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Long-Range Planning Cost Model for Support of Future Space Missions by the Deep Space Network

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This article suggests a simple model to do long-range planning cost estimates for Deep Space Network (DSN) support of future space missions. The model estimates total DSN preparation costs and the annual distribution of these costs for long-range budgetary planning. The cost model is based on actual DSN preparation costs from four space missions: Galileo, Voyager (Uranus), Voyager (Neptune), and Magellan. The model was tested against the four projects and gave cost estimates that range from 18 percent above the actual total preparation costs of the projects to 25 percent below.

The model was also compared to two other independent projects: Viking and Mariner Jupiter/Saturn (MJS later became Voyager). The model gave cost estimates that range from 2 percent (for Viking) to 10 percent (for MJS) below the actual total preparation costs of these missions.

A rule of thumb based on these six missions is that the average annual DSN preparation cost is $7.2 million in 1987 dollars.

I. Introduction

Many times, the Office of Telecommunications and Data Acquisition (TDA) is required to provide quick, rough budgetary estimates for potential future projects. Because of the lack of definition at the very early stages, it has been very difficult to make meaningful long-range planning estimates. The purpose of this modeling effort is to improve the process for these estimates by providing supportable values in proper context, and thereby gaining time for developing the carefully thought out and reviewable cost estimates that are required before cost commitments are made.

This section describes the objectives of this article and gives a brief description of the Deep Space Network (DSN), its role in supporting the National Aeronautics and Space Administration (NASA) exploration of space, and its basic services to space missions. Then, an overview of the article is presented.

A. Study Objective

The objective of this study is to develop a model that can be used in the early planning stages to estimate both the DSN cost to prepare for future space-mission support and the allocation of these costs over the life of the project. DSN preparation costs for a mission occur when minimum requirements for a supported new mission lie outside the installed DSN capability. This proposed model is useful for long-range budgetary planning, but does not replace the need for a detailed cost estimate. Also, the model provides "ballpark" numbers that can be used to check detailed "grass roots" estimates. The original approach to this study was to develop a mathematical model for the cost of a DSN project, to be a function of time and of various cost categories such as a new uplink frequency, a telemetry upgrade, etc. However, as the data analysis began to develop, it was noted that a simpler model using only the length of the project as a parameter could effectively represent the data.

B. The Deep Space Network

The NASA DSN is a multimission telecommunications and radio-metric data facility used to support NASA's exploration of space, research in space science, and advanced technology investigations. The Network has facilities located on three continents (North America, Europe, and Australia), with tracking complexes at intervals of 120 degrees of longitude. The Network's basic services are (1) reception of telemetry from spacecraft, (2) transmission of commands to spacecraft, (3) measurement of radio-metric data for spacecraft navigation, and (4) radio science measurements.

C. Overview of Article

In Section II, the purpose of each of the four space missions is summarized, and the TDA modifications that were required to support these four missions are described. The methodology for collecting the data and the cost history are summarized in Section III. The cost models developed using this cost data are presented in Section IV. In Section V, the results from the models are compared to the actual data. In Section VI, the use of the model for future-cost estimates for budgetary planning is described. Finally, as an "external" check, in Section VII, the model is compared to two independent projects, Viking and Mariner Jupiter/Saturn (MJS).

II. Background of Space Missions

Presented in this section is a brief overview of the four missions that were analyzed for DSN cost modeling: Galileo, Voyager (Uranus), Voyager (Neptune), and Magellan.

A. Galileo Space Mission

The Galileo spacecraft is a Jupiter orbiter that includes a probe for penetrating the atmosphere of Jupiter. Galileo's launch was planned for 1986, but due to the Challenger (STS-51L) loss, the launch date was delayed to 1989. This delay has resulted in a skewed cost profile for the DSN preparation for the mission. The primary objectives of the Galileo space mission are to investigate the chemical composition and physical state of Jupiter's atmosphere and satellites and to study the structure and dynamics of Jupiter's magnetic field. This space mission is the first outer-planet mission that will (1) perform a detailed observation of Jupiter's system, (2) send an orbiter, which has a probe to penetrate the atmosphere of Jupiter and which will provide 22 months of orbital operations to map Jupiter's surface, and (3) use a dual-spin spacecraft and a complex Venus-Earth-Earth-Gravity-Assist (VEEGA) trajectory. The spacecraft carries 19 instruments, 12 by the orbiter and 7 by the probe. Galileo was launched on October 18, 1989 [1,2,3].

