Cost Management and Planetary Probes: Getting a Deep Space Object off the Ground in 20 Years or less and Then What?

Mark Graziani

Abstract

Interplanetary probes have been utilized in some of the most fascinating discoveries that mankind has ever experienced, and capture the awe and wonder of children and scientists alike. The amount of information they produce overshadows the fact that these silent travelers have only existed for less than fifty years and undertake the riskiest traveling ever mapped. The entire field of planetary science owes an immense debt to these probes for their tireless dedication, endurance, and steadfast reliability. Each different family of probes is a unique state-of-the-art technological creation designed to perform flawlessly and endure the harshest environments known. Either spectacular successes or colossal failures are the end result of the efforts of the scientists, engineers, and computer technicians connected to these mechanical extensions of human curiosity.

However, the sense of wonder that these robotic surveyors create comes after a long process of planning, design, and construction. Often, the journey from idea to launch can span twenty years or more and must survive critics, budgetary cuts, economic fluctuations, and changes in the political spectrum. It is almost like a rugged training period for the embryonic probe foreshadowing the rougher tasks that lie ahead in its existence. In order to budget for the creation, launch, mission, and afterlife of a planetary probe, NASA follows a complicated and dynamic costing process. This system attempts to plan, monitor, and restrain the costs involved while still creating a viable machine that is at the pinnacle of contemporary engineering and technology.

Mark Graziani
J Russell Construction
two-nimrods@juno.com

1. Introduction

1.1 Background

Long ago in mankind's past, some self-aware human looked up into the sky and was the first to wonder about a world larger than his own immediate environment. Up until that time, the ever-pressing survival needs of food, shelter, and protection exclusively dominated the early human's thought processes which left room for little else. However, there is always a first, and we owe our sense of wonderment and curiosity to this nameless, sentient being, forever lost in antiquity.

Early members of agricultural societies began using the moon and sky to guide their planting and harvesting in order to maximize success. Since calendars were a future invention, the farmers' recognition of the seasons came from observations of the two equinoxes and two solstices1. Without a way to measure time, the location of the sun (and direction of movement) indicated the impending season. At night, patterns of stars were given designs and names (constellations) and were fodder for creativity and artistry. Increasing transportation by boat and later ship began to rely on the stars for guidance at night when land was not visible. While studying the sky, early thinkers noticed that certain lights moved with respect to the other fixed stars in the constellations. These 'stars' were given a new name in Greek, planetes, meaning 'wanderer'. Written references to the planets began appearing in Greek writings in the fifth century BC (and also much older Chinese documents). At the time, the ancients were aware of five planets (excluding the moon and sun), which have come to be known by their Roman names: Mercury, Venus, Mars, Jupiter, and Saturn. The people at this time knew the planets moved through the sky according to specific cycles and speculated on the mechanism of the universe, but did not know these wanderers were complete, separate worlds.

After the demise of the Roman Empire, little was done concerning the planets while the human race suffered through centuries of the Dark Ages caused by civilization's collapse. As this bleak time was waning in the late 16th century, the new invention of the telescope allowed mankind to once again turn his curious attention skyward. In 1610, Galileo Galilei used a telescope of his own construction to observe the moon and planets and began the modern science of Astronomy. His observations revealed that Venus, Mars, Jupiter, and Saturn had disks and were worlds that orbited the sun as Copernicus, an amateur astronomer, had speculated in his book De Revolutionibus Orbium Coelestium (Concerning the Revolutions of the Celestial Orbs) published in 1543.

As telescopes grew in size, quality, and sophistication, more planets were discovered circling the sun outside the orbit of Saturn. In 1781, the British astronomer William Herschel accidentally discovered the planet Uranus, seeing it as a small disk in his telescope and originally thinking it was a comet. After plotting the orbit of Uranus for some years, it became apparent that another object was gravitationally affecting the planet's path around the sun. In 1845, two mathematicians2 independently predicted where an eighth planet from the sun should exist and in 1846, J. Galle and H. D'Arrest at the Berlin Observatory discovered Neptune very close to where the predictions had placed it.

For the remainder of the 19th century, astronomers were attempting to explain small discrepancies in the orbits of Uranus and Neptune and speculated on a large, undiscovered ninth planet. American astronomer Percival Lowell mathematically predicted where the ninth planet (named Planet X by him) should exist but failed to find it before his death in 1916. In 1930, Clyde Tombaugh discovered the planet Pluto coincidentally close to the location Lowell predicted. Measurements of Pluto's size revealed that it was too small to be Planet X, so the search for other planets continued onward. Currently, calculations with accurate masses of the known solar system's inhabitants have eliminated the need for a hypothetical Planet X to explain the orbits of the outer planets, so no large objects are suspected to exist beyond Pluto.

