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Launch Platform

"A TALE OF TWO UPPER STAGES"

In the minds of its designers and advocates, the Space Shuttle was to be the first part of an infrastructure that would extend from low Earth orbit all the way to the Martian surface. It would be nothing more than a truck for special deliveries. A truck with such a large cargo bay that it would be capable of carrying into orbit the components for a modular space station in low orbit, satellites destined for geosynchronous orbits, modules for outposts on the Moon and Mars; in fact, everything else the American aerospace industry might want to place in space. As remarkable and innovative as it promised to be, one serious pitfall of this space truck was its lack of altitude. In fact, it was realized early on in its development that the operational ceiling would be about 300 nautical miles, while most of the payloads it was to haul would need to operate at higher altitudes, such as geostationary ones at 22,236 miles. Some payloads would be robotic probes to explore the uncharted territories of the solar system; destinations far and beyond the Shuttle's reach.

The solution was to create a "space tug" that would deliver these payloads to the appropriate destinations. The idea was straightforward and elegant. Once placed in space, the tug would serve a number of Shuttle missions. Upon reaching low orbit, a Shuttle would be approached by the tug. The Shuttle's payload would be offloaded to the tug, which would deliver that object to its intended operating orbit. Over time, the tug would routinely commute back and forth between low orbit and higher orbits. It would also be able to retrieve satellites and deliver them to the Shuttle, and then after the crew had repaired and refurbished them the tug would return them to their former positions. The tug would also be employed to transfer astronauts from the Shuttle to a space station and vice versa.

In the last decade of Space Shuttle operations, we grew accustomed to the vehicle docking at the International Space Station. However, because the initial concept was a delivery truck for goods and people in low Earth orbit, its creators did not include a docking capability with a space station; even if the Shuttle was the primary means of assembling a space station, it was to be the space tug that would transport everything destined for the station, including its crew.

D. Sivolella, *The Space Shuttle Program*, Springer Praxis Books,
DOI 10.1007/978-3-319-54946-0_2

The space tug was to be assembled in low orbit from components carried aboard the Shuttle. Its modular design would allow the tug to be configured for each type of mission. For example, after the establishment of an outpost either orbiting around or on the surface of the Moon, or indeed both, space tugs would transport hardware and astronauts to and fro. Satellites could be repaired directly in their operating orbits, as opposed to being dragged down to the Shuttle in low orbit. In this case, the space tug would be complemented with a crew module, and a cargo compartment for the tools and materials required for the servicing activity.

Conceptual studies started as early as 1970, with the intention of having the space tug in service by the time the Space Shuttle was introduced. Unfortunately, NASA's grand plans were soon slashed. In fact, before the final Apollo lunar mission, both the Moon and Mars had been relegated to the indefinite future as likely destinations for missions involving the Shuttle. Worse, the Earth-orbiting space station dropped down the list of priorities as budget cuts were imposed by a Congress skeptical of expanded space exploration. The American space program was becoming a program limited to Earth orbit. Inevitably, doubts arose concerning the need for a space tug. NASA was already struggling to sustain the Shuttle program by insisting it would be the launcher of choice for both the nation's civilian and military space programs. The plan was to commission the Shuttle in the late 1970s. A space tug, if required at all, would not be needed until the mid-1980s, when the agency hoped it would be able to start to build a modular space station. It was considered important to keep the idea of tug alive, to be able to respond when operators expressed their wish to retrieve and refurbish their orbital assets. However, motivated by economic interests, operators did not share this vision. They felt that refurbishing a satellite would add to its overall operational costs and hold back the application of newer and better technologies with new generations of satellites.

Eventually, NASA was able to sell the Space Shuttle as the only launcher that the nation should rely on, but the agency still had to find a way to overcome the vehicle's altitude restrictions.

Mothballing the space tug, in 1974 the agency opened talks with the Department of Defense (DoD) seeking financial backing to develop an expendable Interim Upper Stage (IUS). While the IUS would be much less capable than the space tug because it would be expendable and would not be able to retrieve satellites, it would provide a viable short term solution. The Space and Missile Systems Organization (SAMSO) of the Air Force analyzed the upper stages that were already in use with other launch vehicles to determine whether they could be upgraded and made compatible with the Shuttle to function as the IUS. Safety and financial considerations soon dictated that the IUS must be a solid rocket motor.

In December 1975 the DoD opened an industrial competition for the IUS. The proposals were received in March 1976, and in August Boeing was announced as the winner with a $50 million contract to develop the stage and begin mass production as early as 1978. The company anticipated a requirement for 300 vehicles in the coming decade.

The DoD was skeptical of NASA's argument that the Shuttle should become the nation's sole means of accessing space. They wanted a redundant launcher system in case the Shuttle was unavailable for some reason when a launch was needed. So they elected to keep the Titan family of launchers in service. In order to simplify logistics and inventory, they requested that the IUS be compatible with the Titan III launcher.

When it became evident that the space station would not be funded any time soon and therefore that the space tug might not be needed for another decade, the adjective "Interim" was replaced by "Inertial," as a reference to the inertial navigation system of the new vehicle. This was only a semantic change, but by clearly signaling that the IUS was to become a long term solution it dealt a fatal blow to the space tug.[1]

The IUS was meant to deliver payloads of up to 5,000 pounds to geosynchronous orbit, but in order to be competitive with any other launcher and in particular with the increasing European competition that was already selling services using their Ariane rocket, the Space Shuttle/upper stage combination required to be economically viable for smaller payloads.

"George Low indicated some concerns when he was Deputy Administrator about whether the Shuttle could compete with the Delta launch vehicle or not," remembers Hubert P. Davis, who worked on the space tug concept. "So he said, 'Let's see what we can do with a Delta class of payloads, and how you'd propose to do that.'" Davis carried out a study which he dubbed the "Delta Killer." The result was a request by NASA for a Solid Spinning Upper Stage (SSUS)[2] capable of serving as a "perigee kick motor" to insert a payload of 2,380 pounds into geosynchronous transfer orbit. This was the same capability as the Delta rocket. NASA also requested studies for an SSUS for a payload of 4,300 pounds to match the capability in this role of the Atlas Centaur launcher.[3]

On realizing that the Space Shuttle was intended to write off all other launchers in the American stable, the Space Division of McDonnell Douglas, eager for a slice of whatever conventional launch capability was compatible with the Shuttle, proposed a design that was approved by NASA by the end of 1976. But the aerospace giant was not going to get even a dime for its efforts to develop and manufacture the SUSS; or at least not yet. Cash would flow in response to purchase orders placed by NASA and possibly other users only after the Shuttle was in regular orbital service. In exchange, NASA assured the company it would be the sole supplier of Delta class upper stages. What McDonnell Douglas designed for the Shuttle was heavily based on the Payload Assist Module (PAM), an upper stage that it was already supplying for Delta rockets. The upgraded version would come to be known as the PAM-D, where D indicated a payload capability identical to that of the Delta version. To maximize the profitability of the Shuttle, the PAM-D was made small enough for as many as four to be carried in the payload bay.

The operational advantages of deploying payloads from the Shuttle facilitated an entirely new approach to planning and executing launches. For instance, the design of payloads would benefit from the more benign launch environment afforded by the Shuttle,

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[1] The space tug resurfaced as part of NASA's post-Shuttle planning.

[2] The term "spinning" refers to the common practice of spinning a spacecraft around its long axis during orbital maneuvering in order to increase directional stability. In fact, it is such an effective means of stabilizing the trajectory that it greatly reduces the need for the attitude control system to fire to keep the spacecraft on the right course. Thus the fuel saving is rather substantial.

[3] Strictly speaking, the IUS was to be a two-stage propulsive system. The first stage would boost out of the Shuttle's low orbit to attain a highly elliptical "transfer orbit" and then the second stage would circularize at geosynchronous altitude. In contrast, the SSUS would make only the first of these maneuvers, and the satellite would have to circularize its orbit. Hence the SSUS is also referred to as a perigee kick motor.

permitting the use of lighter and relatively more fragile structures. This was due to the 3-g maximum acceleration that the Orbiter could withstand during ascent to limit the loads placed on the vehicle and to ease the stress on astronauts and space flight participants[4] who lacked experience of the forces endured by jet pilots. Also, in the event of a launch abort the payload would not be lost, it would return with the Shuttle and, once refurbished, could be assigned to the next available flight.[5] Once on-orbit, and prior to deployment, a satellite could be checked out and if damage or a failure was found to have occurred during launch, the deployment could be canceled and the payload safely returned for repair and relaunch, thus preventing the complete loss of a valuable payload and its operational capability.

The IUS and PAM-D were carried into orbit using a reusable aluminum support structure called the Airborne Support Equipment (ASE). There were two models, one for each type of upper stage. The ASE would serve not only as a mechanical support infrastructure to accept the ascent loads exchanged between the Orbiter structure and the upper stage, it would also serve as an in-space launch pad. In both cases, the ASE would also provide services to the upper stage and its payload, such as commands, protection, safing, power distribution, communications, and so forth. Both ASE types were designed to be as self-contained and autonomous as possible, to require only the barest of attention from the crew. Similarities between the two upper stages were also shared in the way in which they would operate. As the Shuttle was being maneuvered into the desired orbit and attitude for satellite deployment, the astronauts would run a pre-deployment checklist to verify that the ascent had not harmed the upper stage and its payload, and to prepare them for the upcoming actions. Next, the ASE would be readied to bring the upper stage to the appropriate configuration. Last-minute updates of the Shuttle's orbital parameters and position would still be possible for upload into the upper stage's navigation software, to refine the precision of the upcoming journey to geosynchronous orbit. If the astronauts were satisfied and all checkouts were given the green light, the upper stage would be spring-released from the ASE to drift free of the Shuttle.

Despite having departed with a small translational velocity, the upper stage would remain in essentially the same orbit as the Shuttle. If the Shuttle were to be in close proximity at the time of engine ignition it would be blasted by the rocket's exhaust, with easy-to-imagine consequences, in particular for the delicate cabin windows. So ignition was scheduled some 45 minutes later, to allow the Shuttle time to withdraw to a safe distance. For further protection from the exhaust, the Orbiter would face its belly toward the rocket.[6]

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[4] As it will explained in Chapter 6, these were the so-called payload specialists.

