figure 2: The "long way" to Mars



atmosphere (Cassini) or a gradual fade-out into the vast expanses of interstellar space (Voyagers 1 & 2). Generally engineers wish to make ΔV as low as possible in order to minimise the mass of fuel needed by the rocket motors to achieve this velocity change and therefore maximise the useful payload mass, i.e. instruments, landers, rovers or whatever the purpose of the mission might have. Let's be clear and confine our research to preliminary design of interplanetary missions, i.e. their feasibility. For this purpose we can suppose that the ΔV is the speed of the s/c relative to the Earth once it has escaped Earth's SoI. We thus choose the trajectory SW or LW which minimises this ΔV.

Now let us take a step back and look at what we have found. Simply by knowing times t_E and t_M, it is possible to compute a best trajectory (which is the best out of a choice of two) which a s/c can follow and a corresponding best value of ΔV. This best ΔV is therefore a function, f, of t_E and t_M and can be written mathematically as follows:

$$\Delta V = f(t_E, t_M) \quad (2)$$

But this only gives us one ΔV value, there may be other combinations of t_E and t_M which give a lower ΔV. Indeed we can express the problem as what values of t_E and t_M minimise the value of ΔV? Such a problem is known as a 'Nonlinear Programming' problem, NLP.

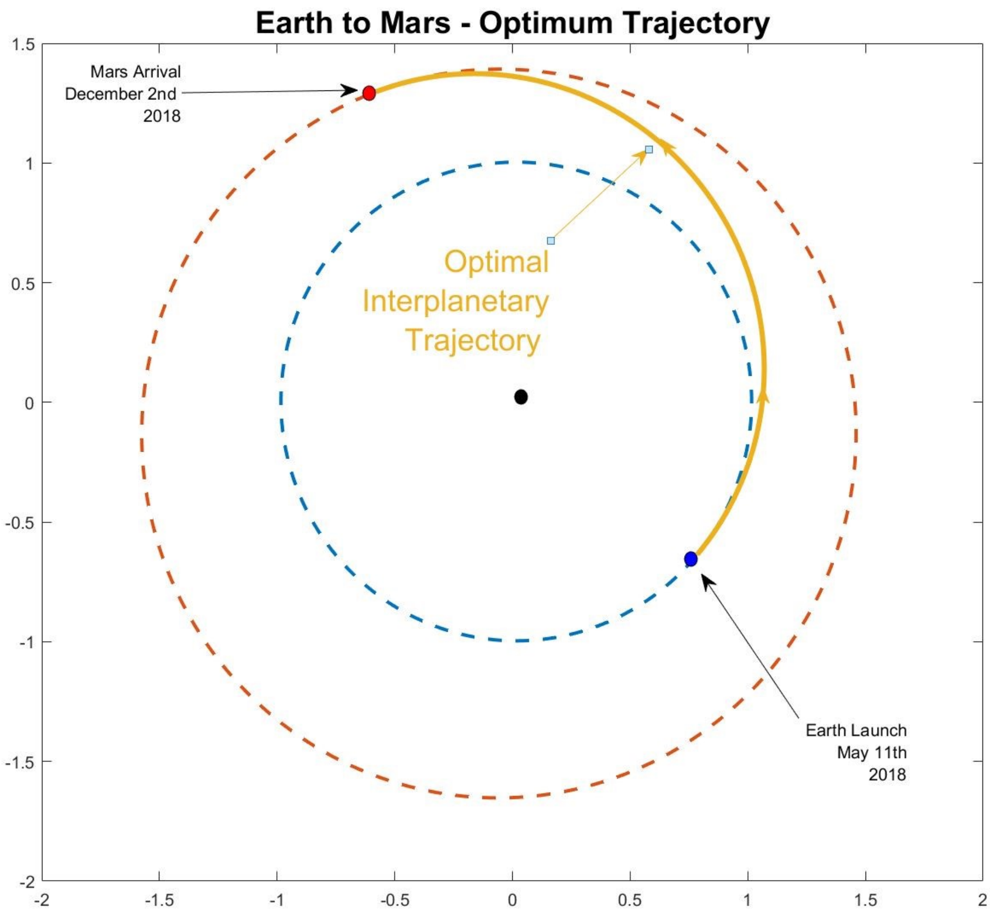
NLP problems appear in different contexts, not just for preliminary spacecraft mission design, but all sorts of scenarios, often to do with transportation, where there is some objective which needs to be minimised relative to certain design parameters and often with constraints.

For my software, 'Optimum Interplanetary Trajectory Software', OITS, I used a NLP tool called 'NOMAD'. Figure (3) shows the optimal solution for a launch in 2018.

Often interplanetary missions are not confined to just two celestial bodies such as Earth and Mars, there may be more than two. Let us take for example the case of the 'New Horizons' mission. This NASA mission was targeted to flyby Pluto and from there head off into the Kuiper Belt (where it subsequently would fly very close past the object known as Arrokoth). Its primary mission was a Pluto flyby. OITS gives the optimal trajectory directly from Earth to Pluto as one which would take 14 years and require a ΔV at Earth of 12.5km/s, all this assumes a launch in 2006, which was the launch year of New Horizons. Clearly for the mission designers, a 14 year wait before the return of any useful scientific data would be undesirable. The question then arises: is there some way of significantly reducing the mission duration without altering the mission's total ΔV? Indeed, if we constrain the mission duration to be 9.5years, the value eventually selected by NASA New Horizons mission planners, the resulting trajectory calculated by OITS is shown in figure (4) and has a ΔV at Earth of 14.0km/s – beyond the scope of available launch systems of the time. The solution to this problem is one of gravitational assist.