In 1930, American Astronomer F.C. Leonard speculated "that in Pluto there has come to light the first of a series of ultra-Neptunian bodies, the remaining members of which still await discovery but which are destined eventually to be detected."3 Later astronomers hypothesized that many small planetoid objects reside approximately in the ecliptic4 beyond the orbit of Neptune and this region has been (incorrectly) named the "Kuiper Belt."

The first trans-Neptunian object (besides Pluto) was discovered in 1992 by D. Jewitt and J. Luu at the University of Hawaii. Since then, some 250 planetoid objects of various sizes have been discovered near and beyond the orbit of Pluto which prompted the International Astronomical Union to (controversially) strip Pluto of its status as a planet. Currently, Pluto (along with the asteroid Ceres and the Trans-Neptunian Object Eris) is a 'dwarf planet'.

1.2. The Solar System Today

The solar system today is a complex and dynamic mechanism far larger and more sophisticated than the pre-20th century perception that it is like a large clock with a small number of large, mathematically precise parts. Although the orbits of any object around the sun are precisely governed by Newtonian (and Einsteinian) mechanics, the solar system's inhabitants currently number in the millions and are comprised of planets, dwarf planets, moons, asteroids, trojans, centaurs, comets, Kuiper Belt Objects (KBOs), and Oort cloud[11] objects. A brief description of each follows as a foundation for the topic of the rest of the paper. Regardless of its traveling companions, the sun remains the overwhelmingly dominant member of the solar system with 99% of the mass.

The Sun:
Diameter[5]-1,392,000 kilometers (865,000 miles), (109 Earths wide)
Mass-2,000,000,000,000,000,000,000,000,000,000 kilograms (332,946 Earths heavy)

Solar System Inhabitants, Radially outward from the Sun
(Distances from the sun measured in Astronomical Units: 1AU=92 million miles)
(Earth is 1 AU from the Sun)
(Sizes in kilometers, masses in Earth units-Earth=1)

Object Name and Description	**Current Estimate of Size (diameter)**	**Current Estimate of Mass**	**Distance from Sun (av. AU)**	**Moons**
Mercury (planet)	4,878 km, .383 Earths	.055	.38	0

Venus (planet)	12,104 km, .95 Earths	.815	.72	0
Earth (double planet)	12,756 km (Earth) 3,477 km, .273 Earths (Moon)	1 (Earth) .0123	1 for both	Footnote 6
Mars (planet)	6,794 km, .533 Earths	.107	1.52	2
Ceres (dwarf planet)	487.3 km, .038 Earths	.00016	2.77	0
Asteroids7	0-500 km	<.000045	2.8 (av.)	N/A
Jupiter (planet)	143,884 km, 11.28 Earths	317.8	5.2	63, plus trojans8
Saturn (planet)	120,536 km, 9.45 Earths	95.15	9.5	60, plus trojans
Centaurs8	Unknown	unknown	6-40	N/A
Uranus (planet)	51,118 km, 4 Earths	14.54	19.2	27
Neptune (planet)	50,538 km, 3.9 Earths	17.2	30	13
Pluto (dwarf planet)	2,324 km, .18 Earths	.0021	39.4	3
Kuiper Belt Objects9	0-2500 km	.0028	30-100	Unknown
Comets10	1-50 km	<.000001	0-50,000	N/A
Oort Cloud11	Unknown	unknown	≈50,00011	N/A

All these objects are extremely fascinating inhabitants of our local region of the galaxy and are certainly worthy of study. With the exception of the Earth's moon, the majority of these objects have only been seen up close by mankind within the past fifty years. Some, like Pluto, KBOs, and centaurs, have never been seen except as slowly moving, dim points of light in a telescope. Despite all the achievements that humans have made on the Earth, the greatest accomplishments to date have involved the exploration of space that will eventually transform us from a gravitationally bound to a space-faring species. At that time, we will be free to explore the unlimited expanse and potential of our island in the universe, the Milky Way galaxy.

The unmanned exploration of Earth's solar system companions is a very expensive and highly risky endeavor that takes *decades* of planning by teams of the most intelligent humans alive. Each planetary probe (or family of probes) is a unique creation that is at the nexus of cutting edge science, technology, and engineering. Due to the vast distances the probes must travel, they must be unfailingly reliable and able to function almost autonomously; radio instructions (traveling at the speed of light) from ground controllers can often take *hours* to reach the probe, and the probe's response takes *hours* to return back to Earth. Each of the probes are designed with a product life in mind, but many of them soldier onward far past their expected life span as a triumphant testimonial to the engineers that created them. NASA's mission costs are divided over different segments of a planetary probe's existence: (1) Concepts, Formulation, and Development, (2) Operations, and (3) Research.