[5] During the ascent four so-called intact abort modes could be invoked based on altitude, velocity and severity of the emergency. For each abort mode the Orbiter was expected to be capable of safely landing either back at the Kennedy Space Center or at an airport in Europe or Africa. Other abort modes were possible for even more serious conditions such as loss of all three main engines. These were called contingency modes and they entailed the Shuttle trying to reach an emergency landing strip on the US East Coast or just reach a safe altitude from where the astronauts would bail out. For a contingency abort mode the chance of survival of the Orbiter and its payload were much reduced if compared to an intact abort mode.

[6] This is akin to placing your hands in front of your face to shield it from a nearby explosion.

Yet exposing thousands of delicate tiles to something that could conceivably cause real damage to the vital thermal protection system sounds like insanity! Considering that there was no capability to inspect the condition of the thermal tiles on the belly, let alone any means to repair any damage,[7] how were the crew to have known of any flaws? We shall never know because, fortunately, such a scenario never arose.

PAYLOAD ASSIST MODULE MAIDEN FLIGHT

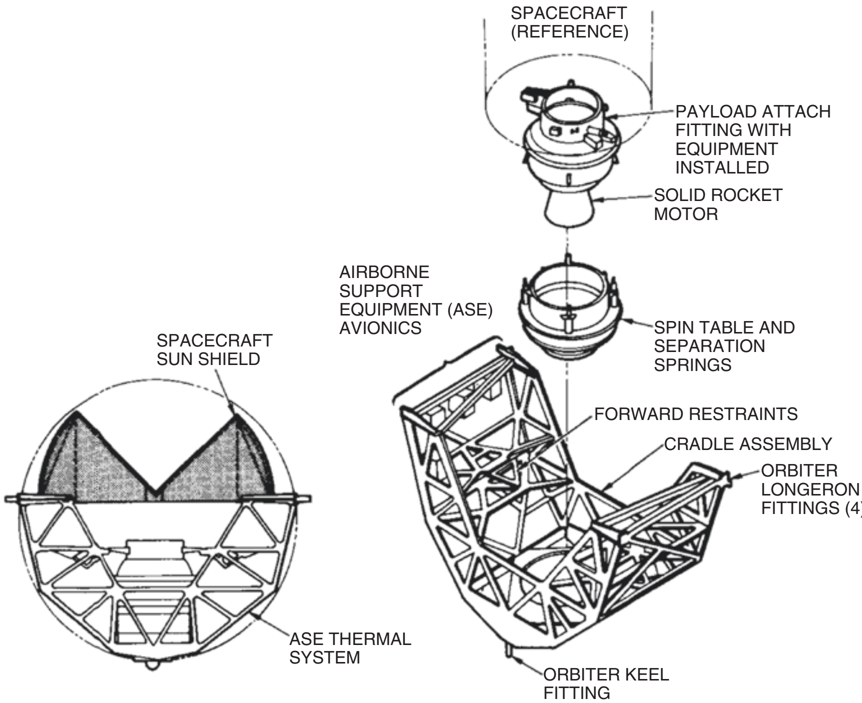
The Space Shuttle's first satellite deployment occurred on November 11, 1982, when *Columbia* carried two commercial communication satellites. It was a pivotal moment in the Shuttle program. In fact, as the previous four test flights had proved the vehicle operational, *Columbia* was now ushering in the era of cheap and reliable commercial operations. As NASA saw it, the program was open for business, ready to receive a steady cash flow from its customers with the overall goal of pushing aside all of the competitors.

Each satellite was tucked inside the protective cocoon of the ASE that housed its PAM-D. In this case, the ASE was an open truss structure cradle made of machined aluminum frame sections with chrome plated steel longeron and keel trunnions. The cradle supported the spin table and associated drive system that formed the mounting platform for the vertical installation of the PAM-D/satellite. The nominal envelope for the installation was constrained to a cylindrical volume 7.16 feet in diameter and 8.4 feet in height on the centerline. The envelope size was chosen in order to provide commonality with the Delta launch vehicle. In this way, should the Space Shuttle not be available for some reason, the payload could be transferred to a Delta as a backup. Once confidence in the Shuttle was sufficient to retire the expendable Delta, the extra volume available within the Orbiter's payload bay could be exploited to expand the nominal envelope to 9 feet in diameter inside the cradle and 10 feet above it.

To protect the cradle and the upper stage from the fluctuating temperatures of the orbital environment, the external surface was covered with multi-layered insulation thermal blankets. Atop the cradle was a tubular frame supporting a sunshield made of Mylar insulation. The sunshield panels were fixed on the side, and stationary, but the portion that covered the top of the spacecraft formed two clamshell-like sections that were closed in order to protect against thermal stresses when the payload bay doors were opened soon after the Shuttle achieved orbit.

The PAM-D itself was rather simple, using a Star-48 solid-fueled motor made by Thiokol that had a maximum propellant load of almost 4,273 pounds. The Payload Attach Fitting (PAF) on top of the motor casing made the mechanical interface with the satellite. It had retractable fittings to deal with spacecraft-to-cradle lateral loading during ascent, and a spring-loaded system to provide the impetus required to separate from the cradle. The PAF also housed the electrical interface connectors between the solid motor and the spacecraft, the redundant safe-and-arm device for motor ignition, telemetry components, and S-band transmitters.

[7] In fact, both capabilities would be added many years later following the *Columbia* accident.



Space Shuttle PAM-D system hardware.

Within 8 hours of lifting off, STS-5's crew were ready to make *Columbia* the first orbiting manned launching pad. The first to benefit from this exclusive infrastructure was SBS-3, which was a privately owned communications satellite.[8] To prepare for the deployment, the crew went through a series of checks and payload configuration procedures. Meanwhile, *Columbia* was maneuvered so that its open payload bay was facing the direction desired for firing the upper stage.

"The concept of the satellite in itself is simple. They are meant to be deployed by spinning," notes STS-5 mission specialist Joe Allen. "And the way you do it is just put the satellite on a table that will spin, like you put a record on a record player. You put it down and then you cause it to spin. In the case of the communications satellite, it is mounted on the table prior to launch, then you go to orbit…Once there you cause the table to spin and you point the Shuttle in exactly the right direction, and then at precisely the right part of the orbit you release arms that are holding the satellite to the table top. When you release the arms, springs on which the satellite sits expand to give it a very gentle push out, spinning very beautifully."

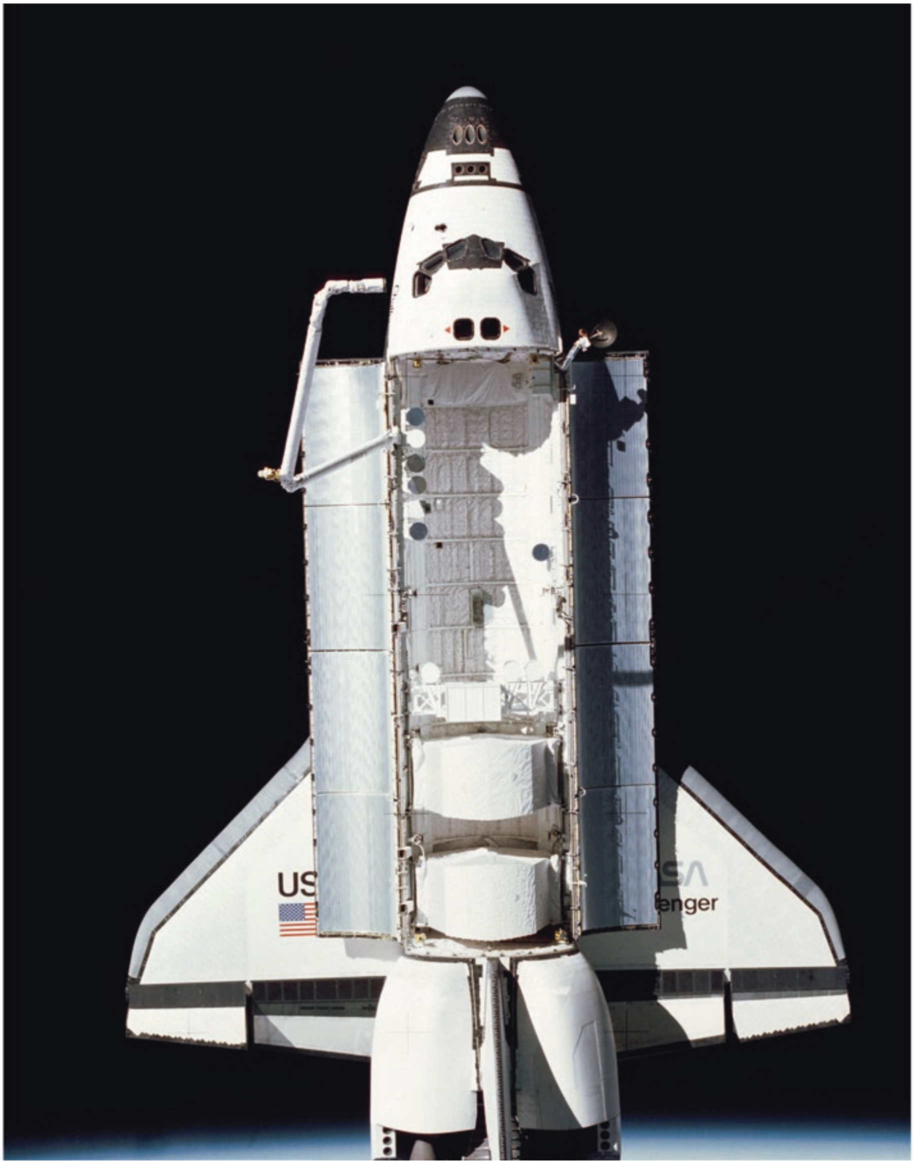
Allen's crewmate William B. Lenoir was in charge of the deployment. He coined the term Orbital Launch Director. At that early point in the Shuttle program, the crew were in

[8] Hughes Aircraft Company had built the spacecraft for Satellite Business System, a private communications company which was owned by subsidiaries of Aetna Life and Casualty, COMSAT General Corporation, and IBM.

communication with Mission Control for only the 15–20% of an orbit which was covered by the limited number of NASA ground tracking stations. But orbital mechanics required that the satellite be deployed when the Shuttle was crossing the equator, which would occur during one of the communication blackout zones. This meant the crew needed to decide for themselves whether to proceed with or abort the deployment. As Lenoir explains, the astronaut in charge of the satellite operations, “really was the launch director, the final say for whether you launched it out of the Shuttle or not.”

With the PAM-D carrying SBS-3 drifting out the payload bay at 3 feet per second and spinning at 50 rpm, the astronauts’ responsibility for this payload was complete.