A gravitational assist is a means by which a body's kinetic energy relative to a fixed reference frame (in this discussion the body is a spacecraft and the chosen reference frame is relative to the sun, i.e. heliocentric), can be either increased or decreased as a consequence of an encounter with another much larger body, for example a planet. Inevitably, the laws of energy conservation must be obeyed and so this energy is not 'free'; in fact there is an

Figure 3: The "Optimum Trajectory" to Mars



equivalent loss (or gain) in kinetic energy experienced by the planet. However the change in speed manifested by this change of energy is really only apparent in the s/c as it has a much smaller mass compared to that of the planet. A gravitational assist is therefore a useful means by which the ΔV of an interplanetary mission can be reduced whilst still achieving the mission's objectives. Alternatively where there is an available ΔV budget and the mission duration needs to be reduced, a gravitational assist may be a useful method of achieving this.

We take equation (2) and change our nomenclature such that now time $t_1 = t_E$ and $t_2 = t_M$. We can add a third time t_3, and extend equation (2) as follows:

$$\Delta V = f(t_1, t_2, t_3) \quad (3)$$

Indeed using this nomenclature, t_1 and t_2 need not necessarily refer to encounter times at Earth and Mars respectively, they could be any planets we care to select. However as we are launching from Earth, we set planet number 1 equal to Earth, and as we are arriving at Pluto, planet number 3 equal to Pluto. But what about planet number 2, the middle planet which will generate a gravitational assist (GA)? The theory as to which planet or combination of planets should be exploited to deliver the best combination of GA's (i.e. the theoretical minimum ΔV trajectory) for a given target celestial body is actually a mathematical pursuit in its own right and there has been considerable literature on the subject. The best combination of planets is often more a question of experience and even intuition on the part of the mission designer.

In the case of New Horizons, it so happens that Jupiter is an ideal candidate for various reasons not least of which is the fact that Jupiter has a huge mass which makes it ideal for executing a GA. Figure (5) shows the New Horizons trajectory with a Jupiter GA, as solved by OITS. The total ΔV for this trajectory turns out to be 12.6km/s which is a result! We now have a 9.5 year mission duration, with about the same ΔV as the 14 year direct trajectory from Earth to Pluto. Such is the power of a gravitational assist.

I must add a note here in regard to the faithfulness of the solutions found by OITS with respect to that achieved in a real-life interplanetary mission. Bearing in mind OITS is a preliminary mission design tool, it is not the case that the trajectory generated by OITS should be identical to that realised in an actual mission. The 'patched conic' assumption is the overriding reason for this, but there are other forces such as solar radiation pressure and magnetic which OITS does not model and will contribute to any observed discrepancies. We have so far used OITS to generate an optimum interplanetary trajectory to Mars in 2018, how close is it to that followed by NASA's Mars Insight Lander? And how does OITS mission to Pluto with a Jupiter GA compare with New Horizons? Table 1 on the next page gives a comparison using data from wiki.

But why restrict the s/c trajectory to one GA? It is perfectly possible that in terms of minimising ΔV, a multi-GA mission would yield significantly superior results to a direct transfer or for that matter a trajectory with only one GA. With this in mind, we can generalise equation (3) to a trajectory of N encounters as follows:

$$\Delta V = f(t_1, t_2, .., t_i, .., t_N) \quad (4)$$

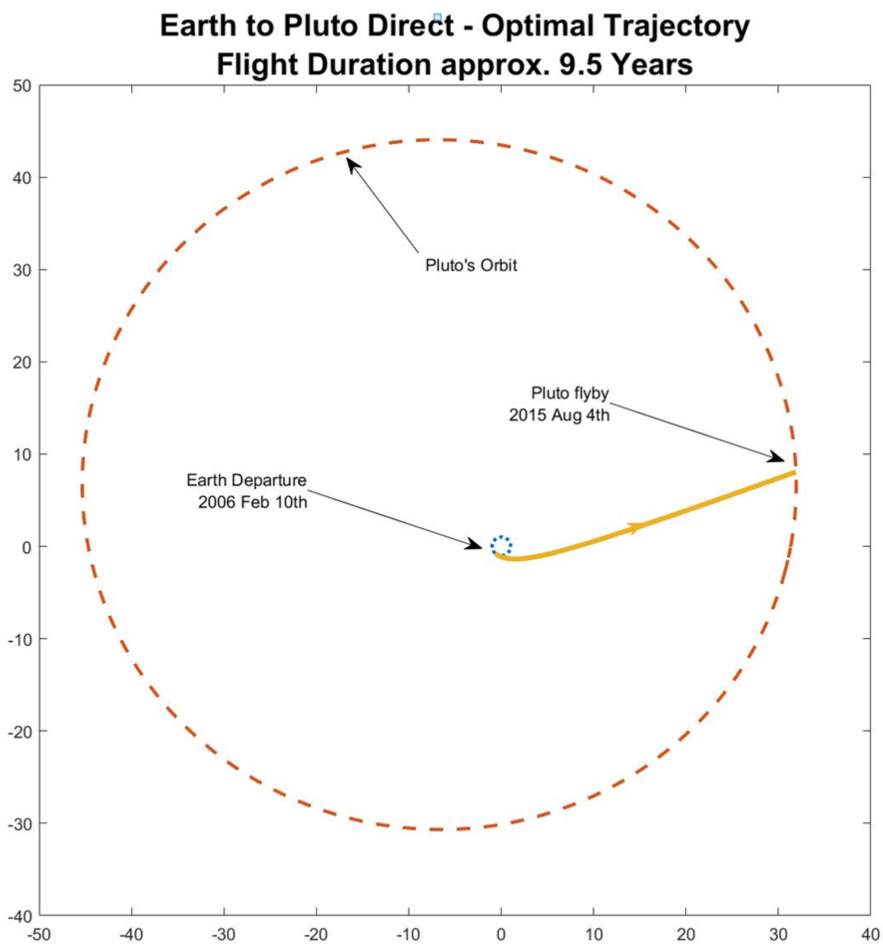


Figure 4: Earth to Pluto Direct

Table 1. Comparison of OITS Results with Two Real Missions: Mars Insight and New Horizons

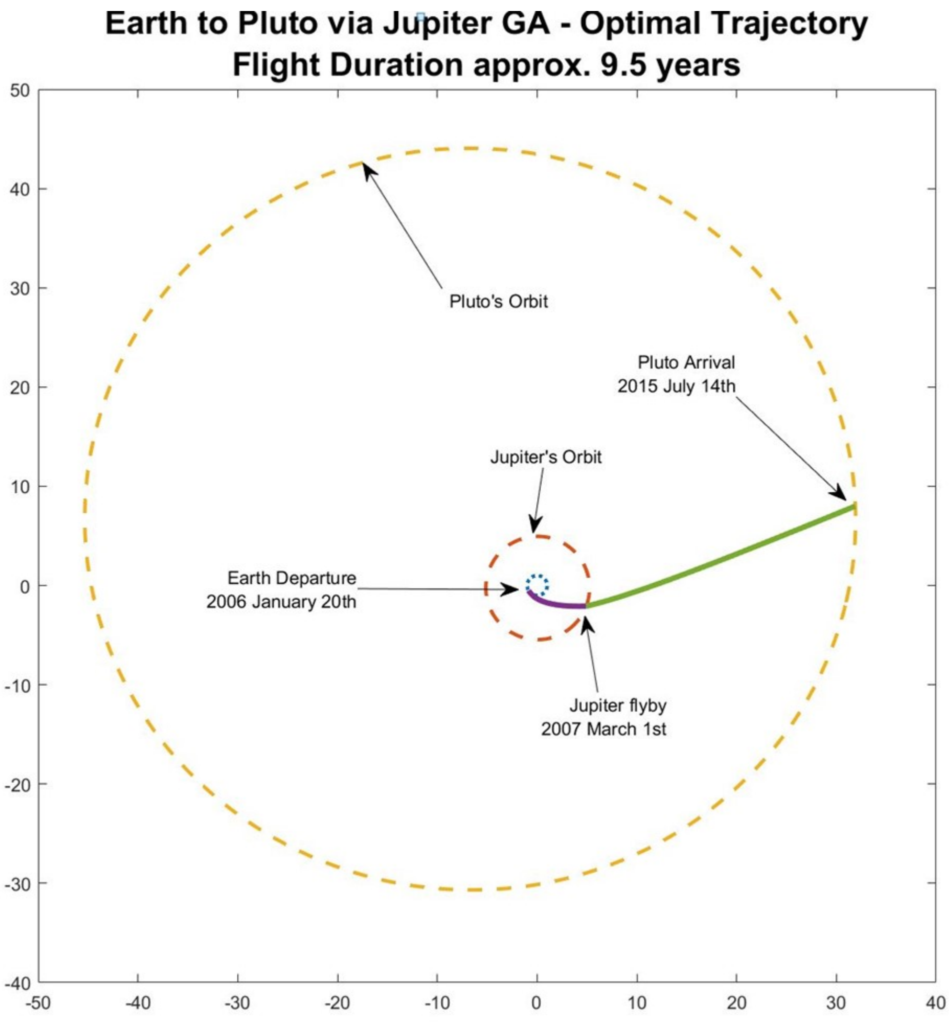
NASA Mission	OITS Trajectory	Launch Year	Actual Launch Date	OITS Launch Date	Actual Arrival Date	OITS Arrival Date	Actual Overall Mission Duration (days)	OITS Overall Mission Duration (days)	Actual Date of Jupiter Closest Approach	OITS Date of Jupiter Closest Approach	Actual Altitude at Closest Approach to Jupiter (km)	OITS Altitude at Closest Approach to Jupiter (km)
Mars Insight Lander	Earth-Mars	2018	5th May	11th May	26th Nov 2018	2nd Dec 2018	205	205	N/A	N/A	N/A	N/A
New Horizons	Earth-Jupiter-Pluto	2006	19th Jan	20th Jan	14th Jul 2015	14th Jul 2015	3463	3462	28th Feb 2007	1st Mar 2007	2.3 million	2.3 million

A case in point is the JUpiter ICy moon Explorer, or JUICE for short. Launching in 2022, this is an ESA planned mission to Jupiter dedicated to exploring its moons Ganymede, Callisto and Europa. Its interplanetary trajectory has altogether 7 encounters, i.e. N=7, and the payoff is huge as this is almost a ‘free-ride’ to Jupiter requiring very little ΔV. There is therefore very little fuel required, in turn allowing a much higher useful payload mass when JUICE arrives at Jupiter, 7 years after launch. The sequence is Earth, Earth, Venus, Earth, Mars, Earth, Jupiter. Figure (6) shows the solution found by OITS.