2. A Brief History of Probes, Pre-1970's

The Space Race between the United States and the Soviet Union began in October, 1957, when the USSR launched the Sputnik satellite, much to the consternation of the United States. It launched the first planetary probe *Luna 1* in early 1959 which (accidentally) flew past the moon and settled into a heliocentric orbit between Earth and Mars. The first probe to reach another world was *Luna 2* which crashed onto the moon in late 1959. The United States followed with a large number of probes (many of which failed) designed to orbit, photograph, and land on the moon. Soon, the American planetary scientists turned their attention to other planets and launched a series of successful explorers named *Mariner*. The 1960's and early 1970's were a developing time for planetary probes and the maturing science would prove to be the foundation of successful Apollo and planetary missions continuing on to this very day.

A. ***Table of the Early Probes***

The U.S. Trailblazers

Name and Year	Destination	Notable Accomplishments
Rangers 1 and 2, 1961	Moon	Failed at Launch
Rangers 3 and 5, 1962	Moon	Missed Moon
Ranger 4, 1962	Moon	Crashed
Ranger 6, 1964	Moon	Arrived, Cameras Failed
Rangers 7,8,9, 1964-65	Moon	Arrived Safely
Lunar Orbiters (5) 1966-67	Moon	Orbited Safely
Lunar Surveyors 1,3,5,6,7,	Moon	Arrived Safely
Lunar Surveyors 2,4	Moon	Crashed
Mariner 1, 1962	Venus	Destroyed on Launch
Mariner 2, 1962	Venus	First flyby of another planet; functioned for 129 days total
Mariner 3, 1964	Mars	Failed after Launch
Mariner 4, 1964	Mars	First pictures from space, operated for 3 years
Pioneers 6,7,8,9, 1965-68	Sun	Pioneer 6 holds the record as the oldest working spacecraft; last contacted in 2000
Mariner 5, 1967	Venus	Detailed observations of Venus, operated for 6 months
Mariner 6, 1969	Mars	Detailed observations of Mars
Mariner 7, 1969	Mars	Detailed observations of Mars, first probe reprogrammed in space
Mariner 8, 1971	Mars	Destroyed on Launch
Mariner 9, 1971	Mars	First probe to orbit another planet
Mariner 10, 1973	Mercury	First probe to use a gravity assist trajectory, only probe to go to Mercury until 2004

3. Post 1970 Probes

3.1. Failed Missions and Costs

The 1970's saw an increase in the sophistication and complexity of the planetary probes and the missions they would undertake. Since the scientists and engineers barely had 15 years of experience in this uncharted area of science, many costly failures were yet to come.

The *Mars Surveyor'98* mission was two separate spacecraft consisting of a climate orbiter and a polar lander launched in 1998 intending to study the weather and climate of Mars. The orbiter was lost due to a miscalculation in trajectory due to confusion between metric and English units of measurement. The polar lander was lost when an erroneous sensor signal caused the lander to crash onto the surface. The development, launch, and maintenance of the mission cost $328 million dollars.

The *Mars Observer* was launched in 1992 to study the climate and geoscience of Mars. Three days before entering into orbit, all communication with the probe was lost for unknown reasons. The current location of the probe is unknown and the total mission cost was $980 million dollars.

3.2. Space Probe Jewels of the 1970's

The Pioneers

Since the inner solar system had been reasonably studied by the Mariner spacecraft, in the late 1960's the attentions of scientists turned toward the asteroid belt and the outer solar system. In 1969, two new space probes, named Pioneer 10 and 11, were designed and built to travel through the asteroid belt toward Jupiter and Saturn and onward. Both the spacecraft and their trajectories were designed to eventually escape the solar system and become the first man-made objects intended to enter *interstellar space.* All prior probes eventually became 'space junk' after their lives ended and they each settled into individual heliocentric orbits to remain until the end of time. The two Pioneers, however, were given subsequent missions after their primary functions were complete. As long as they remained working and able to communicate with Earth, their tasks would continue indefinitely. Pioneer 10 was launched in March 1972 and was the first probe to ever enter the asteroid belt, which it did in July 1972. It flew past and studied Jupiter in December 1973 and then began its infinite journey out to interstellar space. It continued to send data to Earth until its weak signal was last received by the Deep Space Network on January 23, 2003. At this time it was 7.5 billion miles from Earth and had operated for almost 31 years. It is traveling toward the star Aldebaran which it will reach in approximately 2 million years.

Pioneer 11 was Pioneer 10's sister ship designed to fly past Jupiter and then onward to Saturn via Jupiter's gravity. It was launched in April 1973 and arrived at Jupiter in December 1974. The probe passed approximately 21,000 miles from Jupiter's cloud tops and used the planet's gravity to 'slingshot' it toward Saturn. It arrived at Saturn in September 1979, passing a mere 13,000 miles from the planet's cloud tops and actually dove *through* the extensive ring system. It continued to function until declining power ceased communications with Earth in November 1995. At the time, it was 4.1 billion miles from Earth and will continue to travel toward the constellation Aguila. It will reach one of the stars in the constellation in about 4 million years.