The deployment of SBS-3. In the background, the sunshield doors are closed prior to deployment of the Anik C-3 satellite later in the mission.



An iconic picture of *Challenger* during STS-7, showing the typical arrangement of multiple PAM-Ds in the payload bay.

In accordance with the plan, mission commander Vance DeVoe Brand and pilot Robert F. Overmyer performed a series of burns to move *Columbia* out the way, to avoid the exhaust from the PAM-D's engine. Some 45 minutes later, the clock on the stage fired the rocket motor to boost the satellite on its way to geosynchronous orbit. As *Columbia* was facing its belly towards this activity, the astronauts were not able to witness the event with their eyes.

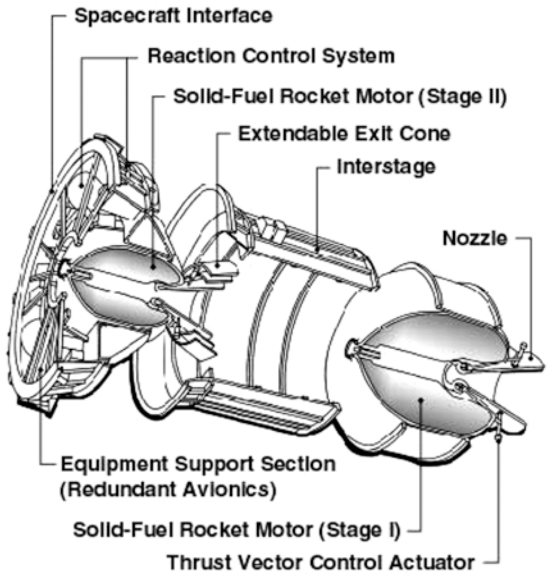
The next day, November 12, the show was repeated with the Canadian Anik C-3 communications satellite playing the leading role. With the approval of orbital launch director Joe Allen, the satellite was successfully deployed.

Releasing satellites in space was not new, because it was a necessary part of every mission by an expendable launch vehicle. And, after all, a key aspect of designing the PAM-D for the Shuttle was to retain compatibility with the Delta rocket as a backup option. Nevertheless, in space nothing can be left to chances, even a task as mundane as launching a satellite. As Lenoir remarks, “It was another case of never been done before, hasn’t been invented.” In fact, there had been concerns about the capability of the Shuttle to serve as an orbiting launch pad, particularly about whether it would be as stable as a launch pad on the ground. These concerns were answered by the arrival of the two new satellites in geosynchronous orbit several days later.

SPACE SHUTTLE INERTIAL UPPER STAGE DEBUT

The successful launches of SBS-3 and Anik C-3 were evidence that indeed the Space Shuttle/PAM-D combo was a winning team. Would the same prove true for the IUS? In the early afternoon of April 4, 1983, STS-6 set sail to answer this question. With a length of 17 feet, a diameter of 9.5 feet and a mass of 32,500 pounds, the cylindrical upper stage was an impressive sight. Furthermore, the payload, TDRS-A, was much larger than the commercial satellites deployed by the previous mission.

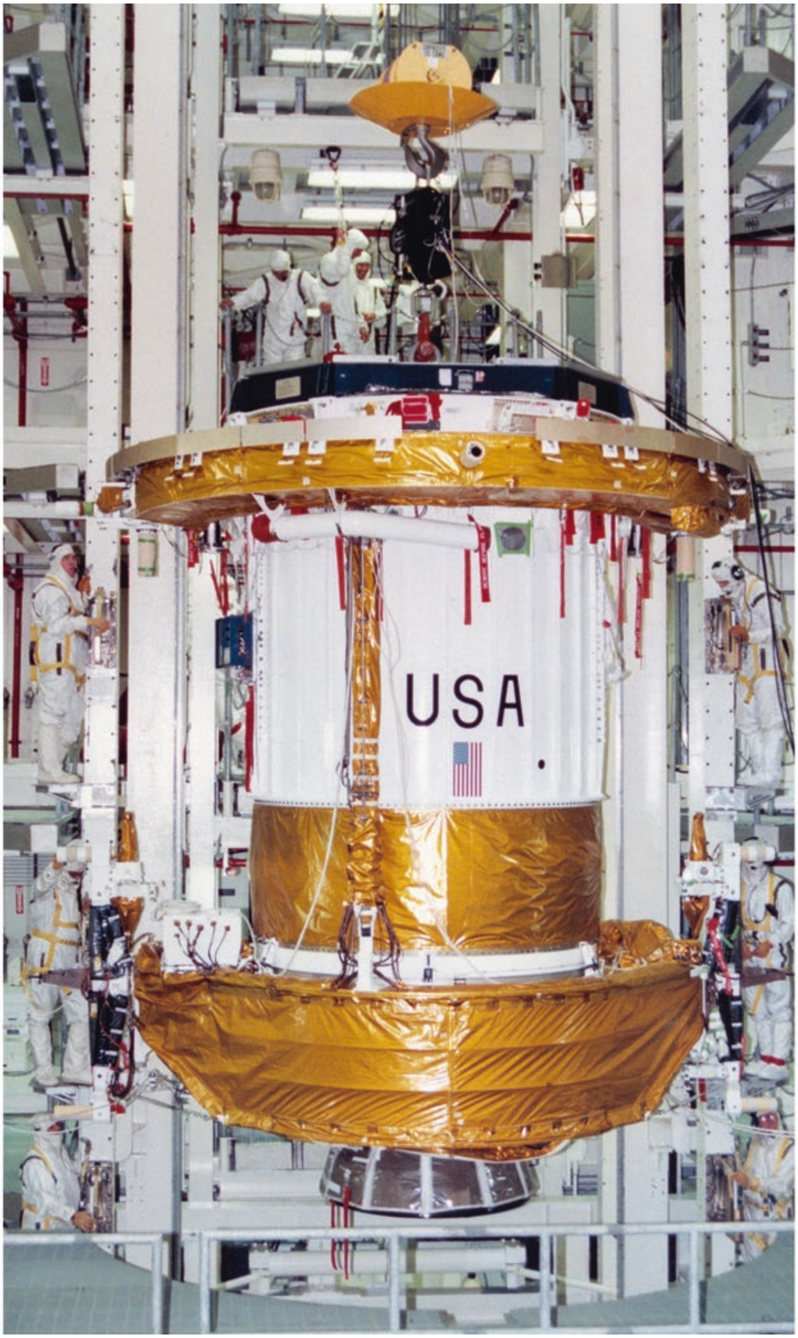
Physically, IUS consisted of an aft skirt, aft (first) stage, an interstage, a forward (second) stage, and an equipment section. Both stages employed solid propellant and movable nozzles for thrust vectored control. Redundant electromechanical actuators permitted up to 4° of steering on the large first stage motor and 7° on the smaller second stage motor. A hydrazine monopropellant reaction control system allowed attitude control in the coasting and thrusting phases, as well as impulses for accurate orbit injection. The majority of the avionics and control subsystems were housed in the equipment section, which also included a 9.84-foot-diameter interface mounting ring and an electrical interface connector segment to mate the spacecraft to the upper stage. Access doors allowed for replacement of components even with the spacecraft on the upper stage. A number of advanced features distinguished the IUS from other upper stages. It had the first completely redundant avionics system developed for an unmanned space vehicle, to enable it to correct in-flight features within milliseconds. It also had a redundant computer system, the second computer of which was capable of taking over the functions of the primary computer if necessary. Finally, the carbon composite nozzle throat allowed the high temperature rocket motor to operate for a long duration.



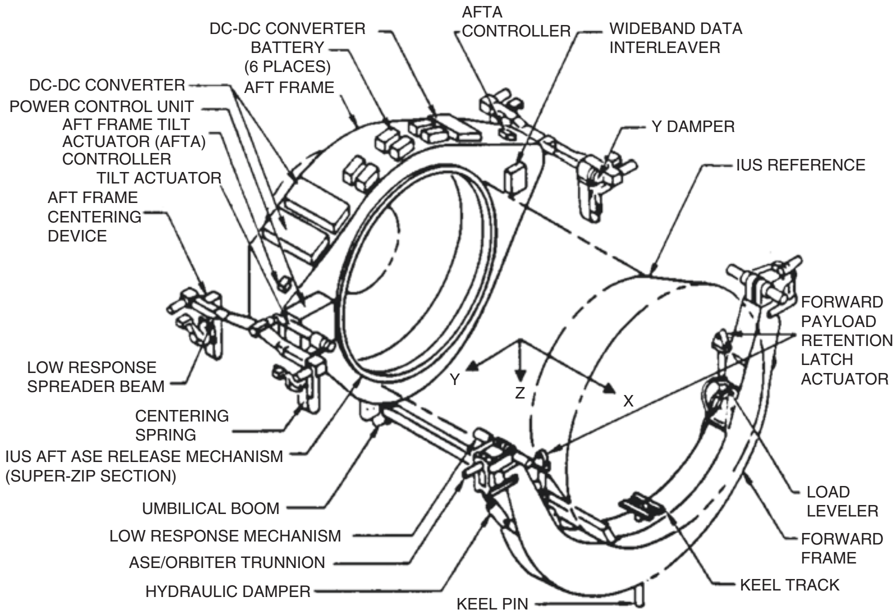
An exploded view of the Inertial Upper Stage.

As an IUS/spacecraft combination would be very heavy and would occupy almost the full length of the payload bay, the airborne support equipment was split into an aft and forward frame. The aft end of the IUS was inserted through the ring structure of the ASE aft frame, installed at the rear of the bay. Likewise, the IUS forward end was restrained by the semi-circular ASE forward frame. To reduce the ascent loads imposed on the IUS and to protect its aluminum skin-stringer construction, dampers were installed on the attachment points of the aft frame to the payload bay and on the forward frame. The ASE also offered housing for the batteries, electronics, cabling, and communication services to support the vehicle and its payload.

On attaining orbit, a sequence of actions similar to those performed on STS-5 was executed. After pre-deployment checks, the Orbiter adopted the right attitude for IUS release. Once again, the release required flipping just a few switches. However, the mechanics of deployment required a different sequence of actions since the IUS was designed for payloads much larger than those carried by the small PAM-D. In fact, STS-6 was tasked to deploy the first member of a constellation of Tracking and Data Relay Satellites (TDRS) for a brand new communications system that would replace the network of ground stations in support of the Shuttle and miscellaneous scientific missions.