The major improvements to the DSN associated with the Galileo mission are narrow channel bandwidth (NCB), very long baseline interferometry (VLBI) equipment at the 70-meter stations, and both NCB and wide channel bandwidth (WCB) VLBI equipment at the 34-meter stations. These provide the needed improvement in the navigation capabilities. Other significant upgrades in the radio metrics and radio science categories were the Block II Meteorological Monitor Assembly (MMA), improved frequency standards, and a variable second local oscillator for the Multimission Receiver (MMR).[1]

B. Voyager (Uranus) and Voyager (Neptune)

Voyager 2 was launched on August 20, 1977, on a flight path that would allow it to become the first spacecraft from Earth to observe the planets Uranus and Neptune. In this study, the DSN preparation costs for the Voyager (Uranus) and the Voyager (Neptune) missions have been considered separately from the costs for the basic MJS mission. Voyager 2 made its closest approach to Uranus on January 24, 1986, passing within 110,000 kilometers of the planet's center. The main objective of Voyager (Uranus) was to provide a basic characterization of Uranus, its satellites, and its rings, which it did very well [4,5].

On August 24, 1989, Voyager (Neptune) sailed over the north pole of Neptune, within about 4850 kilometers of the visible cloud tops. The Neptune encounter was Voyager 2's closest encounter with any object in its 12-year trip to the outer solar system. The objectives of this mission were to provide data on magnetic fields and charged particles at Neptune, to probe deep into Neptune's atmosphere with Voyager's radio waves, and to search for new rings and satellites.

One of the major improvements to the DSN needed for the Voyager-Uranus encounter was the decrease in receiver threshold to compensate for the ever-increasing distance of the spacecraft from Earth. This effort included: the 34-m/64-m array, the Parkes Observatory equipment, and DSN arraying in Australia; and new 34-m antenna/microwave/low-noise amplifier equipment and baseband-combining equipment. A new 400-kW transmitter for uplink commanding was also provided for spacecraft-emergency purposes. New telemetry formats were accommodated with new capabilities in software and hardware for correlation of received data. Upgrades in the frequency standards and coherent reference generators (CRGs) were made. Open-loop receiver hardware was provided.

The Voyager-Neptune encounter preparations for the DSN carried on many of the same tasks as were required for the Uranus encounter. The 64-m antennas were expanded to 70 m, including an improved-precision antenna reflector surface for both S- and X-band improved performance. Improvements were made to the X-band low-noise maser amplifiers, and antenna-mounted cold backup X-band masers were installed on the 34-m high-efficiency (HEF) antennas. The planetary ranging assembly (PRA) computers were replaced and a precision power monitor (PPM) was implemented at Signal Processing Center, SPC-60. A new monitor and control system and noise-adding radiometer were designed and supplied for the Parkes antenna in support of the Neptune encounter. Also, new additions to the total array were implemented—one incorporating the Japanese 64-m antenna at Usuda and the other the National Radio Astronomy Observatory (NRAO) radio astronomy Very Large Array (VLA) in New Mexico. JPL supplied the 27 VLA antennas with new X-band feed horns and dual-channel X-band solid-state low-noise amplifiers. The Usuda antenna was supplied with an ultra-low-noise maser amplifier and backup by the Jet Propulsion Laboratory (JPL).[1]

C. Magellan Space Mission

The Magellan space mission to Venus was originally conceived as the Venus Orbiting Imaging Radar (VOIR). As first envisioned in 1980, the VOIR spacecraft was to carry a high-resolution synthetic aperture radar (SAR) and six other instruments, most of them for atmospheric studies. The VOIR was de-scoped to the single-instrument Venus Radar Mapper (VRM) in 1984 and then renamed Magellan in 1986. It is managed for NASA by JPL.

The primary objective of this mission is to investigate the origin and evolution of Venus by obtaining a global radar image of the planet. The spacecraft will perform two types of investigations: radar and gravity. The radar investigations will produce (1) continuous images of at least 70 percent of the planet with no systematic gaps except for one pole and with a surface resolution of at least 1 kilometer and (2) a global topographic map with a range of resolution commensurate with the SAR range of resolution. The gravity investigation will measure the distribution of gravity potential around Venus [6,7].