The Vikings

The Viking 1 and 2 probes consisted of two-component spacecraft with an orbiter and a lander, designed to study Mars. The two were launched in August and September of 1975, and arrived at Mars in June and August of 1976, respectively. The combined craft orbited the planet for approximately one month until suitable landing sites for the landers were found. The landers were deployed and both successfully landed on the surface of Mars, becoming the first machines to land on another world (excluding the moon). Moreover, both landing probes were actually *robotic*, capable of performing digging and chemical analyses in the search for life. The Vikings sent back the first pictures mankind had ever seen of another planet's surface. Each continued to function and both sent weather reports and endured storms and different seasons on the planet. They both radioed pictures and data to Earth until their lives came to a quiet end. The Viking 1 lander operated for 6 years and 3 months until a human error caused its computer to fail. The Viking 2 lander functioned for 3 years and 7 months until its batteries failed. All in all, the 1 billion dollar mission was a great success and bolstered America's bicentennial celebration in 1976.

The Voyagers

In the late 1970's, the Voyager 1 and (especially) 2 spacecraft were the greatest single accomplishments of mankind up to that point and far exceeded the achievements of their predecessors, Pioneers 10 and 11. Voyager 1 was launched in September 1977 on a gravity-assisted trajectory to Jupiter and Saturn. It arrived at Jupiter in March 1979, and conducted detailed studies of the planet and its moons. It used Jupiter's gravity to propel it toward Saturn, which it reached in November 1980. It conducted significant studies of the planet and especially of Saturn's cloud-enshrouded moon Titan. Saturn's gravity propelled Voyager 1 even further making it the fastest man-made object in the solar system. It is currently 107 AU (9.8 billion miles) from our planet and continues to function and communicate with Earth. Its extended mission is to study the heliosphere and to search for the heliopause[12] and is expected to have enough electrical power to transmit until at least 2025, some 48 years after launch.

Voyager 2 is the most productive space probe in history. It was launched in August 1977, on a gravity assisted trajectory to Jupiter, Saturn, Uranus, and Neptune. It used a rare, fortuitous alignment of the four gas giant planets and the gravity from each to propel it to its next destination. It arrived at Jupiter in July 1979, Saturn in August 1981, Uranus in January 1986, and Neptune in August 1989. Everything humans currently know about Uranus, Neptune, and their moons comes from Voyager 2's visit to these two planets. The probe's visit to Neptune officially ended the search (and need) for a large planet X to deflect the orbit of Neptune. Like Voyager 1, Voyager 2 is currently on a mission to search for the heliopause in a different region (from Voyager 1) of the solar system and is expected to function until at least 2025. It is currently 85 AU (7.9 billion miles) from the Earth on its journey toward interstellar space.

C. Current Missions and Product Life

The Jet Propulsion Laboratory[13] currently has ten active space probes studying the solar system:

Name	Planet Studied	Launch Date	Original Life Expectancy	Current Status
Cassini-Huygens	Saturn (Cassini) Titan (Huygens)	October 1997	4 years (Cassini) Huygens landed on the surface of Titan and survived for 90 minutes.	In April, 2008, its mission was extended for two more years.
Dawn	Vesta & Ceres (asteroid, minor planet)	September 2007	8 years	Expected arrival at Vesta in 2011
Deep Impact-Epoxi14	Tempel 1/ Hartley 2 (comets)	January 2005	1 year	Mission has been extended until October 2010
Mars Rovers	Mars	June/July 2003	3 months	Both rovers continue to work and their missions have been extended until 2009
Mars Odyssey	Mars	April 2001	2 years	Mission extended until September, 2008
Mars Reconnaissance Orbiter	Mars	August 2005	4 years	Currently in primary mission
Phoenix	Mars (north pole)	August 2007	92 days	It is not expected to last the entire Martian winter
Stardust-Next15	Wild 2/Tempel 1 (comets)	February 1999	7 years	Mission extended until 2011
Ulysses	Sun (N and S poles)	October 1990	4 years	Spacecraft will be turned off in July, 2008 after almost 18 years of operation
Voyagers 1 & 2	Heliopause	August/ September 1977	5 years	Mission is expected continue until 2025
New Horizons	Pluto	January, 2006	10 years	Mission will not begin until nearing arrival at Pluto in 2015

Of the 11 missions NASA is currently supporting, only four (Dawn, Mars Reconnaissance Orbiter, Phoenix, and New Horizons) are in their initial (allocated) mission mode. The remaining spacecraft have forged ahead long after their estimated life span and original funding has ended. NASA (and the world's scientists) benefit from the additional data gleaned from the extremely harsh space environments, but the cost of extending the missions of these rugged and intrepid craft can be costly.