An Inertial Upper Stage during ground processing. Its large size is evident from the technicians working on it.



The Inertial Upper Stage Airborne Support Equipment hardware.

Almost three-quarters of the length of *Challenger*'s payload bay was occupied by the IUS/TDRS-A combination.[9] How was such a long payload to be deployed? The robotic arm could not be used, because the IUS had not been designed to be handled by it. Instead, the ASE was to perform the task. The aft frame could be tilted upward to elevate the front of its payload above the crew cabin of the Orbiter. On completion of the pre-deployment checks, the retention latches on the forward frame of the ASE were commanded to release. Then an electromechanical actuator tilted the aft frame to an angle of 29°. The TDRS-A was now just above the payload bay, and ready for the ground to verify its telemetry. Had a fault been found in the satellite that canceled its deployment, the ASE would swing down again to restore the IUS/satellite in the bay. Since the checks were satisfactory, the crew raised the aft frame to 58°, into the so-called deployment position. With separation imminent, the attitude control system of the Orbiter was inhibited to ensure stability during the process.

Just short of 10 hours after lift-off, the crew of STS-6 enjoyed the awesome sight of the massive complex placidly passing over their cabin at a rate of just 0.4 feet per second. The Orbiter then performed a maneuver to open the range to a safe distance, and some 45 minutes after its release the IUS fired its first stage.

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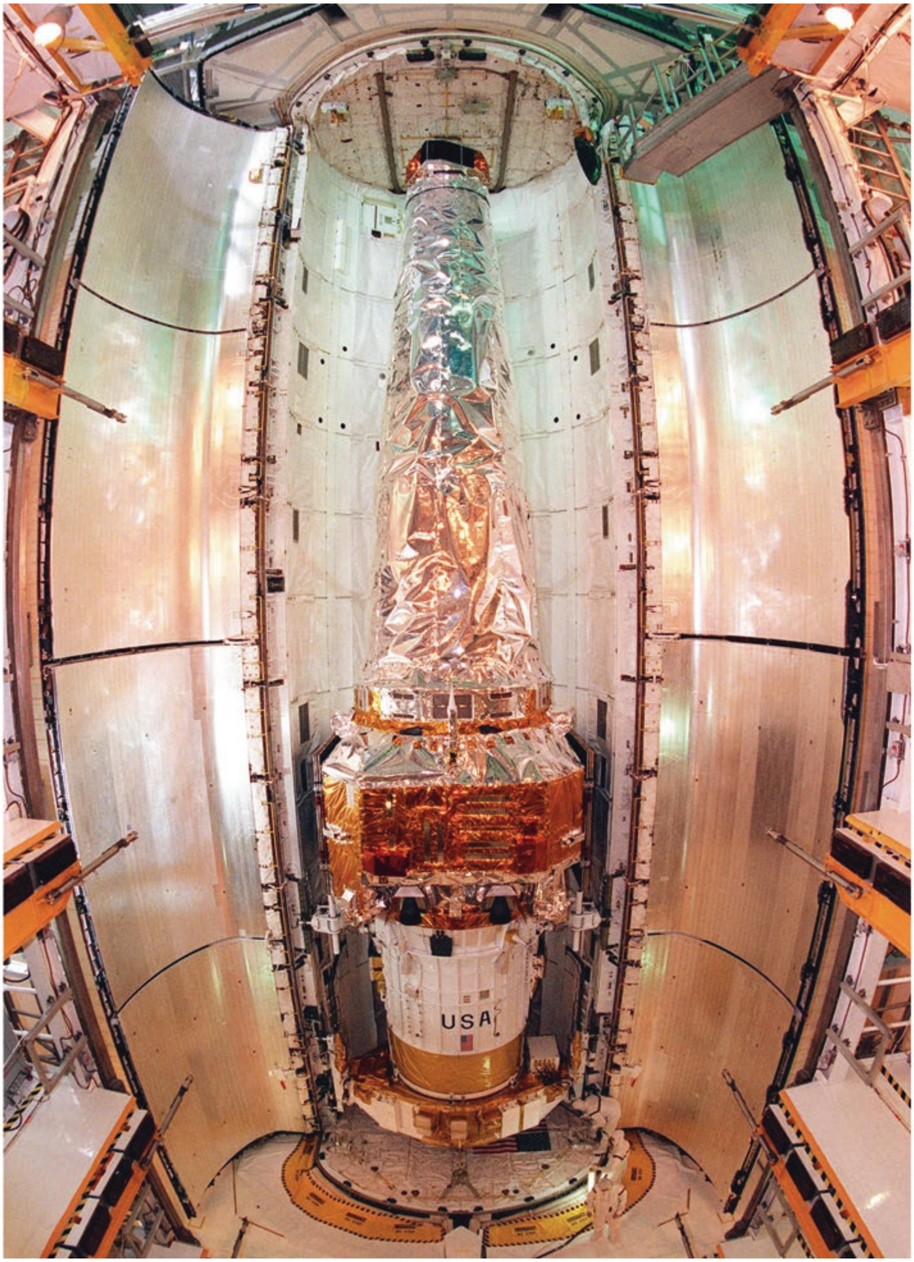
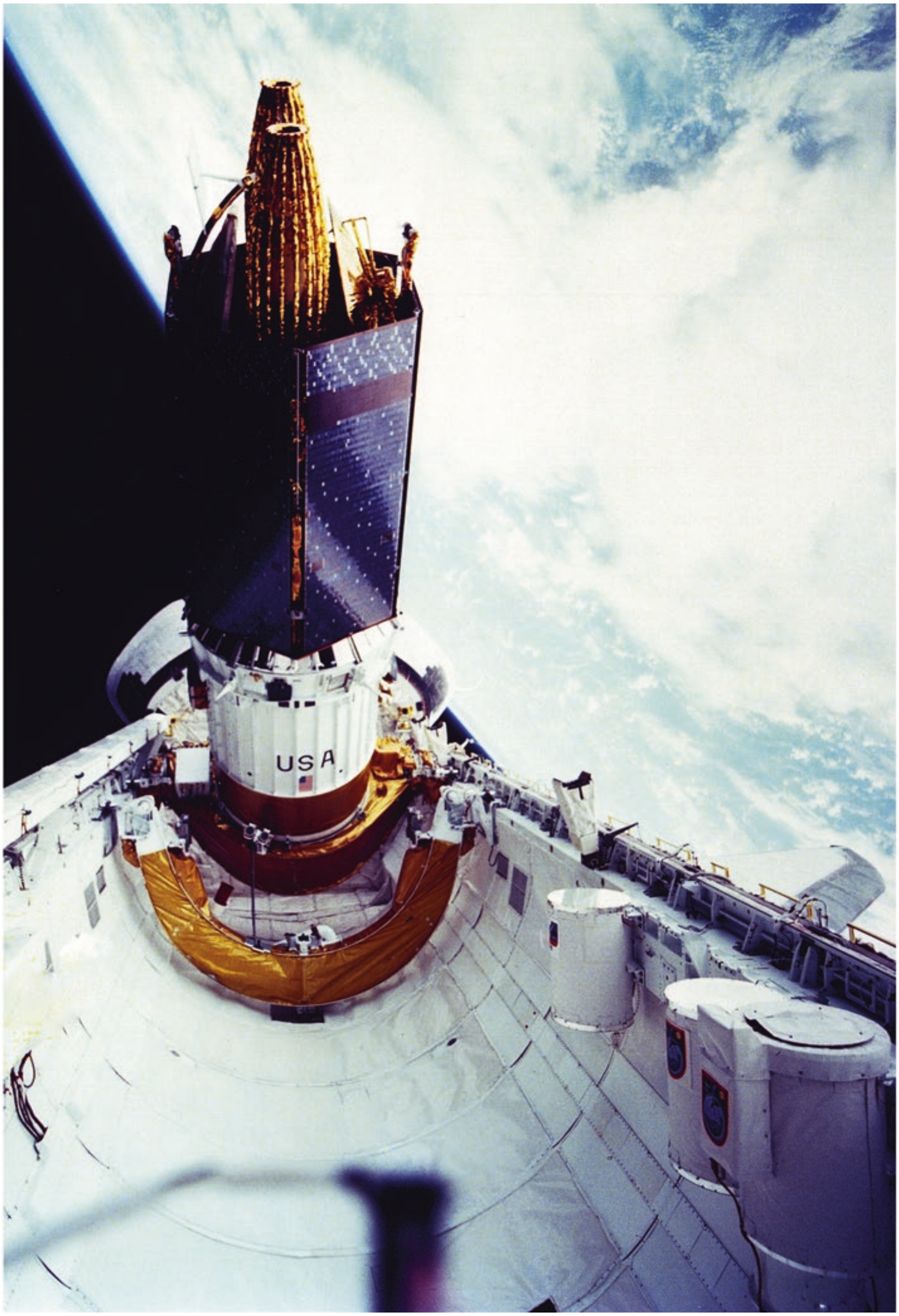
[9] In fact, this would be typical for any Shuttle-based IUS deployment.



The IUS/satellite combination took full advantage of the Orbiter's payload bay. Visible in this case is the Chandra X-Ray Observatory atop the last IUS ever to be deployed by the Shuttle. The telescope was so long that there were only a few inches between it and the forward bulkhead of the payload bay.



An Upper Inertial Stage and its payload raised to the deployment position.

The Upper Inertial Stage and its payload begin their journey to geosynchronous orbit. Clearly visible in the background are the forward and aft frames of the airborne support equipment. Both are covered with gold-coated thermal insulation blankets.

With the IUS gone, the payload bay looked rather vacant. The aft frame of the ASE was returned to its normal position and locked in order to withstand the loads of re-entry.

Between 1982 and early 1986, the Shuttle routinely delivered various commercial satellites, logging a total of twenty successful deployments with PAM-D and two by IUS.[10] The *Challenger* accident on January 28, 1986, had significant repercussions on how NASA would continue to operate the Shuttle. One of them was that it would no longer be available to commercial customers since it was unreasonable to gamble the lives of astronauts to deploy a satellite that could be as effectively launched using a conventional expendable rocket. But there were exceptions such as the deployment of the Syncom IV on STS-32,

[10] This include the deployment of the Magnum electronic signals intelligent (ELINT) satellite by STS-51C, the first Space Shuttle mission flown for the DoD.

the delivery of five TDRS satellites, and several other satellites for the Department of Defense. The final use of an upper stage by a Shuttle was STS-93 in July 1999, when *Columbia* deployed an IUS which maneuvered the enormous Chandra X-Ray Observatory into an elliptical orbit inclined at 77° to the equator with an altitude that ranged between 6,000 miles and 86,400 miles.