The new requirements on the DSN imposed by the Magellan mission include the modifications (seven subsystems) for providing an operational 20-kW X-band uplink at three 34-m stations. High-density recording systems will be implemented to accommodate the Magellan data rates. The baseband assemblies are being upgraded. Implementation of hardware transfer-level frame synchronization of telemetry data is being done. Magellan-related

[1] "Narratives covering FY'82, FY'86, and FY'88," TDA work authorization documents (WADs) (internal documents), Jet Propulsion Laboratory, Pasadena, California, 1983, 1987 and 1989.

predicts capability is being incorporated in the network support subsystem (NSS).

The Block IV receiver at Compatibility Test Area 21 (CTA 21) was upgraded to accommodate X-band Doppler. The closed-loop receivers in the 34-m and 70-m subnets have been provided with rapid acquisition capability to accommodate the multiple Magellan acquisitions during each scheduled track, due to planetary occultations. Engineering and equipment are being provided for various VLBI upgrades, including an improved radio source catalog and modifications to the delta VLBI software to accommodate the low Sun-Earth-Probe (SEP) angles.[2]

III. Cost Data

The annual cost obligations used in this article are taken from Telecommunications and Data Acquisition (TDA) Work Authorization Documents (WAD Obligations Performance Reports), and do not include construction of facilities cost, spacecraft cost, transportation cost, and/or other logistics costs.[3] All costs used in this article are adjusted for inflation to 1987 dollars using the NASA inflation index. The DSN costs for each project are collected into the following subsystem upgrade categories:

(1) (M/O) maintenance and operations

(2) (D/L) downlink frequency

(3) (U/L) uplink frequency

(4) (TEL) telemetry upgrade

(5) (G/T) gain over system-noise temperature

(6) (CMR) upgrade command rate

(7) (CMP) upgrade the effective radiated power

(8) (R/M) radiometric accuracy upgrade

(9) (R/S) radio-science stability upgrade

(10) (VLBI) very long baseline interferometry system

(11) (OTH) other

Inspection of the 11 category costs revealed that for each mission, costs are primarily assignable to three or four categories. This is summarized in graphical form in Fig. 1. If a future mission calls for a significant upgrade in a particular category, these historical category data can be helpful in predicting mission costs.

The total cost data for the four space missions, Galileo, Voyager (Uranus), Voyager (Neptune), and Magellan, is summarized in Table 1. For example, Table 1 shows for Galileo the annual costs from fiscal year (FY) 1979 to FY 1988, mission total cost ($47,186K), annual average cost ($4,719K), the standard deviation of annual costs ($2,673K), the maximum annual cost ($8,275K), the minimum annual cost ($1,052K), and the range ($7,223K). A comparison of the four space missions gives the following results:

Mission	Total DSN preparation cost, $M	Average yearly cost, $M	Maximum yearly cost, $M
Galileo	47.2	4.7	8.3
Voyager (U)	35.9	7.2	13.1
Voyager (N)	36.0	9.0	12.3
Magellan	32.5	8.1	13.8
Average	37.9	7.3	11.8
Standard deviation	6.3	1.8	2.4

It can be seen that the average yearly cost and also the maximum yearly cost are fairly close for the last three projects.

The TDA costs for DSN preparation that are covered in this article are relatively small as compared to the total mission costs, as shown below [2,6,8].

Mission	Total mission costs: 1987, $M	DSN preparation costs: 1987, $M	DSN/total, %
Galileo	1006 [2]	47.2	4.7
Voyager (U) Voyager (N) Voyager (JS)	841.2 [8]	169.4	20.1
Magellan	413 [6]	32.5	7.8

[2] "Narratives covering FY'82, FY'86, and FY'88," TDA work authorization documents (internal documents).

[3] "Obligations Performance Reports, 1972–1988," TDA work authorization documents (WADs) (internal documents), Jet Propulsion Laboratory, Pasadena, California, 1973–1989.

IV. Cost Models

A number of models were compared to the cost data. The Rayleigh distribution [9] did a good job of describing the DSN preparation cost for each of the four space missions and also for the composite, which is the average cost of the four missions.

A. Galileo Space Mission

The total DSN preparation cost for Galileo was fitted to the Rayleigh distribution, and the following model was obtained:

$$Y_t = 1983t \exp(-0.0224t^2)$$

where Y_t is the cost for DSN preparation to support Galileo in year t and $(t = 1, 2, \ldots, n)$, t is the number of the year in the life of the DSN preparation for Galileo support, n is the total years of the DSN preparation, and the total cost of the DSN preparation is $\sum Y_t$. The model shows a coefficient of determination (R^2) of 71 percent (R^2 indicates the precision of the model, or the amount of variability in the total cost that can be explained by the model [10]). The cost data and the costs predicted by the model are shown in Table 2 and Fig. 2.