D. Active Missions and Budgeted Cost: NASA/JPL

Mission	Planet Studied	Costs (US $)
Cassini-Huygens	Saturn (Cassini)	Total17: 3.26 billion
Dawn	Vesta & Ceres	Total: 449 million
Deep Impact-Epoxi	Tempel 1/ Hartley 2	Total16: 40 million
Mars Rovers	Mars	Initial mission: 820 million Annual costs: 20 million
Mars Odyssey	Mars	Initial mission: 297 million Annual costs: 17.5 million
Mars Reconnaissance Orbiter	Mars	Total: 500 million
Phoenix	Mars (north pole)	Total: 420 million
Stardust-Next	Wild 2/Tempel 1	Total16: 25 million
Ulysses	Sun (N and S poles)	Total17: 1.54 billion
Voyagers 1 & 2	Heliopause	Total (1972-1989): 865 million Annual: 4 million
New Horizons	Pluto	Total: 700 million

4. Spotlighted Mission

4.1 New Horizons Pluto Kuiper Belt Object Express

The New Horizons-Kuiper Belt Object Express space probe began its existence in the minds of a group of Pluto-interested scientists in 1989. Previously, the trajectories of Voyagers 1 and 2 were calculated to maximize the number and quality of gas giant studies. Voyager 1 was slated to study Jupiter and Saturn (with a close flyby of Titan) while sacrificing a gravity-assisted propulsion to Pluto while Voyager 2 was ticketed to pass all four giant planets. The desire to explore the ninth and only unobserved planet would have to wait. Unfortunately, Pluto's unusually elongated orbit would bring it closest to the sun in 1989 (29.6 AU at perihelion[18]) before beginning its travels outward to its aphelion (49.3 AU in 2114). Because of the planet's distance from the sun and very elliptical orbit, the best time for studying the planet (for sunlight, for surface temperature, for fuel, and for travel time) is close to perihelion.

In 1989, NASA commissioned a study to analyze the possibility of sending a very small, 350 kg space probe to Pluto. The possible trajectories of the 'Pluto 350' mission ranged from a direct flight using only rocket propulsion to a gravity-assisted trajectory involving one or more planets. With each 'slingshot' planet, the initial rocket power requirements became lower but the trajectory calculations and travel time became much greater.

Independent of the Pluto 350 team, another group of scientists was developing the Pluto Fast Flyby (PFF) mission, where a pair of very small, 140 kg probes would pass on either side of the planet. The PFF mission would use a heavy rocket to get the probes to Pluto in about seven years. In 1992, NASA asked the research team to choose between the two and the group (succumbing to NASA's bias against the Pluto 350) chose the PFF for further study.

The PFF was intended to use a Russian heavy rocket to get it into space. However, in 1995, pressure from NASA to reduce the cost and the influence from planetary scientists to expand the scope of the mission to include other Kuiper Belt Objects caused the plans to be redesigned and renamed the Pluto/Kuiper Express (PKE). Soon thereafter, budgetary pressure reduced the mission from two spacecraft to one. By the year 2000, with a cost now exceeding 1 billion dollars, the mission was cancelled.

The cancellation of the PKE mission started a public outcry on many different fronts; the public media, NASA advisory committees, the world's scientists, and children fascinated with space all began pressuring NASA to reconsider the mission. Pennsylvania high school student Ted Nichols created a 'Save the Pluto Mission' website replete with visitor's signatures and the Planetary Society took up the cause, collecting more than 10,000 letters of support. All the efforts had a positive effect, because in late 2000 NASA asked for new proposals for a Pluto mission costing no more than 500 million dollars.

By early 2001, the agency had five proposals, of which it selected two: New Horizons and POSSE (Pluto and Outer Solar System Explorer). By the end of the year, New Horizons was the choice to make the 3.6 billion mile journey to the ninth planet. It would be launched by NASA's most powerful rocket and would make the trip (with some gravitational help from Jupiter) in nine years. In the time between 2002 and the probe's launch in January 2006, Congress threatened to cut the funding for the mission on various occasions, but ongoing pressure from the public and scientific communities kept the mission alive.

On January 19, 2006, New Horizons left the ground and set a new record as the fastest spacecraft ever launched from Earth. It passed the moon in 3 hours (it took Apollo 3 days to get there) and arrived at Jupiter in 13 months (Voyager 1, the previous record holder, arrived at Jupiter after 18 months of travel). New Horizons used its full complement of instruments studying the Jovian (Jupiter and all its moons) system in early 2007 and is now on its way to Pluto traveling along at 45,208 miles per hour. It is expected to arrive in the vicinity of Pluto and Charon on July 14, 2015, and will then search for other Kuiper Belt Objects within its trajectory range to approach and study.