OITS was originally developed by me in 2017 to research interplanetary missions. Serendipitously, this was the very year the first interstellar object, designated ‘Oumuamua, was observed travelling through our solar system. Unfortunately it was discovered after its closest approach to the sun, i.e. perihelion, when it was receding from the sun at an extremely high speed. A mission to intercept it would be a challenging question of catch-up. However as a result of research using OITS conducted by myself in conjunction with the ‘Initiative for Interstellar Studies’, a mission was found to be just achievable. This will be the subject of the next article which will appear in the July—August issue of CAPCOM.

Adam Hibberd
March 2020

Figure 5: Earth to Pluto via Jupiter Gravity assist.



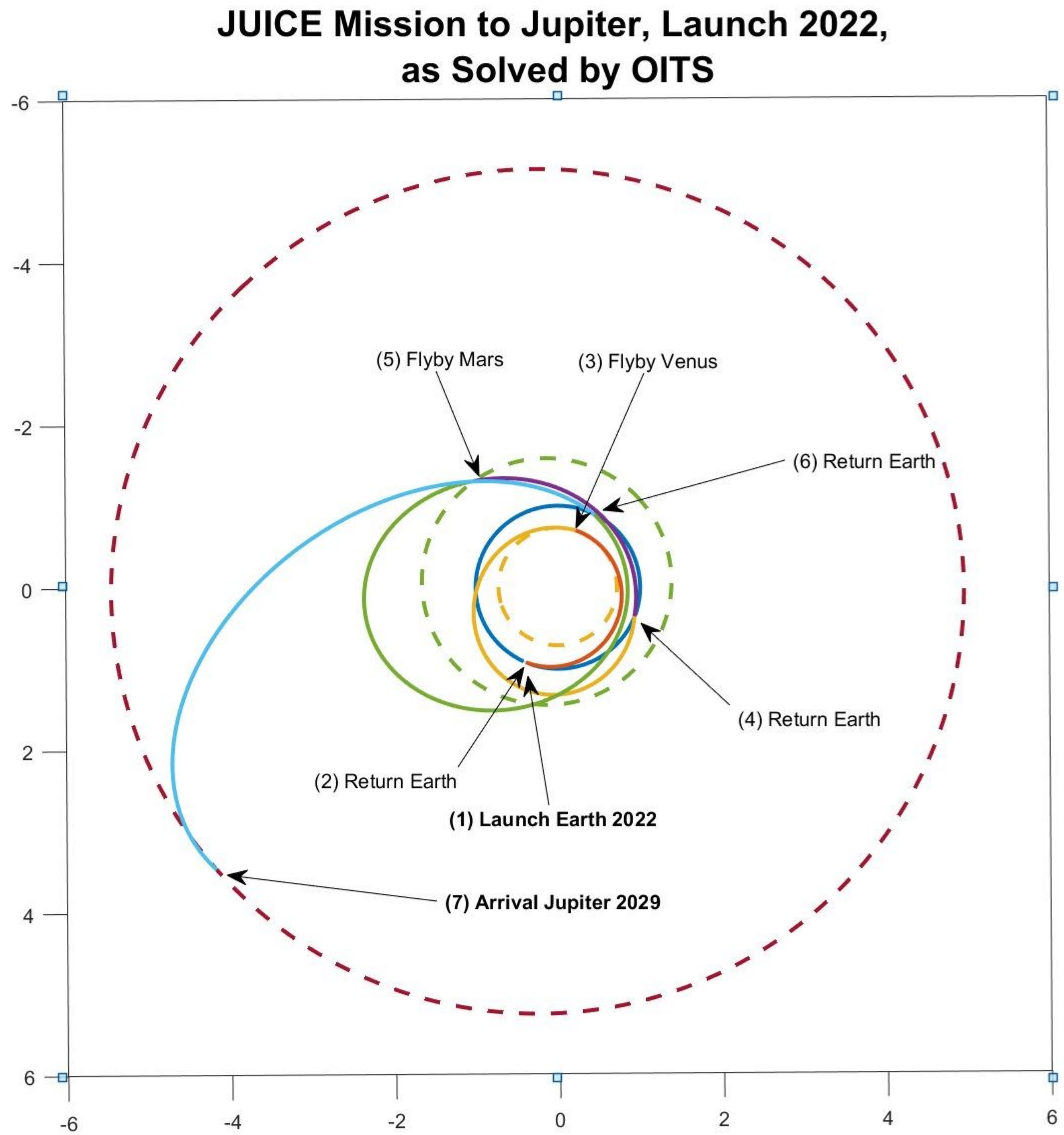


Figure 6: JUICE Mission to Jupiter

About the Author

Adam was educated in Coventry at Stoke Park Comprehensive School and subsequently attended the University of Keele, gaining a joint honours degree in physics and maths. He worked in the '90s as a software engineer on the on-board flight program for the European Ariane 4 launch vehicle; including the production, maintenance, real-time testing and post-flight analysis, his speciality being the guidance algorithm. He is also a pianist and composer and, as a member of musical trio 'Superheroes Dream', produced a vinyl under the Coventry Tin Angel Record Label. He developed his Optimum Interplanetary Trajectory Software, 'OITS' in 2017 as a personal challenge to learn the MATLAB programming environment and language. He then used it to investigate missions to interstellar objects (the work being published in Acta Astronautica) and now is a research volunteer for the 'Initiative for Interstellar Studies'.