DEATH STAR

Even before the IUS entered service, both the USAF and NASA knew that it would not be too long before they would need to develop a new, more powerful upper stage. Although spacecraft mass was not expected to exceed the IUS's 5,000-pound lifting capability to geosynchronous orbit until at least the mid-1980s, both institutions had projections showing that satellites were bound to grow steadily in mass by the end of the decade. For instance, the Department of Defense was already approving projects which, by 1987, would weigh up to 5,500 pounds, grow to 6,200 pounds in 1988, and reach the range 8,000–10,000 pounds by the end of the decade and start of the 1990s. Likewise, the commercial communications satellite industry, which NASA was eager to tap into as a source of revenue for the Shuttle, was projecting a 12,000-pound mass requirement by the mid-1990s.

There are several advantages in increasing the mass of a spacecraft. For instance, a larger satellite can carry a greater load of propellant with which to extend its life in terms of station-keeping and attitude control, thereby requiring fewer replacements to be launched, resulting in significant cost savings to its customers or owners. A bigger spacecraft also provides more room for payload hardware,[11] and hence increases the services or capabilities that can be offered to mission planners or customers. Though counterintuitive, it can also be cheaper. In fact, when mass is a constraint, spacecraft designers have to rely on expensive miniaturized avionics and system hardware. This obliges them to devote considerable effort to devising the optimal way to squeeze the multitude of onboard systems and payloads into the available volume. Interference between components of a system, or between different systems, is also more likely if they are in close physical proximity, and overcoming this requires expensive ground testing and delays production and launch. However, the development of very large or very heavy satellites is clearly pointless if there is no means of launching them.

This was the situation in which the American satellite industry, both civilian and military, was being forced to face in the mid-1970s. As retirement plans were being drawn for all of the existing expendable launchers in anticipation of the introduction of the Space Shuttle, satellite builders and customers became reticent to develop or require larger spacecraft, as they were aware of the lifting capability limitation of the Space Shuttle/IUS combination. Unless a more powerful upper stage that would be capable of delivering the requisite performance was approved for development, then it would make no sense to plan for spacecraft which would not be able to leave their clean rooms. The risk was that they

[11] While a spacecraft is considered as the payload for a launcher, the payload of a spacecraft is the equipment designed to perform the desired mission. The remaining mass consists of propellant and the hardware needed to operate the spacecraft and its payload.

might turn to the competition and require launch services onboard the fledgling European launcher Ariane, with a resulting severe loss of revenue for NASA. Besides a more powerful upper stage would also benefit the agency's planetary exploration missions such as Galileo which was to orbit Jupiter and the International Solar Polar Mission (ISPM)[12] that was to investigate our parent star.

Generally speaking, deriving the final requirements for this type of mission is an iterative process in which the launch lifting limitations are accommodated in several ways. For instance, low energy trajectories for specific launch opportunities may be assisted by planetary fly-bys, even though this will significantly increase the journey time, maintenance costs, and likelihood of a malfunction occurring before the craft reaches its destination. Another alternative consists of splitting the original probe into two or three smaller spacecraft that are launched separately as soon as an opportunity presents itself. This is also akin to reducing the mission's objectives, simplifying and making the spacecraft lighter at the expense of the scientific return and the value of the program. Often two or more alternatives are combined. As a case in point, for the Galileo mission, which comprised an orbiter for Jupiter and a probe to penentrate the atmosphere, NASA considered dispatching them by separate Shuttle/IUS launches, with each vehicle proceeding independently to its target. Along with Galileo and the ISPM, other planetary projects were in the pipeline, particularly a Saturn orbiter with probes for the atmospheres of the planet and its largest moon Titan, probes for the atmospheres of Uranus and Neptune, and a mission to rendezvous with a number of asteroids.[13]

In 1982 Congress told NASA and the USAF to collaborate in the development of a form of the Centaur upper stage, already used with the Atlas launcher, for the Space Shuttle. This was disappointing because those institutions were seeking to develop a brand new ad-hoc booster with inbuilt potential for future growth, such as to become a space tug or an orbital transfer vehicle that could be either manned or automated. However, as that project would have required funding on the order of $1,000 million compared to the estimated $250 million cost of adapting the Centaur for the Shuttle, it is easy to understand why Congress chose the latter. Adapting the Centaur had the additional advantage of bolstering the know-how of the American aerospace industry in cryogenic engine technology, enabling it to compete more effectively with the new European Ariane launcher.

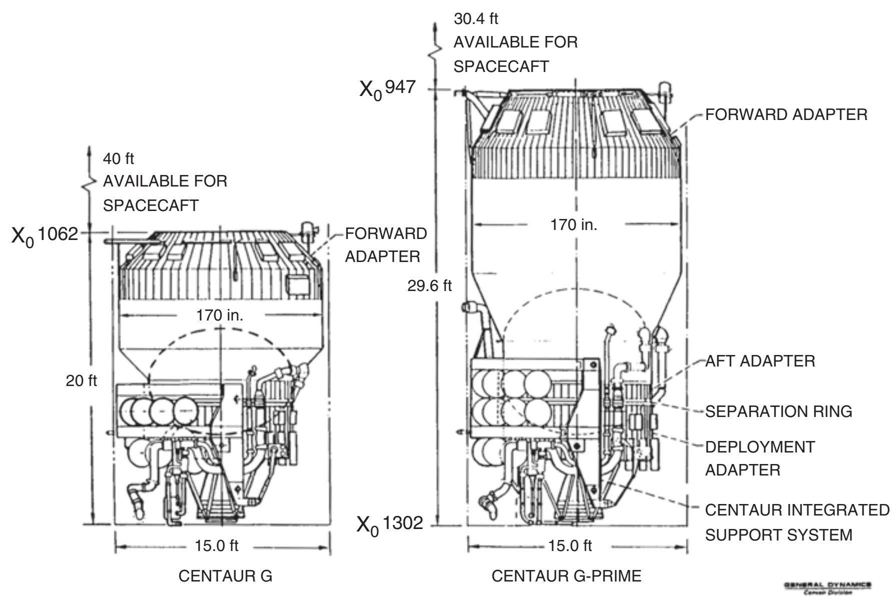
The chief difference between the Centaur and the IUS was their propellants. In general terms, one way to increase a rocket's performance is to make its tanks larger and hence able to carry more propellant for longer burns. The type of engine is also a factor, as different propulsion configurations can yield significantly different thrusts. Despite the old saying that size doesn't matter, it did in the case of an upper stage for the Shuttle because the propulsive stage and its payload had to fit within the payload bay. At 60 feet, the length of the payload bay was particularly constraining. It is easy to appreciate that the longer the upper stage, the smaller the volume available for the payload it was to carry, thereby penalizing the mission objectives and capabilities. At the same time, mass was a key limiting factor on the size of an upper stage. In fact, the Orbiter and upper stage/payload combination could not exceed 65,000 pounds. It is also easy to appreciate that the heavier the

[12] The International Solar Polar Mission was later renamed Ulysses.

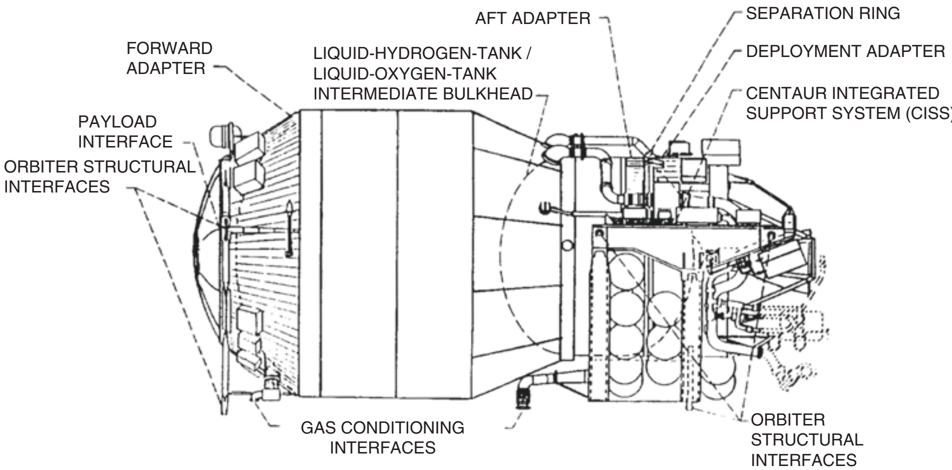
[13] At that time, no asteroid had been subjected to a close fly-by and they were entirely mysterious.

propulsive stage, the small the mass that it could carry. Both the size of the payload bay and the mass limitations of the Shuttle had the potential to seriously threaten the payload mass growth envisaged by NASA and the USAF, which was the driving reason for seeking a replacement for the IUS in the first place.

The only strategy for maintaining both size and mass within acceptable limits was to switch to an upper stage with cryogenic hydrogen and oxygen propellants, because this combination offers the greatest energy density. The Centaur upper stage used on the Atlas was that type of vehicle. Although a Shuttle Centaur would serve the needs of both NASA and USAF, it was soon realized that a one-size-fits-all approach was impractical as the civilian and military missions had radically different requirements. So there would have to be two versions of the Centaur for the Shuttle. The Air Force configuration named Centaur-G had to be capable of placing a 40-foot-long, 10,000-pound payload into geo-synchronous orbit and it would be roughly 19.5 feet long and 14.2 feet wide. It would be a shorter but fatter version of the Centaur in use with the Atlas, which was 30 feet long and 10 feet wide. The NASA variant, the Centaur-G-prime, was to be 29.1 feet long and 14.2 feet wide in order to escape from Earth and place a payload on an interplanetary trajectory. Both versions would be carried in the Shuttle's payload bay in a manner similar to the IUS, tilted to the proper angle prior to deployment, and ejected by a mechanism called the Centaur Integrated Support System.



Space Shuttle Centaur configurations.



Space Shuttle Centaur-G-prime configuration and major structural interfaces.

Since NASA had already conducted feasibility studies for a Shuttle version of the Atlas Centaur, the space agency was assigned overall management responsibility for both new variants and a joint NASA/Air Force Joint Program Office would supervise their development. As General Dynamics was the designer and manufacturer of the Centaur for the Atlas, it was only reasonable to select them as the prime contractor for the new versions. Another sensible choice was to use the same dual RL-10 engine configuration as the existing variant. And the engine maker, Pratt & Whitney, would make improvements to squeeze even more thrust out of the engine nozzle. Finally, Honeywell and Teledyne were to develop the sophisticated avionics needed to safely and accurately navigate and control such a high performance vehicle.