B. Voyager (Uranus), Voyager (Neptune), and Magellan Space Missions

Cost models were developed for DSN preparation for three other space missions, Voyager (Uranus), Voyager (Neptune), and Magellan. The Magellan model follows a different form since its annual costs are still increasing (see Section IV.C.2). These models and their R^2s are

Mission	Model	R^2, %
Galileo	$Y_t = 1983t \exp(-0.0224t^2)$	71
Voyager (U)	$Y_t = 6583t \exp(-0.0861t^2)$	92
Voyager (N)	$Y_t = 4879t \exp(-0.0308t^2)$	75
Magellan	$Y_t = -9358 + 10574t - 1193t^2$	99

C. Composite Model

1. Total mission period. A general long-range planning cost model for support of future space missions by the DSN has also been developed. This model is called the "composite model," since it uses the average annual DSN preparation cost data of the above four space missions. The data from Table 1 are rearranged to a "year of mission" format in Table 3 and averaged by year as shown in Table 4. The resulting composite model is

$$Y_t = 3613t \exp(-0.0311t^2) \quad (1)$$

and the total cost of a mission is

$$Y(\text{total}) = \sum Y_t \quad (2)$$

The composite model has a goodness of fit (R^2) of 87 percent, and, therefore, could be used to give cost estimates for preliminary budgetary planning for future space missions. Table 3 and Fig. 3 show the actual cost data of the four missions and costs as predicted by the model. Table 4 and Fig. 4 show the actual composite average cost data of the four missions and costs as predicted by the model.

2. Growth period. During the growth period (or early stages) of DSN preparation for a space mission, the DSN annual preparation costs are generally increasing—for example, during the first two years of Voyager (U), the first three years of Voyager (N), the first four years of Magellan, and the first five years of Galileo. To get better accuracy in predicting the DSN annual preparation costs during the growth period, the following model is used:

$$Y_t = -4738 + 8786t - 1322t^2 \quad (3)$$

where Y_t is the cost for DSN to support the space mission in year t. The growth model shows a coefficient of determination R^2 of 99 percent. A comparison of the DSN actual average annual preparation costs of the four missions versus those same costs as predicted by the growth model is as follows:

Year, Y_t	Average annual cost: actual, \$K	Average annual cost: model, \$K	Model minus actual, Δ in \$K	Error, %, Δ/actual
1	2652	2726	+ 74	+ 3
2	7769	7546	− 223	− 3
3	9501	9722	+ 221	+ 2
4	9331	9254	− 77	− 1
Average/ year	7313	7312	− 1.25	+ 0.25

A comparison of the composite model derived from all four missions, Eq. (1), the growth model, Eq. (3), and the actual average annual costs of the four missions for the first four years gives the following:

Year, Y_t	Annual cost: composite model, $K	Annual cost: growth model, $K	Actual average annual cost, $K
1	3502	2726	2652
2	6381	7546	7769
3	8193	9722	9501
4	8787	9254	9331
Average/ year	6716	7312	7313

On the average, the annual cost for the DSN to support a mission during the growth period is about $7 million.

V. Back-Testing the Composite Model

The composite model was checked with four missions: Galileo, Voyager (U), Voyager (N), and Magellan. The actual total preparation costs of the missions and those costs as predicted by the composite model are shown below:

Space mission	Preparation cost: actual, $M	Total cost: model, $M	Model minus actual, Δ in $M	Error, %, Δ/ actual
Galileo	47.2	55.9	+ 8.7	+ 18.0
Voyager (U)	35.9	35.2	− 0.7	− 1.9
Voyager (N)	36.0	26.9	− 9.1	− 25.0
Magellan	32.5	26.9	− 5.6	− 17.0
Average/ mission	37.9	36.3	− 1.6	

The actual preparation costs for Voyager (U), Voyager (N), and Magellan were larger than those predicted by the model. However, Galileo actual preparation costs were less than the model predicted. This is probably a result of the Galileo launch slipping from 1986 to 1989 because of the Challenger loss. Therefore, a larger value for n was used in the model, due to this slippage. On the average, the difference between a mission actual total preparation cost and that predicted by the composite model is about $1.6 million, or 4 percent of actual total preparation cost.

The difference between the actual average annual cost and the predicted average annual cost is $730,000, as shown below.