"We Have Capture"

Remembering Shuttle-Mir, 25 Years On

By Ben Evans

Twenty-five years ago, this summer, six U.S. astronauts and four Russian cosmonauts circled the Earth together in a remarkable exercise of co-operation between two former superpowers and ideological foes. In June 1995, Space Shuttle Atlantis and her crew of seven performed the first docking between an American spacecraft and a Russian space station, linking up smoothly with the sprawling Mir orbital outpost and its own three-man crew. For several days, they performed joint scientific and medical research, shared meals and marked an occasion which united their respective space programmes. And when the two ships parted company, each had different crew members, as Atlantis returned to Earth with an outgoing Mir crew and the most flight-experienced U.S. astronaut and the station continued its journey with fresh two-man crew. In many ways, STS-71 marked a watershed moment and laid the cornerstone for the International Space Station.

The moment had taken a long time to arrive. American and Soviet manned ships had docked in Earth orbit in July 1975, during the Apollo-Soyuz Test Project (ASTP), but it was a stand-alone mission and not part of a long-term co-operative effort. That said, there were hopes of flying a cosmonaut aboard the shuttle and even performing a docking with a Salyut space station. Unfortunately, the Soviet invasion of Afghanistan in 1979 and a steady deterioration in relations between the superpowers scuppered those plans. However, with the collapse of the Soviet bloc in the early 1990s and the risk of Russian technology haemorrhaging to undesirable locations like Iran, the United States was keen to foster co-operation with its old enemy. In July 1991, U.S. President George H.W. Bush and Soviet General Secretary Mikhail Gorbachev agreed to fly a cosmonaut on the shuttle and an astronaut for several months aboard Mir. By June of the following year, such plans had evolved to include a shuttle-Mir docking flight. In October 1992, cosmonauts Sergei Krikalev and Vladimir Titov came to the United States to begin training and in February 1994 astronauts Norm Thagard and Bonnie Dunbar likewise headed to Russia.

Almost 20 years since the first American/ Russian link up in space with the Apollo Soyuz Test Project, Astronaut Robert L Gibson, STS-71 Mission Commander, shakes the hand of cosmonaut Vladimir N Dezhurov, Mir-18 commander on 29 June 1995.

Image credit: NASA

Krikalev flew an eight-day shuttle flight in early 1994 and Titov flew a year later on a mission which performed a close rendezvous with Mir, testing many of the tools and procedures for an actual docking. By this stage, the co-operative effort had expanded to include as many as ten shuttle-Mir dockings, up to four long-duration flights by U.S. astronauts and the possibility of using Russia's Soyuz spacecraft as an assured crew return vehicle for the ISS. And in June 1994, the STS-71 crew was named for the first shuttle-Mir flight. Commanding the mission was NASA's chief astronaut, Robert "Hoot" Gibson, with Charlie Precourt as his pilot and mission specialists Ellen Baker, Greg Harbaugh and Bonnie Dunbar. They would be joined for the first half of their flight by the Mir-19 crew of cosmonauts Anatoli Solovyov and Nikolai Budarin, with the outgoing Mir-18 crew of Vladimir Dezhurov, Gennadi Strekalov and Norm Thagard returning home with them. As such, STS-71 would become the first and only shuttle flight to launch with seven crew members and return to Earth with eight. And in so doing, it would become the first shuttle mission to land with different crew members and with a larger number of crew members than that with which it had launched.

As Dezhurov, Strekalov and Thagard prepared for their launch from Baikonur in Kazakhstan aboard Soyuz TM-21 on 14 March 1995, however, the situation turned increasingly ugly. The United States had already pledged to pay Russia some $400 million for up to 21 months of NASA astronaut time on Mir, up to ten shuttle dockings, a specialised docking module and exclusive use of the station's Spektr and Priroda modules for research. Spektr was scheduled to launch in February 1995, just before Thagard's arrival, carrying up to 2,500 pounds of research gear for him to use. But the collapse of Russia's rouble in October 1994 conspired to delay Spektr until May 1995, meaning Thagard would spend two months aboard Mir with relatively little to do. Nevertheless, he set a record for the longest single spaceflight by an American citizen. By the time he returned to Earth aboard STS-71, Thagard had chalked up 115 days in space, far exceeding the 84 days logged by the final Skylab crew in February 1974. And when he counted his four previous shuttle flights, Thagard had accrued a total of 140 days away from Earth.

With STS-71 scheduled to launch between 19-24 June 1995, it serendipitously became the 100th U.S. manned spaceflight since Alan Shepard's suborbital mission aboard Freedom 7 in May 1961. Due to the requirements of achieving rendezvous with Mir on the third day of the mission, and ensuring the optimum use of propellant, Atlantis had only five to ten minutes available in 'launch window' time each day. "Rendezvous started right here," said Precourt of the launch. "We had to wait for the moment in time when Mir's orbit was directly overhead of us and we could insert ourselves into the same plane that they were in."