By 1985, the new Centaur development was already struggling to negotiate what was becoming a steeply uphill path. Its budget was rapidly rising due to higher-than-anticipated costs arising from multiple working shifts and issues of quality control.[14] Other delays were due to NASA changing the redundancy requirements on complex systems which required their redesign. Integration with the Orbiter structure was also proving difficult, as the support structure within the payload bay needed to be altered to ensure it would be able to accommodate the heavy upper stage and payload safely. When the weld of the hydrogen tank for a test article sprang a leak during a pressure test, a 4-month delay was introduced to strengthen the damaged structure and add the modification to the flight unit. Avionics qualification was another hurdle that resulted in delays and financial overruns. The first space-worthy unit of the Centaur-G-prime was not delivered to NASA until September 27, 1985.

Naturally, development of the Centaur-G for the USAF was severely affected by the issues encountered by its civilian counterpart, and further exacerbated by the self-imposed

[14] Historically, the space industry does not apply shift working to the manufacturing of space-worthy hardware. In fact, it enhances the risks of degrading the quality of assembly arising from human factor errors, such as incomplete handovers, typically arising when maintaining production across shifts.

requirement to make it compatible with both the Shuttle and expendable launchers such as the Titan 34D.[15] In fact, while the upper stage would be supported on both its front and aft ends within the Shuttle payload bay, on the Titan only its aft end could be secured. This difference substantially influenced the size and position of elements of primary importance. A "bolt-on kit" was proposed as a possible solution. In this way, the Centaur-G would be developed to be compatible with the Titan and if it was required to ride in the Shuttle the augmentation would provide the revisions to the structural interface. Another issue was that the Titan 34D was displaying lower-than-expected performance and it was being hoped the Centaur-G would be able to compensate for this shortfall. In fact, the USAF would have been almost better off to design two subtypes of the Centaur-G, one optimized for the Shuttle and the other for the expendable launcher. Indeed, in April 1985 General Dynamics suggested that the Air Force should terminate the Titan-based Centaur-G because the alterations would add risk, complexity, and might eventually prove to be impractical. A less-than-ideal relationship with NASA and concerns with their quality control processes were other factors impairing the design of the Centaur-G. Soon, however, all these issues would vanish because in the wake of the loss of *Challenger* on January 28, 1986, the Shuttle Centaur program was canceled.

Rarely is there satisfaction in the cancellation of a space program, but that of the Shuttle Centaur was warmly welcomed, particularly by the astronaut corps. STS-61F had been assigned the first such flight, with the upper stage carrying the Ulysses solar probe. Then on STS-61G another Centaur would have dispatched Galileo to Jupiter. Chief Astronaut John Young routinely described these two flights as the "Death Star" missions. This was a darkly humorous reference to peculiarities in the design of the Centaur that presented an extraordinary potential to kill the astronauts in charge of its deployment. One important issue was safety during an ascent abort. As STS-61F's commander Frederick H. Hauck put it, "If you've got a return-to-launch-site abort or a transatlantic abort and you've got a rocket in the cargo bay that is filled with liquid oxygen and liquid hydrogen, you've got to get rid of those propellants. You've got to dump them while you're flying through this contingency abort. To make sure it can dump safely, you need to have redundant parallel dump valves, helium systems that control the dump valves, and software to make sure those contingencies can be taken care of. And then when you land, you're sitting with the Shuttle Centaur in the cargo bay. If you haven't been able to dump all of it, you're venting gaseous hydrogen out of one side and gaseous oxygen out of the other side. That's just not a good idea."

The entire upper stage design was flawed by the fact that it was never meant to be human rated, and the human rating process was carried out in the face of continuous cost savings. "The whole concept of taking something that was never designed to be part of the human space program, that had his many potential failure modes, was not a good idea because you are always saying, 'Well, I don't want to solve the problems too exhaustively. I'd like to solve them just enough, so that I've solved them.' What does that mean? You don't want to spend any more money than you have to in order to solve the problem, so you're always trying to figure out, 'Am I compromising too much or not?' And the net result is you're always compromising."

[15] Although the USAF was ideally to use only the Space Shuttle for all of its payloads, uncertainty about how well it would perform led to the agreement to retain an expendable vehicle capability until the Shuttle had proved its worth.

To save on structural mass, the Centaur's tanks for both the Atlas and the Shuttle versions were made of very thin aluminum alloy panels. Lacking internal stiffening, both the hydrogen and oxygen tanks were pressurized to maintain their shape. As Hauck recalls, "If it's not pressurized, it is going to collapse by its own weight. If it were not pressurized, but suspended and you pushed on it with your finger, the tank walls would flex."

Another weight saving solution was to have a common bulkhead between the two propellant tanks, in a similar fashion to that of the second stage of the Saturn V. As Gary W. Johnson, who was Deputy Director of the Safety, Reliability and Quality Assurance (SR&QA) Directorate, recalls, "The big concern we had was… it would take very little delta pressure across that [wall] to cause it to break and really cause a problem [because if hydrogen and oxygen are mixed together the result is a violent explosion]. Instead of having a direct delta-P alarm system in there that would shut down the pressurization system or try to safe the systems if you were getting close to that pressure, they had a computer program that tended to try to manage the pressure in the oxygen tank and manage the pressure in the hydrogen tank, and between these two pressures that you're managing, then try to make sure you met the requirements for the delta-P. But there wasn't a direct measurement, and that was the real concern we had…The Safety Panel was insisting that we had to have something separate on that."

Owing to the volatile nature of liquid hydrogen and oxygen, the Centaur would be fueled on the launch pad just hours prior to lift-off. Johnson and his team had further worries concerning the propellant loading system. "Loading was to employ plumbing through the Shuttle and then into the Centaur. The plumbing lines had so little margin in them that if we suddenly had to stop propellant loading when loading the external tank, the hammer-type pressure you get – the pulse from suddenly shutting that off – stood a very good chance of rupturing the lines in the Orbiter, causing the loss of the entire vehicle on the pad. That was a big safety concern. We didn't have sufficient margin in those lines."

Also worrisome was the way in which the flight hardware was being approved for space despite its not having passed ground testing. This was an issue that profoundly concerned Johnson. "I was reviewing, going through some of the paperwork, and I noticed on some of the critical relay boxes that send commands from the computer, that they'd suffered failures in testing for vibration. I didn't see in the paperwork any real closeout that said that that hardware ought to be certified yet. Yet we had papers signed off by the people involved, saying things were certified and all ready to go. It looked to me, that we still had some open problems which we had yet to fix. I called in the engineer responsible for that system. I was quizzing him about how we'd gone through everything, and there were these problems. I said, 'What's the rationale for signing that this is ready to go?' I could see the young engineer was visibly shaken, and he confided that he'd been forced to sign off by his management."

Another safety issue that Hauck remembers bringing up at a meeting pertained to redundancy in the helium system which would pressurize the tanks and force feed the propellants into the combustion chambers of the twin engines. During a launch abort, this system would have expelled the propellants from the tanks to bring the Orbiter's weight down to a manageable level for a safe landing. "In early to mid-January 1986, we were working an issue to do with redundancy in the helium actuation system for the liquid oxygen and liquid hydrogen dump valves, and it was clear that the program was willing to compromise on the margins in the propulsive force being provided by the pressurized helium. We were very concerned. We went to a [safety review] board to argue that it was not a good idea to compromise on this feature. The board turned down the request." That meeting was quite revealing, so much so that soon afterward Hauck called in his crew and expressed his concern about how NASA was willing to sacrifice the safety of their mission. He reassured them that if anybody wanted off the mission, he would support their decision. The crew stayed together.

If you are wondering why these smart people were willing to risk their lives, fully aware of how dangerous it would be to fly with the Centaur, you need to understand the historical context.

As STS-61F's mission specialist John M. Lounge admits, "We assumed we could solve all these problems. We were still basically bulletproof. Until *Challenger* [was lost] we reckoned we were bulletproof and the details would be worked out." Hauck echoed this sentiment. "We'd never killed anybody in space up to that point. I mean, there was a certain amount of sense that it would not happen." Besides you must also consider that an astronaut would accept risk in order to fly in space, in particular for a high profile mission. As Lounge says of his thinking at that time, "It was a privilege to be assigned to an important mission, so our attitude was that we just had to work it out." And if the astronaut was a Navy aviator like Hauck, then pride was also a major factor: "I probably had an ego tied up with it so much that, you know, 'I can do this. Heck, I've flown off of carriers and I've flown in combat, and I've put myself at risk in more ways than this. I'm willing to do it.' So I didn't ever think of saying, 'Well, I'm not going to fly this mission.'"

While the *Challenger* investigation was underway, and as more and more details emerged of the poor safety culture within NASA, the Shuttle Centaur was still kept alive despite of the numerous safety issues. However, it was living on borrowed time. Well before the end of 1986, NASA Administrator and former astronaut Dick Truly decided to close the program for good. The Shuttle Centaur never flew in space, and missions were revised to use the less powerful Inertial Upper Stage.

As of May 2016, the sole surviving test article for the Centaur-G-prime is on display at the NASA Glenn Research Center in Cleveland, Ohio.

The idea of a cryogenic upper stage for use on the Shuttle was resumed for a brief period in the early years of the new millennium. In fact, Boeing's Advanced Shuttle Upper Stage (ASUS) concept was tested in 2000 at the NASA Marshall Space Flight Center. The plan was that the stage would be empty at the time of launch and then be filled during ascent by drawing liquid hydrogen and liquid oxygen directly from the Shuttle's external tank. The propellant transfer concept was a pressure-fed rapid chill and fill system which consisted of a spray bar located in the center of each tank and running its full length. At the start of the filling operations, the propellant would chill down the tank wall, and the vaporized propellant would be expelled through a typical vent system. When the wall had achieved an acceptable temperature, the vent valve would be closed to initiate the actual propellant loading, which would take 5 minutes to complete. This was a smart idea, because it would tap into the available reserve of hydrogen and oxygen that typically remained in the external tank after its separation from the Orbiter. In this way, there would be no reduction in the payload capacity of the Shuttle. Also, because the chill and no-vent fill process was being considered for on-orbit transfer of propellant, it was reasoned that the lessons learned from using the ASUS would assist the development of reduced gravity cryogenic propellant transfer technology. Although testing proved that the concept would work, in the wake of the *Columbia* accident it never received a chance to prove itself on a mission.