5. NASA's Budget

NASA's annual budget is established by Congress and is very susceptible to changing political winds in Washington. Because of the very high price tags and sometimes colossal failures, the agency always seems to be on the verge of losing at least some of its funding. However, since the groundbreaking work done by NASA is a major driver of technology and science, and supports the economy, they forge ahead with grand dreams and ideas. Because the time span from idea to implementation to mission conclusion (and oftentimes many years of post-mission duties) is usually measured in decades, NASA must allocate its funds across all of its active programs. Because of the size and diversity of NASA's activities, it divides its responsibilities and moneys according to the following breakdown:

Science (all types)
Aeronautics (research in future aircraft)

Exploration (development of future manned spacecraft)
Space Operations (space shuttle, space station, etc)
Education (academia and teachers)
Cross-Agency Support (internal operations of NASA)

The science category is broken down into four subcategories:

Earth science (satellites and Earth research)
Planetary science (planets, moons, asteroids, and comets)
Astrophysics (galaxy studies, star formation, extra-solar planets, etc.)
Heliophysics (sun research and space storms)

Of the above 11 space probe missions that NASA has active, 9 are involved in planetary science and two (Voyager and Ulysses) are studying heliophysics. Furthermore, each mission falls into a larger family (e.g. Mars Exploration) with missions in all stages of development that have specific goals and benchmarks to meet. Each family of probes is broken down on a timeline with costs allocated to each fiscal year, for example[19]:

Mission Directorate: Science Theme: Planetary Science Program: Mars Exploration

Project	Fiscal Year 20XX (P = prior)																Phase Dates	
	P	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	Beg.	End.
Mars Odyssey																	4/97 4/99 4/01	4/99 4/01 9/08
Mars Exploration Rovers																	5/00 8/01 6/03	8/01 6/03 9/09
Mars Reconnaissance Orbiter																	1/01 7/02 8/05 10/11	7/02 8/05 9/11 9/14
Mars Scout (Phoenix)																	8/03 3/05 8/07 8/08	3/05 8/07 8/08 10/09
Mars Science Labs																	11/03 8/06 9/09 10/12	8/06 9/09 10/12 10/15
Mars Express																	1/00 9/00 6/03 10/05	9/00 6/03 10/05 8/08

=Concepts =Formulation =Development =Operations =Research

6. NASA Cost Calculation Methodology

For any mission, NASA follows a set of six life cycle phases designated by the letters A-E. Its cost methodology loosely ascribes twelve tasks (in three distinct groups: Project Definition, Cost Methodology, and Estimate) *to each* of the six phases in order to assemble a dynamic, flexible system that is as accurate as possible given the risks and uncertainties intrinsic to the process. Because the missions involve years or decades of planning and rely on the best technology and science available at the time, a simple model for costs is not accurate enough for the large price tags involved. Any of the missions can involve multiple cost studies, involving such tools as Project Life Cycle Cost Estimates (LCCEs), Independent Cost Estimates, Non-Advocate Reviews, Independent Annual Reviews, and Cost Estimate Reconciliations[20]. Moreover, there are many different entities involved in the costing process, including: the Government Accounting Office (GAO), Congress, NASA's Headquarters, Enterprise Leaders and Program Managers, scientists and engineers, logisticians, the Independent Program Assessment Office, and the Inspector General[21].
The twelve tasks for each phase are as follows:

1. Receive the request and understand the project
2. Prepare or obtain a work breakdown structure
3. Obtain or participate in the development of the project technical description
4. Develop ground rules and assumptions
5. Select cost estimating methodology
6. Select or construct a cost model
7. Gather and normalize data
8. Develop a point estimate
9. Develop reserves from cost ranges and cost risk assessment
10. Document the cost estimate
11. Present and/or brief the results
12. Update the cost estimates on a regular basis

Subsection I: Project Definition-tasks 1-3
Subsection II: Cost Methodology-tasks 4-7
Subsection III: Estimate-tasks 8-12

Pre-Phase A is the Conceptual Definition facet of a mission where combinations of performance levels and costs are compared so a selection can be made to proceed to the next step, phase A. For tasks 1-3, the goal is to arrive at rough order of magnitude estimates for the costs and to formulate technical baselines for the proposed projects. For tasks 4-7, rough ground rules are established, a cost methodology is chosen or constructed (either parametric or analogy)[22], and multiple estimates involving varying scenarios are quickly assembled. For tasks 8-12, an early estimate of risk is important as well as uncertainty in the cost estimating process. The timeline of the project is analyzed and the first opportunity to publicly present and debate the mission occurs. Throughout this phase, the project is evolving and will require repeated cost revisions while an entire spectrum of ideas is presented and the costs, benefits, and risks of the proposed missions are scrutinized.

Phase A is the Conceptual Design state of a project where alternative projects are described in more detail, showing the engineering and operations concepts needed for the mission. For tasks 1-3, technical risks and engineering performance parameters are studied and compared with emerging technologies and a preliminary work breakdown structure is assembled for each separate project. For tasks 4-7, the ground rules and assumptions are refined and presented in more detail. At this step, initial contact with the members of the potential supply chain is recommended and their input is amalgamated into the revised estimates. The most important aspect of this phase is the accumulation of data to replace the assumptions from pre-phase A. For tasks 8-12, the data is assembled into a point estimate for each project, where the missions are costed without analyses of the cost, schedule, and technical risks that will be determined later. As all the possible projects are moving through this phase, the process of selection is slowly reducing the number while the detail and documentation for the remaining missions grow and take shape. At the end of phase A, the surviving projects are presented to the decision makers in order to secure funding and a Cost Analysis Data Requirement (CADRe) may be needed for each.