Celestial mechanics might have co-operated, but weather certainly did not, and an initial attempt to fly on 23 June was scrubbed as lightning was recorded a few miles from the pad. Heavy clouds and thunderstorms put paid to a second try on the 24th, which garnered much annoyance from Mir crewman Strekalov, who wanted to get home for his daughter's wedding. At long last, and with only a 60-percent chance of good weather, Gibson and company threaded the needle at 3:32 p.m. EDT on 27 June and roared smoothly into space. Interestingly, they inserted into one of the lowest initial orbits ever achieved by a shuttle, with an apogee of 180 miles and a perigee of 98 miles. This allowed them to close the 8,000-mile distance to Mir at a rate of about 1,000 miles with each 90-minute orbit. Four hours into the flight, Gibson and Precourt pulsed Atlantis' Orbital Manoeuvring System (OMS) engines to slightly lift their altitude and slow their rate of closure on the space station.

As the pilots executed the rendezvous, the remainder of the crew busily activated the Spacelab module in the shuttle's payload bay for a week of medical research and powered up the Orbiter Docking System (ODS) to permit Atlantis to link up with Mir's Kristall module. (The latter had originally been planned for dockings with Russia's ill-fated shuttle, Buran, and it was a measure of some irony that the only shuttle which ultimately used Kristall was an American one.) Docking day, 29 June, also happened to be Precourt's 40th birthday and proved a busy one for the entire crew.

The STS-71 crew patch design depicts the Orbiter Atlantis in the process of the first international docking mission of the Space Shuttle with the Russian space station Mir. The names of the 10 astronauts and cosmonauts who will fly aboard the Orbiter are shown along the outer border of the patch. The rising Sun symbolizes the dawn of a new era of cooperation between the two countries. The vehicles Atlantis and Mir are shown in separate circles converging at the center of the emblem symbolizing the merger of the space programs of the two spacefaring nations. The flags of the United States and Russia emphasize the equal partnership of the mission. The joint program symbol at the lower center of the patch acknowledges the extensive contributions made by the Mission Control Centers of both countries.

Image credit: NASA/Bob McCall

Shortly before 4 a.m. EDT, the pilots fired the shuttle's OMS engines to position themselves about nine miles 'behind' Mir. This set Gibson up for the Terminal Initiation (TI) burn, which served to fly Atlantis 'beneath' the station along the Earth Radius Vector (or 'R-Bar'), tracing an imaginary line from Earth's centre up to the station. This approach profile was quite different from previous shuttle rendezvous, in that in used Earth's own gravity gradient to naturally brake the final approach and provided a margin of safety in the event of a thruster failure, as well as avoiding plume impingement upon the Mir solar arrays. Gibson took manual control of his ship at 2,600 feet and used inputs from Atlantis' rendezvous radar and laser sensor to reach a station-keeping halt at 250 feet. Permission to proceed was jointly granted by NASA Flight Director Bob Castle and Russian Flight Director Viktor Blagov and Gibson advanced toward Mir at 1.2 inches per second, halting again at 33 feet. The ODS was placed into its 'active' configuration, extending the capture ring outward and disengaging its five locking devices. Physical contact between Atlantis and the station came at 9 a.m. EDT, some 250 miles above Lake Baikal. And with a combined mass of 507,000 pounds, they became the largest single manned vehicle ever operated in space.

"Houston, Atlantis," Gibson radioed. "We have capture!"

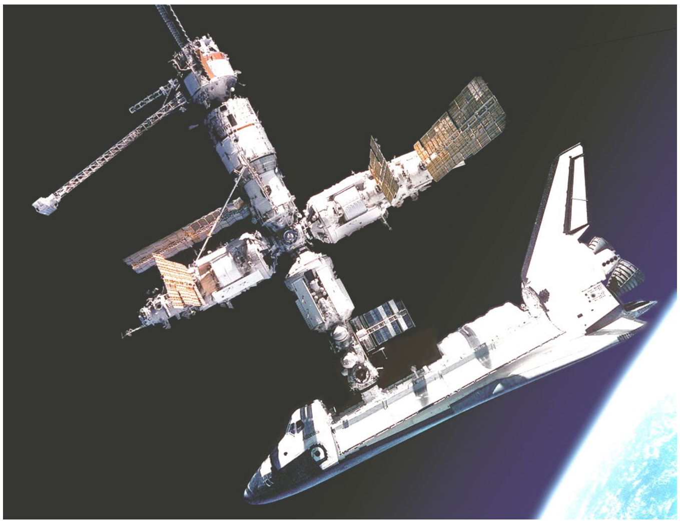
"Copy, capture," replied Capcom Dave Wolf in Houston. "Congratulations Space Shuttle Atlantis and Space Station Mir. After 20 years, our spacecraft are docked in orbit. Our new era has begun."

Following a process of pressurisation and leak checks, the hatches were opened and in a highly symbolic gesture, the respective commanders of the two ships—Gibson on the shuttle, Dezhurov on Mir—shook hands. Precourt joked to Thagard that he was upside down, to which the United States' most seasoned spacefarer retorted that, actually, the STS-71 newcomers were *really* upside down.

One of the earliest acts was a welcoming ceremony for the ten crew members aboard Mir, after which the specially moulded seat liners for Solovyov and Budarin were moved over to the Soyuz TM-21 spacecraft, which they would use for their return to Earth in September 1995. At the same time, Dezhurov, Strekalov and Thagard officially became STS-71 crew members and recumbent seats were set up on Atlantis' middeck. "Another modification was to use the recumbent seats of the shuttle," said Baker after the flight, "so that they would have the gravity vector going through their chest, rather than the head to the toes, which made the forces of re-entry a lot easier on them."