In the second semester of 2002, NASA Marshall Space Flight Center undertook a 6-month evaluation study of a High Energy Upper Stage (HEUS) concept. Proposed by Northrop Grumman, it again envisaged a liquid-fueled upper stage but unlike the Centaur or ASUS it would use storable propellants like monomethyl hydrazine and nitrogen tetroxide. These are simpler to handle than cryogens but, being hypergolic, these propellants will spontaneously ignite upon coming into contact. Two types of upper stage were considered: one with liquids and the other with storable gels. Apart from propulsion, their subsystems were based largely on heritage hardware in order to minimize cost, risk, and development schedule.

Unfortunately, this study did not progress past the concept stage. If it had reached the development phase and the assembly shop, the HEUS would have been an ideal candidate to deliver the James Webb Space Telescope (JWST) as the successor to the Hubble Space Telescope (HST) and the Space Interferometry Mission (SIM) which was to seek exoplanets.[16]

GATEWAY TO THE SOLAR SYSTEM

The demise of the Centaur upper stage for the Shuttle and the grounding of the fleet following the loss of *Challenger* had a severe detrimental effect on the deep space exploration program. White-dressed technicians preserved the Magellan, Galileo, and Ulysses

[16]The Space Interferometry Mission was canceled due to the complex and expensive technology needed to image alien words located tens or hundreds of light year away. The JWST is currently scheduled for launch in 2018 onboard an Ariane 5 launcher, marking a significant coup for the Europeans.

probes in space-worthy condition awaiting a revised launch schedule. In the meantime, new trajectories had to be computed for future launch opportunities based on planetary alignments that took into account the withdrawal of the powerful upper stage. In due course, all these probes would be safely dispatched using the solid-fuel Inertial Upper Stage.

The first was the Venus-bound Magellan. In any historical period, Venus, almost a twin of Earth, has captivated the imagination and attention of the amateur as well as the professional astronomer. To their frustration, however, the surface of the planet is hidden from view by an opaque atmosphere. It was not even possible to identify how rapidly the planet rotated on its axis. This was finally measured in 1961, when radio signals were beamed at the planet by the most powerful antennas and the reflections analyzed. Venus rotates in a retrograde manner, in the direction opposite to that of its orbital motion. In effect it spins up-side down. Furthermore, its rotation is extremely slow, its axial period of 241.5 terrestrial days being longer than the 224.7 days that it takes to travel around the Sun. Later it was found that the surface of the planet could be investigated by processing radar echoes to produce images. Then US and Soviet probes equipped with radar instruments were placed in orbit around the planet to map it. An almost global map was provided in 1978 by NASA's Pioneer 12 (also called Pioneer Venus Orbiter). This spanned 92% of the surface at resolutions in the range 30–84 miles. In 1983 the Soviet Venera 15 and 16 orbiters achieved the outstanding resolution of 1.25 miles, but their coverage was limited to the northern hemisphere above 30° latitude.

By 1988, NASA hoped to improve on this resolution and extend the map to cover the entire surface. In fact, in the wake of the successful optical mapping of Mars by Mariner 9 in 1972,[17] it started a feasibility study for an equivalent mission to Venus. This Venus Orbiting Imaging Radar (VOIR) was meant to use a Synthetic Aperture Radar (SAR) to map up to 70% of the planet at a resolution of better than 400 meters. The radar was also to collect altimetry data and operate passively to sense emissions from the surface. But VOIR did not make it past the drawing board and in 1982 the project was canceled. The following year NASA proposed the Venus Radar Mapper (VRM) as a simpler but more focused mission. All of the non-radar experiments had been removed. Only the core science objectives of the deceased VOIR were retained, namely to investigate the geological history of the surface and the geophysical state of the interior. By 1986 the rather unattractive acronym was replaced with the more fitting moniker of Magellan, to honor the Portuguese explorer Ferdinand Magellan whose expedition in the early 16th century was the first to circumnavigate the Earth to reveal the vast nature of its oceans. Likewise, it was hoped that the Magellan probe would provide a global understanding of our near twin.

To save on development costs, Magellan was mostly constructed with spare parts salvaged from other missions. For example, the 12-foot-diameter high-gain antenna, used alternatively for SAR mapping and data transmission to Earth, was a spare from the Voyager project, as were the primary structure and the small thrusters for attitude control. From the Galileo project, Magellan obtained the command and data handling system, the

[17] Mars has such a thin and transparent atmosphere that it is very easy to observe its surface with both ground-based telescopes and orbiting probes.

attitude control computer, and the power distribution units. The medium-gain antenna was a spare from the Mariner 9 mission.

The initial plan was for Magellan to be deployed by a Shuttle in April–May 1988 and pursue a Type-I trajectory that would reach Venus in just under 4 months. From launch to arrival, the spacecraft would have traveled less than 180° around the Sun. The *Challenger* accident in January 1986 grounded the Shuttle fleet until operations resumed in September 1988. The next available opportunity for a Type-I trajectory was October 1989. But this was the same period in which the Jupiter-bound Galileo probe was scheduled to launch. In order to avoid further delaying that mission, it was decided to launch Magellan in April–May 1989. The IUS could not to send Magellan on a Type-I trajectory. The relative positions of Earth and Venus at that time meant it had to fly a longer Type-IV trajectory where it traveled one and half times around the Sun on a cruise lasting 15 months. The lengthened journey time was compensated by a reduction in launch energy and Venus approach speed. On May 4, 1989, after just five revolutions of the Earth at an altitude of 160 nautical miles, Magellan was deftly deployed by STS-30 *Atlantis* to begin its journey to explore undiscovered lands. This was an important moment for NASA, because it marked the resumption of planetary exploration, which had been moribund for over a decade.

The Galileo mission was next. In the early 17th century the Italian astronomer Galileo Galilei spent countless hours observing the heavens using a crude telescope. One of the celestial objects he loved to watch was the majestic Jupiter which, to his astonishment, revealed itself not only as a planet but also to possess four prominent moons. This dealt the death blow to the Aristotelian-Ptolemaic view of the universe, supported by the Catholic Church, that all celestial objects revolved around the Earth. Indeed, using his observations of the Jovian system along with data gathered on the motions of other planets, Galileo strongly defended the Copernican concept in which all of the planets, including the Earth, revolve around the Sun. It was fitting that the Jupiter-bound probe carried into orbit by STS-34 *Atlantis* in the afternoon of October 18, 1989, was named in honor of this Tuscan astronomer. It would become the first spacecraft to enter into orbit around Jupiter to conduct long-term observations of the planet, its magnetosphere, and its moons. A small probe was to be released to make direct measurements of its atmosphere.

The cancellation of the Shuttle Centaur meant the Galileo mission had to use the less powerful IUS. As a result, it had to follow a very roundabout route that exploited a series of gravity assist fly-bys. It would not reach its destination until December 7, 1995, having flown by Venus once and Earth twice in what was dubbed the Venus-Earth-Earth Gravity Assist (or VEEGA) trajectory.[18]

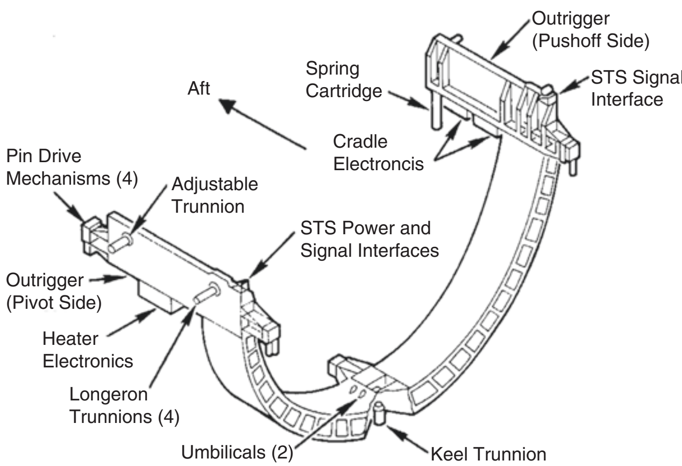
The STS-41 flight concluded the brief period in which the Shuttle launched deep space missions. Lifting off in the morning of October 6, 1990, *Discovery* carried the Ulysses probe on a mission to study for the first time the polar regions of the Sun. The mission design required a close pass over the Jovian poles to steeply incline the plane of the spacecraft's orbit out of that in which the planets travel around the Sun. Although the probe was not very large, to compensate for the lack of a Centaur it was necessary to augment

[18] If the Centaur-G had been available, the voyage to Jupiter would have lasted just 2.5 years. On the other hand, the lengthy detour provided opportunities to study Venus using new sensors and the first close fly-bys of asteroids.

the IUS with a payload assist module based on that created as a perigee kick motor for geosynchronous satellites[19] as a third stage to reach Jupiter in 1992. This would be the first and only time that such a combination of upper stages developed for the Shuttle was used.

ADDITIONAL UPPER STAGES

The PAM-D and IUS were not the only satellite delivery systems available to Shuttle customers. On several occasions, large Hughes-built Syncom spacecraft were simply rolled out the payload bay in what was informally known as the Frisbee deployment mode. As the first satellite to be designed specifically for the Shuttle, it was sized to snugly fit the width of the payload bay. This wide body provided enough room to add perigee and apogee kick motors. In effect, the spacecraft had its own built-in upper stage. The fee NASA charged for carrying a satellite was scaled by the fraction of the payload bay that the package occupied. A wide but squat satellite that was carried on its side saved the client money.[20] The satellite was attached to a cradle in the payload bay at five contact points, four on the longerons and one on the keel.



The main components of the cradle for the Frisbee deployment mode.

To prepare for a Frisbee deployment, the Shuttle would be oriented with its tail in the direction of travel and the payload bay facing down, in order that the spin axis of the

[19] This third stage was labeled a PAM-S.