Space mission	Average annual cost: actual, $M	Average annual cost: model, $M	Model minus actual, Δ in $M	Error, %, Δ/ actual
Galileo	4.72	5.59	+ 0.87	+ 18.0
Voyager (U)	7.18	7.04	− 0.14	− 1.9
Voyager (N)	9.00	6.72	− 2.27	− 25.0
Magellan	8.12	6.72	− 1.39	− 17.0
Annual grand average	7.25	6.50	− 0.73	

VI. How to Use the Model

The long-range planning cost model for support of future space missions by the DSN is developed from historical cost data as a composite cost average of four space missions: Galileo, Voyager (Uranus), Voyager (Neptune), and Magellan. The model is

$$Y_t = 3613t \exp(-0.0311t^2)$$

where Y_t is the cost in year t for DSN preparation to support a mission ($t = 1, 2, \ldots, n$), and n is the total number of years for DSN preparation. The total DSN preparation cost is = $\sum Y_t$.

For example, to estimate the DSN preparation budget for a future project, sum the annual preparation costs predicted by the model over the life of the project (n), as shown below:

Year, t	Composite model annual predicted cost, Y_t, \$M	Predicted DSN preparation total cost $\sum Y_t$, n years						
		4	5	6	7	8	9	10
1	3.5							
2	6.4							
3	8.2							
4	8.8	26.9						
5	8.3		35.2					
6	7.1			42.3				
7	5.5				47.8			
8	3.9					51.7		
9	2.6						54.3	
10	1.6							55.9

For example, a DSN preparation of four years is predicted to have a total cost of \$26.9 million, and a total cost of \$35.2 million is predicted for a DSN preparation of five years, and so on. It should be noted that since the historical data covered DSN tasks from $n = 4$ to 10 years, extrapolating outside that range of years should be avoided. It should also be cautioned that there are missions differing considerably in scope and/or complexity from the mission set analyzed here.[4] In such cases the required DSN equipment might well mean a cost greater (or less) than that indicated by the model. Obviously, good judgment must be used.

VII. Results

A. Comparison With Other Independent Missions

The composite model developed from the four missions was also tested against two other independent missions, Viking and Mariner Jupiter/Saturn (MJS, later renamed Voyager).

DSN preparation time for Viking was $7\frac{1}{4}$ years—from 1971 through 1977, including the fiscal year transition quarter of 1976–1977. Using the table in Section VI, \$47.8 million is obtained for $n = 7$ years, and one-fourth of the difference between $n = 7$ and $n = 8$ is added, to get \$1 million. The total predicted cost from the model is therefore \$48.8 million, as compared to the actual cost of \$49.7 million.[5,6]

DSN preparation time for MJS was harder to define. It was recognized before the Jupiter encounter that the MJS mission would require a significant enhancement of the received signal for the Saturn encounter. It appears reasonable to apportion the DSN preparation costs for the MJS mission into two phases: (1) $8\frac{1}{4}$ years' duration (1972 through 1979, including the 1976/1977 fiscal year transition quarter), and (2) 5 years' duration (1977 through 1981). Using this model of MJS, the total predicted cost is \$87.6 million. The actual value was \$97.5 million.[5,6]

Note that the annual average of these two projects is \$7.15 million, which is essentially the same as the \$7.25 million average for the four projects used to develop the model. Therefore, a rule-of-thumb is that DSN preparation for a mission has an annual average preparation cost of \$7.2 million in 1987 dollars. The results are summarized below.

Space mission	Total cost: actual, \$M	Total cost: model, \$M	Model minus actual, Δ in \$M	Error, %, Δ/actual
MJS	97.5[5,6]	87.6	− 9.9	− 10.2
Viking	49.7[5,6]	48.8	− 0.9	− 1.8

A comparison between the actual average annual preparation cost and the predicted average annual cost of the missions is \$500,000, as shown below.

Space mission	Average annual cost: actual, \$M	Average annual cost: model, \$M	Model minus actual, Δ in \$M
MJS	7.4	6.6	− 0.8
Viking	6.9	6.7	− 0.2
Annual grand average	7.15	6.65	− 0.50

[4] J. W. Layland, private communication.

[5] "Narratives covering FY'82, FY'86, and FY'88," TDA work authorization documents (internal documents).

[6] J. W. Layland, private communication.