Phase B is the Preliminary Design aspect of a mission where the engineering of the creation (space probes, in this case) is outlined down to the minutest systems, following the technical baseline for the project. For tasks 1-3, a detailed CADRe is required for each component or subcomponent far exceeding the detail of phase A. For tasks 4-7, the cost estimating retreats from the historical-looking parametric and analogy methods and begins a forward-looking parametric (less-preferred) or engineering (more-preferred) estimates supported by actual experts in the fields and/or supply chains. Moreover, in phase B the costs are compared with a Non-Advocate Review and an Independent Cost Estimate to determine their accuracy and actual costs from contractors are being incorporated into the estimates. For tasks 8-12, the point estimate from phase A is refined and a risk assessment is constructed. At this stage, the design is fairly static with the major aspects (of the space probe) solidified while possibly retaining flexibility in the subsystems. The costs and risks become very specific and the NASA estimators scrutinize the assumptions, cost drivers, and conduct frequent probabilistic risk assessments while the surviving projects are reduced to a few. In no other stage are accurate cost methodologies more important. Also, NASA (with the help of external experts) conducts a return on investment (ROI) analysis very similar to the standard business model.

Phase C/D is the combined Design, Development, Test and Evaluation, and Production (DDT&EP) of the project, where one final mission is selected based on the reports from earlier phases. In this stage and for tasks 1-3, the entire project (including costs) is summarized in detail and the work breakdown structure is refined to reflect every minor system of the spacecraft. Also, the CADRe is updated to accurately reflect all the requirements of the mission and a review of bidder cost proposals is conducted. For tasks 4-7, the project estimates are refined by focusing on design, development, and testing data as well as now incorporating forward-looking Operations and Support Costs which were disregarded up to this phase. The estimating methodology for the mission is cemented and is preferred to be the engineering buildup method. It includes current data and information including separate direct labor requirements and direct materials. Also, overhead elements like Other Direct Costs, General and Administrative Expenses, Materials Burden (i.e. Indirect Materials Cost), and fees are added to the estimate using the absorption costing method. For tasks 8-12, the point estimate and the risk assessment are refined to their most detailed and are in a state of constant refinement because small and large occurrences in the DDT&EP process affect both. In this phase, budgets, schedules, and technical parameters are closely monitored so that negative trends can be corrected early. In this stage, a Continuous Cost-Risk Management (CCRM) plan is fully implemented and while the spacecraft is in production, costs, risks, and cost-risk knowledge are captured using methods called EVM (Earned Value Management)[23] and IFM (Integrated Financial Management)[24]. The completeness and accuracy of the cost management is very important at this stage of development, not only for this project's Life Cycle Cost Estimate (LCCE), but as the analogy cost methodology of Pre-Phase A for different, future missions.

Phase E is the Operations, Support, and Disposal state of a mission where all estimates of costs are refined and only require updates to ensure the accuracy of the LCCE for the project and future data collection. The cost methodology in this phase is the actual costs incurred as the mission unfolds. Also, it is an excellent time to evaluate the predictability of the cost estimates from the early phases in order to refine the various models used. Upon completion of the mission, the estimators reconcile the estimates at completion with the cost and performance data and ensure that all the information is captured for future use.

Since planetary probes often exceed their intended life span, a contingency plan must be in place to accommodate extra-mission potential. As has been shown, the two Voyagers are expected to function and return data for approximately 48 years, far in excess of their 5 year lifespan. The two Mars rovers were expected to survive for three months; they have been operating for five years and may operate for years to come. New Horizons has a post-mission project after its encounter with Pluto in 2015 to visit other Kuiper Belt Objects in its possible trajectory paths. Both Stardust-Next and Deep Impact-Epoxi are 'retread' missions that were developed from spacecraft still operating and carrying fuel after their missions were over. When this occurs, NASA estimators must proceed from Phase E back to Phase D to re-evaluate and re-estimate the costs for an extended mission.

7. Conclusion

NASA's cost estimating is a dynamic, labyrinthine system developed from the spectacular successes and failures of the past fifty years. Originally driven by the tensions of the Cold War, the space program and the planetary probes developed from it have become a symbol of growth and achievement for all mankind. However, the increasing complexity of the engineering, technology, costs, and risks involved in the probes require that these detailed steps and phases be followed. With an ever-increasing database, significant learning curve, and closely monitored budgets, the process may become more streamlined, compartmentalized, and computerized in the future. The trend is for planetary spacecraft to more become assemblages of modular components usable for all probes and less of unique creations that require extreme, ground-up engineering. Even now, there is a movement for off-the-shelf, low-cost missions that may greatly broaden our horizons without breaking the bank. We live at an exciting time when we all may someday witness the first intrepid *human* pioneers embarking on a journey to visit or live on another world; an opportunity given to us by the unmanned, reliable explorers that preceded us to the other planets.