[20] As will be discussed in greater detail in Chapter 12, the cost of deploying a satellite from the Shuttle was based on a formula that took into consideration the ratio of either the mass or the length of the cargo, whichever was the greater, in relation to the Shuttle's total capacity.

satellite would point in the correct direction for the perigee motor to thrust, as if it had just been released by an expendable launcher. Locking pins at four of the contact points would be retracted by electrical motors, each pin requiring about 5 minutes. A pyrotechnic device at the fifth contact would then be initiated to allow for the release of a spring that would push one side of the satellite upward as the other side pivoted. This provided simultaneously for a rotation and translation maneuver which imparted an initial separation velocity of 1.3 feet per second with a stabilizing spin of about two revolutions per minute. Thirty seconds later, the Syncom would be automatically activated. One effect was to start the onboard clock that would time the maneuvering events such as commanding the reaction control system to increase the spin rate to 33 rpm. Some 45 minutes later, and with the Shuttle at a safe distance and attitude, the perigee kick motor would ignite to achieve an elliptical orbit with an apogee of 9,000 miles and then be jettisoned. The liquid-fueled apogee motor would perform a series of maneuvers to raise the apogee to 22,236 miles and circularize the orbit.

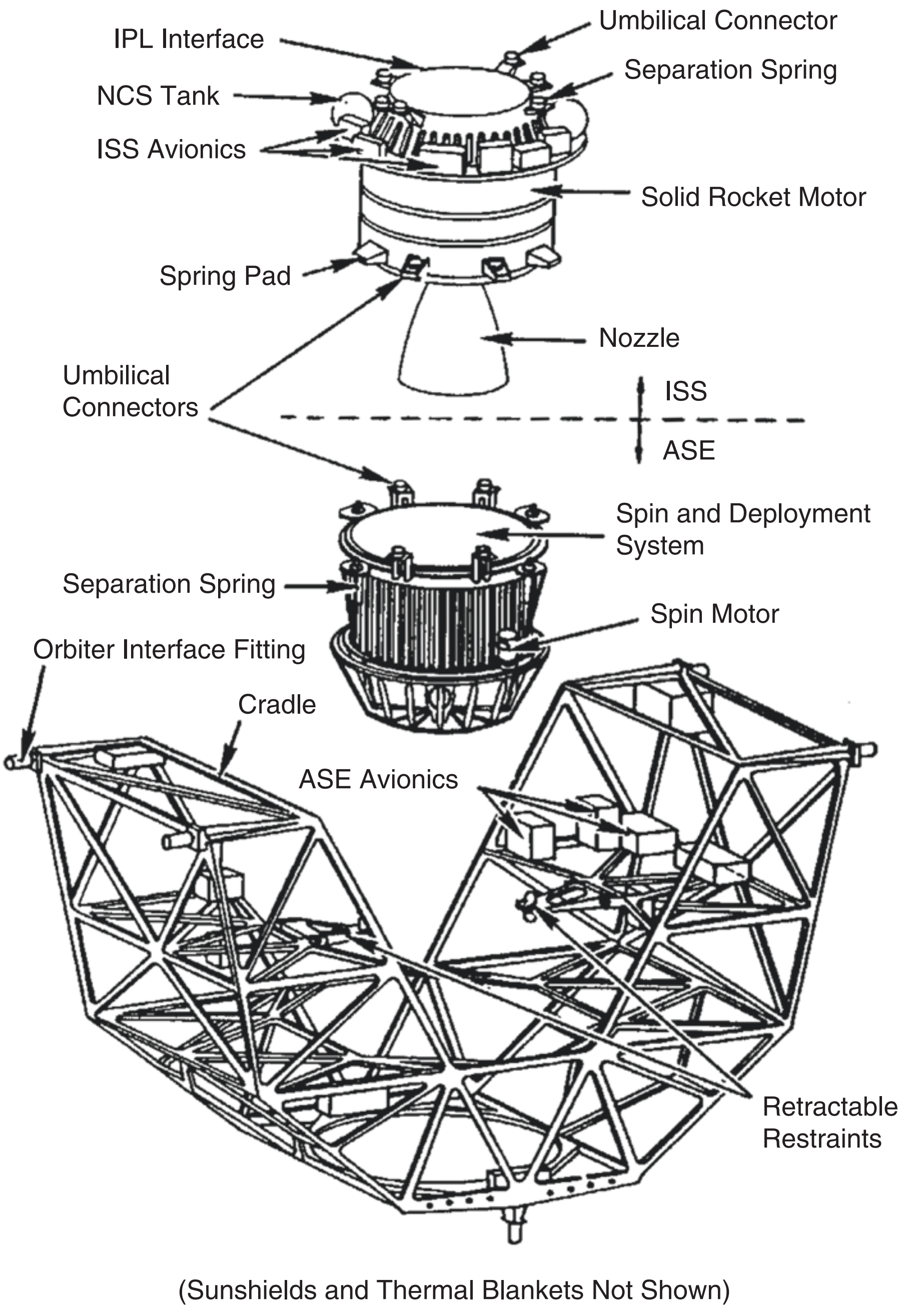
A Syncom satellite rolling out the payload bay. In the background is the cradle covered in a gold-coated insulating Mylar blanket.

On October 23, 1992, *Columbia* deployed the Italian-built LAGEOS II satellite as the primary objective of the STS-52 mission. This Laser Geodynamics Satellite was a 900-pound, 24-inch sphere whose surface gave it the appearance of a large pitted golf ball because it was covered with 426 almost equally spaced three-dimensional prisms mostly made of a fused silica glass called Suprasil. From any ground station participating in the LAGEOS project, a laser beam illuminating the satellite would be reflected back by any one of the prisms. Measuring the round trip travel time and multiplying by the constant speed of light would precisely measure the distance that separated the spacecraft from the ground station. By tracking the LAGEOS satellites for a number of years, scientists would be able to characterize the movement of the ground stations. This would enable them to monitor the motion of the planet's crust, characterize the "wobble" in the axis of rotation, collect information on the Earth's size and shape, and more accurately determine the length of its day.

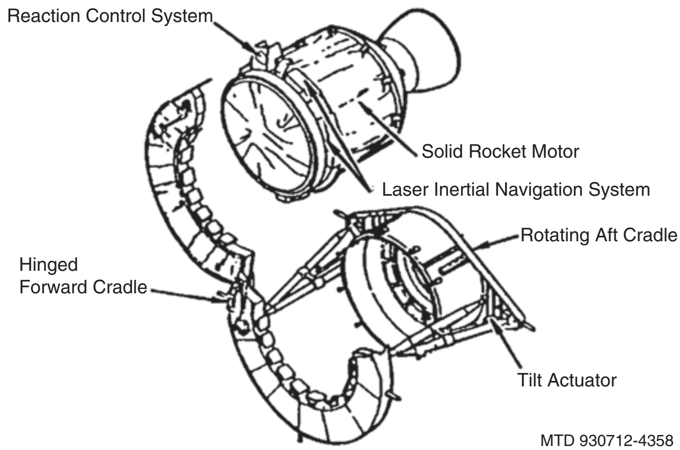
Such a simple spacecraft design, lacking even an onboard system, stemmed from several trade-offs. In fact, to serve as a stable orbital reference point its mass had to be large enough to minimize the effects of non-gravitational forces, yet light enough to be placed into a fairly high orbit. It had to be large enough to accommodate many retroreflectors, but small enough to minimize the influence of the solar pressure. Aluminum would have been too lightweight for the entire body, so it was decided to combine two aluminum hemispheres bolted around a brass core. This selection of materials had the bonus of reducing the interactions with the Earth's magnetic field and thus increasing its orbital stability. The first LAGEOS satellite was launched on May 4, 1976, from Vandenberg Air Force Base in California using a Delta launch vehicle.

With the premature retirement of the PAM-D, NASA was left without a suitable upper stage for deploying a mid-sized satellite such as LAGEOS II from the Shuttle. Instead, the Italian Space Agency (ASI) provided the Italian Research Interim Stage (IRIS) which, unsurprisingly, was a carbon copy of the deceased PAM-D. In fact, it consisted of a solid rocket motor mounted on top of a motorized spinning table that was enclosed within an airborne support equipment cradle equipped with sun shields and the necessary hardware and equipment for stage deployment. The satellite and its LAGEOS Apogee Stage (LAS) were mounted on the IRIS. After leaving *Columbia*, the satellite was propelled into the desired circular orbit at an altitude of 3,600 miles.

The Transfer Orbit Stage (TOS) was another upper stage which was used on the Shuttle only once. This resembled the IUS, but was smaller. Built by Martin Marietta Astronautics Group under the management of Orbital Sciences Corporation, it was a one-stage solid motor propulsion system with a gimbaled nozzle for thrust vectoring, a navigation and guidance system, a reaction control system to adjust attitude or local pointing, and a cradle to support the entire package in the payload bay and facilitate its deployment. The cradle resembled that of the IUS, in that it consisted of forward and aft elements. The forward cradle was a circular beam. Its upper section unlatched and rotated open to permit the aft cradle to pivot the TOS/spacecraft combination to a 45° angle. A pyrotechnic mechanism would then release the upper stage, and springs would gently push the mated pair out of the payload bay.



An exploded view of the Italian Research Interim Stage.



The main hardware of the Transfer Orbit Stage and its associated airborne support equipment.

The first mission for the TOS was in September 1992, when an expendable Titan launcher carried the Mars Observer spacecraft. It made its debut on the Shuttle a year later, when STS-51 *Discovery* deployed the Advanced Communication Technology Satellite (ACTS). This was a joint partnership by NASA and US industry aimed at maintaining America's predominance in the field of satellite communications in the face of intense competition from Europe and Japan. ACTS was a space-based test bed for advanced and high-risk technologies which NASA, industry, and government expected would dramatically enhance the capabilities of the satellite communications industry and reduce the cost of using such a system.

The deployment was successful, but a review of the video of the separation of the upper stage revealed the presence of extensive damage to the structure of the cradle. Sharp metallic debris, as well as non-metallic materials, were readily apparent. The immediate concern was that parts of the aft cradle might work loose and damage the Orbiter during re-entry and landing operations. However, analysis indicated that the payload bay thermal lining was capable of protecting the underlying structure in such an event. The post-flight inspection of the Orbiter mid-body and aft bulkhead found a total of 36 debris hit. Although most of them consisted of rips on the payload thermal blankets, there were three gouges on metal cable trays and one full penetration of the payload bay aft bulkhead. None of these, however, caused any harm to equipment in the aft section. Further investigation determined that incorrect wiring had caused two pyrotechnic cords to detonate, rather than just one.[21] The greater explosive force had damaged the cradle.

Despite its maker's ambitions, the TOS was never used again, either onboard the Shuttle or on an expendable launcher.

[21] The second cord was only a backup and was not meant to be used unless the primary one had failed.

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