For the next five days, the two crews worked together. The results of Thagard's four months of scientific research—disks and cassettes full of data, more than a hundred urine and saliva specimens, 30 blood samples, 20 surface samples, 12 air samples and numerous water samples—were transferred over to Atlantis. A broken computer from Mir was removed and over 900 pounds of water was loaded into tanks and moved over to the station. Inside the Spacelab module, Baker and Dunbar set 15 medical research experiments to work on Dezhurov, Strekalov and Thagard, including metabolic and physiological investigations, studies with a lower-body negative pressure device and efforts to understand the effect of microgravity on their immune systems.

But science frequently gave way to ceremony on this most ceremonial of missions. On 30 June, the two crews assembled in the Spacelab module, with the Stars and Stripes and Russia's tricolour flag providing a suitably patriotic backdrop. There, the astronauts and cosmonauts joined the two halves of a pewter medallion with a relief image of the docked shuttle-Mir combo. A 1/200-scale model of the spacecraft was displayed and a



A view of the US Space Shuttle Atlantis and the Russian Space Station Mir during STS-71 as seen by the crew of Mir EO-19 in Soyuz TM-21. Cosmonauts Anatoliy Y. Solovyev and Nikolai M. Budarin, Mir-19 Commander and Flight Engineer, respectively, temporarily undocked the Soyuz spacecraft from the cluster of Mir elements to perform a brief fly-around. They took pictures while the STS-71 crew, with Mir EO-18's three crew members aboard, undocked Atlantis for the completion of this leg of the joint activities. Solovyev and Budarin had been taxied to Mir by Atlantis.

Image credit: NASA

proclamation of the mission's success was signed by all ten crew members. Unlike ASTP two decades earlier, STS-71 was not a standalone 'détente' mission, but the start of a new era in which the two old enemies would join their human space programmes. "The success of this endeavour demonstrates the desire of these two nations to work co-operatively," the proclamation declared, "to achieve the goal of providing tangible scientific and technical rewards that will have far-reaching effects to all people of the Planet Earth."

It was already intended that Mir's new crew of Solovyov and Budarin would board and undock Soyuz TM-21 from the aft longitudinal port of the Kvant module about 15 minutes prior to Atlantis' own undocking on 4 July to capture still and video imagery. In readiness for the task, on the 2nd, the cosmonauts checked out their pressure suits and performed leak checks of their ship. Finally, on the afternoon of the 3rd, the two crews parted company and the STS-71 crew handed over gifts of flight pins, watches, fresh fruit and tortillas to Solovyov and Budarin.

The "great big, soft Mexican tortillas" were Dunbar's idea. Having trained closely with Solovyov and Budarin for more than a year as backups to Dezhurov, Strekalov and Thagard, she had grown exceptionally close to the two men. She knew Solovyov loved tortillas and, in fact, that both cosmonauts enjoyed American food. Shortly before the hatches were closed between the two ships, Solovyov playfully tried to pull Dunbar over to Mir, asking which side she would like to stay on. As much as Dunbar dearly wanted a long-duration mission, she told Solovyov that she had to return with the shuttle. (As circumstances transpired, the two friends would meet again in January 1998 on another shuttle-Mir docking flight.) The station's hatch by Solovyov and the ODS hatch by Harbaugh on the afternoon of 3 July, setting up for undocking in the early hours of America's Independence Day.

At 6:55 a.m. EDT on the 4th, Soyuz TM-21 undocked from Mir and pulled away to 330 feet, which enabled Budarin to shoot spectacular pictures of Atlantis undocking at 7:09 a.m. EDT. As Gibson moved away to 400 feet, he performed a steady flyaround inspection of the station and the STS-71 crew in turn videotaped the redocking of Soyuz TM-21 with Mir at 7:39 a.m. EDT. Unfortunately, the redocking had to take place a minute sooner than planned when the station's computer malfunctioned and crashed; Mir had been left in free-drift, as planned, but it was a few degrees off its correct attitude and was becoming unstable. Solovyov and Budarin promptly restored the station's systems to normal. For Gibson, watching from Atlantis, the manoeuvres of Soyuz, Mir and the shuttle were nothing less than a "cosmic ballet". Indeed, the pictures snapped that Independence Day in 1995 are among the most stunning from the shuttle era.

With landing scheduled for 7 July, Baker set to work assembling the recumbent seats on Atlantis' middeck to ease the return to terrestrial gravity of Dezhurov, Strekalov and Thagard. Having the Russians aboard the shuttle was a pleasant surprise, although it did afford Dezhurov the chance to execute a prank on Precourt at one point. At one point, the pilot was working on a volt ohm meter on the aft flight deck, fixing a broken circuit, when the cosmonaut floated up behind him and whispered "Pfffffftttt" in his ear. Precourt was so absorbed in his work that he did not even sense Dezhurov's appearance. "You can't jump in space, but you can sure go reeling in zero gravity," Precourt told the NASA oral historian. "I could've choked him, but he had this big grin on his face!"

Early on the 7th, Gibson fired Atlantis' braking thrusters on the first landing opportunity of the day and brought his ship swooping to a smooth touchdown on Runway 15 at the Kennedy Space Center (KSC) at 10:54 a.m. EDT. But for Dezhurov and Strekalov, there was momentary alarm, for both men wondered if they would be challenged by the U.S. immigration authorities for carrying no passports or travel visas. At one point on Mir, Strekalov pulled Thagard aside to express his concerns. "I kept trying to allay Gennadi," Thagard said later. "Of course, he comes from a different culture, but knowing what I know of bureaucracy, I should have been worried a little bit for him, but I couldn't believe that in a million years they were going to arrest Veloga or Gennadi because they arrived in the United States with no passport. I hadn't even thought about it, but Gennadi obviously had been thinking about it quite a lot."