Footnotes:

1. A solstice is when the Earth's axial pole (tilted at 23.5 degrees) is either pointed directly at the sun or directly away from the sun. In the Northern Hemisphere, the summer solstice occurs around June 22 and defines the first day of summer and the longest day of the year. Correspondingly, December 22 is the winter solstice, the first day of winter, and the shortest day of the year. The spring and fall equinoxes are the halfway points between the solstices (i.e. the day and night are the same length), the first day of each respective season.
2. The two mathematicians who independently predicted Neptune's position based on Uranus' orbit were U.J.J. Le Verrier in France and J.C. Adams in England.
3. "What Is Improper about the Term "Kuiper Belt"?", author unknown, www.cfa.harvard.edu/icq/kb.html
4. The ecliptic is the planer projection of the Earth's orbit onto the celestial 'sphere,' which is very, very close to the sun's axial equator.
5. Because the sun produces different wavelengths of light at different depths in its atmosphere, the apparent diameter of the sun changes with the light used to measure it. That is, the diameter of the sun in visible light is different from the diameters of the sun measured in ultraviolet light, infrared light, x-rays, etc.
6. Because of the relatively large ratio of the moon's size to the Earth's, the system of two (along with Pluto-Charon) is a 'double planet.'
7. Asteroids are relatively small rocky bodies generally orbiting the sun between Mars and Jupiter. The largest is Ceres at 487 km. It was once thought they were the remains of a planet, but there is insufficient mass in all the known asteroids to make a planet.
8. Trojans are asteroids captured by the planets Mars, Jupiter, Saturn, Uranus, and Neptune that reside in the orbits of each of the planets, respectively, locked in gravitationally stable LaGrange points either 60° before or 60° after the planet. Centaurs are loose, asteroid or cometary bodies orbiting the sun between Jupiter and Neptune. Since little is known about them, Centaurs could be asteroids, comets, or Kuiper Belt Objects.
9. Kuiper Belt Objects are numerous, small, frozen, dwarf planet sized objects existing in a ring around the sun from 30-100 AU. It is believed that Pluto, some Centaurs, and some moons of Saturn, Uranus, and Neptune are all representative of KBOs.
10. Comets are relatively small, loosely packed 'dirt' and snow objects that exist in huge quantities in the outer solar system. Chance gravitational tugs from the planets draw these objects toward the sun. Because of the chance encounter and their spherical distribution, their choice of orbits is almost infinite. They can circle the sun repeatedly, circle the sun once and escape, or crash into a planet or the sun. Comet Shoemaker-Levy-9 impacted Jupiter in July 1994 in 21 separate pieces. The largest piece of the comet caused an explosion estimated to be 6,000,000 *megatons* of TNT.
11. The Oort cloud is a hypothesized sphere of cometary and other frozen objects residing about 50,000 AU from the sun.
12. The heliosphere is the bubble of outwardly flowing particles originating in the sun. It extends far into space and may not end until approximately one light-year distant (5.9 *trillion* miles). The heliopause is the pressure boundary (flow = zero) between the sun's influence and the combined interstellar wind. It is the official end to the solar system.

13. The Jet Propulsion Laboratory is the NASA research center in Pasadena, California dedicated to planetary studies.
14. The Deep Impact-Epoxi mission is the reuse of the orbiting Deep Impact cometary studies spacecraft. It will conduct a flyby of Comet Hartley 2 in 2010.
15. The Stardust-Next mission is the reuse of the orbiting Stardust cometary studies spacecraft. It will conduct a flyby of Comet Tempel 1 (of Deep Impact fame) in 2011 to study the crater from the deep impact projectile.
16. The reason the costs for Deep Impact-Epoxi and Stardust-Next are so low is because they are reuse of exiting, orbiting spacecraft.
17. The U.S. cost for the Cassini and Ulysses programs are 2.6 billion and 520 million dollars, respectively.
18. Perihelion is the point a planet is closest to the sun. Aphelion is the point a planet is farthest from the sun.
19. NASA's Fiscal Year 2009 Budget Estimate, page Sci-151
20. NASA's 2004 Cost Estimating Handbook, pages 30-31 [The 2004 CEH was used because the 2008 edition is not out yet.]
21. Ibid, page 18
22. The Parametric Mission Cost Model is a MS Excel-based system of cost estimating for space probes utilizing work breakdown structure and project phase to produce reasonably accurate estimates. It accepts probabilistic inputs and performs Monte Carlo simulations to find a range around the project cost. Analogy Cost Models use cost methods from previous, successful missions to predict and target the costs for future missions.
23. Earned Value Management (EVM) is the objective technique that incorporates technical performance, schedule performance, and cost performance into a single cost methodology.
24. Integrated Financial Management (IFM) is the mission to apply business enterprise-like systems that support streamlined and effective business management processes.

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