Dezhurov, Strekalov and Thagard were a little unsteady on their feet after more than 115 days in space. Yet Thagard was the first of them to unstrap from his seat and stand up after Atlantis' landing. "I walked off with no assistance," he said later. "I didn't have that much of a problem." The biggest issue, in fact, was the wiring for biomedical sensors, an electrocardiograph and a blood pressure cuff, which left his arm bruised and limited sensation in his hand. It took America's most experienced astronaut a few days to return to his normal self. "I felt a little awkward; more so than on my shorter shuttle flights," he said. "I had a real sensation that if I were to bend forward, I'd continue to go forward, and if I bent back, I'd continue to go back." Walking down hallways and turning provided the sensation of overshooting the corner and bruising his arm on the wall. "You just don't turn sharply enough," Thagard said, "and that's all because of the gains that change in the vestibular system while you're there." A few days after landing, he did a three-mile jog with Precourt and Baker, which he described as the hardest run he had ever done.

Although it was not the first time a cosmonaut had flown on the shuttle, or the first time an astronaut had flown aboard Mir, the ten days of STS-71 in the summer of 1995 were a significant moment in the future history of the joint U.S. and Russian space efforts. Over the next three years, eight more shuttle-Mir docking missions took

Pathway to the Stars

From Steam Ships to spaceships

By David Armstrong

For those of us of a certain age the development of transport has been a truly phenomenal experience. Poles apart but with a single purpose of travelling further and faster in different environments and now the ingenuity of mankind is there for all to see.

In the first instance, the power of a single horse was the measure of the amount of energy needed to move a load of materials across a certain distance in a certain time, an effort conveniently called horsepower. The mathematicians always wanting to quantify energy or effort in more precise ways defined the standard horsepower as 745.7 watts. The wonderful old Austin 7 of the 1930`s originally having just 7 horsepower or 5,220 watts. To travel at much greater speed and with a combined weight of 165 tons, the famous A4 Mallard`s steam train achieved 126 mph with the availability of 2,450 horsepower (1,826,965 watts / 1.8 Megawatts.

In this modern day era the need for power has grown to unbelievable requirements because of the amount of energy required to enable a vehicle to speed up to 17,500 mph (28,000 km/hr) in order to break away from from Earths gravity. Ironically the amount of fuel needed to propel a vehicle into space is compounded by the very weight of the fuel it`s self. The weight of the Apollo 11 capsule was 15 tonnes compared to the propelling vehicle a Saturn V rocket which weighed 2,970 tonnes on take-off. The Saturn V`s power was rated at 160,000,000 horsepower.

The above is a very simple generalisation of how things have progressed and only refers to the energy requirement of transport old and new. All vehicles of course require countless systems to perform the extra required tasks and most if not all of those have evolved from their own basic beginnings to the advanced bits of equipment now in use.

To land on the Moon, to communicate from there, to send photos and travel all that way and then return home has become a great wonder. In the meantime the next great adventure awaits to visit far and wide beyond our shores.

The saying "it`s not rocket science" is one heard often when describing simple tasks, but then what is rocket science when old steam engines required hundreds of working parts to turn their wheels whilst a space capsule requires a rocket described by some as an oversized firework.

The study of transport is a fascinating one. Knowing what it takes to make the wheels go round or what is required to lift transport into space involves an amount of energy together with the carefully designed engineering required to control the forces that are necessary.

Looking towards the future, when will the first fare paying passengers leave Earth on a ground breaking journey into Space or to a nearby Planet, Thomas Cooke is no longer in the market to further their adventures meaning that work awaits another intepid adventurer.

David Armstrong (I.Eng, MSOE, MIRTE.)

As an engineer I have always felt quite comfortable with numbers, words though are a different matter and as this is my first attempt to write an article, I can only hope the content is of interest to others.

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David Armstrong is a CAPCOM subscriber and spaceflight/ astronomy enthusiast. The Editor is always looking for new content for CAPCOM. Content from subscribers and other enthusiasts is welcome. However insignificant you may think your article idea is, others may not know about it and may find it interesting.

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From previous page…

place, exchanging six American crew members, delivering equipment and supplies and learning how two very dissimilar cultures could work together in space. The endeavour produced its own life-threatening challenges—including a fire aboard Mir and the crash of an unmanned Progress supply ship—but in many ways the shuttle-Mir effort was critical in allowing these two former enemies to work productively together. And today, as the world approaches 20 years of permanent habitation of the International Space Station, the lessons learned on STS-71 continue to bear great fruit.

Image Right: STS-71 and Mir Crews Posing for Posterity

Inside the Spacelab Science Module, the crews of STS-71, Mir-18 and Mir-19 pose for the traditional inflight picture. An important mission for the human spaceflight program, STS-71 was the 100th US human space launch from Cape Canaveral at Kennedy Space Center. Internationally significant, STS-71 was the first US Space Shuttle - Russian Space Station Mir docking and joint on-orbit operation. The Space Shuttle/Mir combination was also then the largest space platform ever assembled and put into orbit.

Image and Text Credit: NASA
www.nasa.gov

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