B. Total DSN Preparation Cost Composite Model

The composite model for total DSN preparation cost presented here is obviously a simple model that has only time duration as a parameter. However, the model does a reasonable job for representing the actual preparation costs for Galileo, Voyager (U), Voyager (N), and Magellan and also for the two independent projects Mariner Jupiter/Saturn (MJS) and Viking. This model could be used for long-range planning cost estimates for budgetary planning of DSN support of future space missions. The model can also be used to check "grass roots" detailed cost estimates. Based on our back-testing the actual four projects against the model, the results are in the range of 18 percent above actual costs to 25 percent below actual costs. This model should only be used for projects comparable in scope (4 to 10 years, and $25 million to $55 million).

References

[1] *Project Galileo*, JPL Fact Sheet, Jet Propulsion Laboratory, Pasadena, California, September 14, 1988.

[2] *Space Exploration: Cost, Schedule and Performance of NASA's Galileo Mission to Jupiter*, GAO/NSIAD-88-138FS, U.S. General Accounting Office, Washington, D.C., May 27, 1988.

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[6] *Space Exploration: Cost, Schedule and Performance of NASA's Magellan Mission to Venus*, GAO/NSIAD-88-130FS, U.S. General Accounting Office, Washington, D.C., May 27, 1988.

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[9] B. Boehm, *Software Engineering Economics*, Englewood Cliffs, New Jersey: Prentice Hall, 1981.

[10] J. T. McClave and P. G. Benson, *Statistics* (4th ed.), New York: Macmillan Publishing Co., 1988.

Table 1. DSN preparation costs summary by fiscal year (1987 $K; FY'79–FY'88)

Mission	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	Total	Average	Standard deviation	Max. (Y)	Min. (Y)	Range
Galileo	1,052	3,822	4,352	4,875	7,010	6,833	8,012	8,275	1,278	1,677	47,186	4,719	2,673	8,275 ('86)	1,052 ('79)	7,223
Voyager (Uranus)				4,482	13,124	8,339	6,211	3,705			35,861	7,172	3,774	13,124 ('83)	3,705 ('86)	9,419
Voyager (Neptune)							4,984	7,308	12,328	11,429	36,049	8,012	3,462	12,328 ('87)	4,984 ('85)	7,344
Magellan							88	6,823	11,824	13,788	35,523	8,131	6,111	13,788 ('88)	88 ('85)	13,700

Table 2. Galileo preparation costs versus Galileo model (1987 $K; FY'79–FY'88)

	FY'79	FY'80	FY'81	FY'82	FY'83	FY'84	FY'85	FY'86	FY'87	FY'88	Total	Average	Standard deviation	Max.	Min.	Range
Costs (C)	1,052	3,822	4,352	4,875	7,010	6,833	8,012	8,275	1,278	1,677	47,186	4,719	2,673	8,275	1,052	7,223
Model (M)	1,939	3,626	4,863	5,543	5,664	5,312	4,632	3,783	2,908	2,111	40,381	4,038	1,382	5,664	1,939	3,725
Δ(M−C)	887	−196	511	668	−1,346	−1,521	−3,380	−4,429	1,630	434	−6,805	−681				

Table 3. DSN actual preparation costs and composite model costs (1987 $K)

Actual	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	Yr. 6	Yr. 7	Yr. 8	Yr. 9	Yr. 10	Total cost	Avg. cost/yr.
Galileo	1,052	3,822	4,352	4,875	7,010	6,833	8,012	8,275	1,278	1,677	47,186	4,719
Voyager (Uranus)	4,482	13,124	8,339	6,211	3,705						35,861	7,172
Voyager (Neptune)	4,984	7,308	12,328	11,429							36,049	9,012
Magellan	88	6,823	11,824	13,788							32,523	8,131
Model (composite)	**Yr. 1**	**Yr. 2**	**Yr. 3**	**Yr. 4**	**Yr. 5**	**Yr. 6**	**Yr. 7**	**Yr. 8**	**Yr. 9**	**Yr. 10**	**Total cost**	**Avg. cost/yr.**
Galileo	3,502	6,381	8,193	8,787	8,302	7,076	5,510	3,949	2,619	1,611	55,930	5,593
Voyager (Uranus)	3,502	6,381	8,193	8,787	8,302						35,165	7,033
Voyager (Neptune)	3,502	6,381	8,193	8,787							26,863	6,716
Magellan	3,502	6,381	8,193	8,787							26,863	6,716

Table 4. Average of four projects' preparation costs versus composite model preparation costs (1987 $K; FY'79–FY'88)

	FY'79	FY'80	FY'81	FY'82	FY'83	FY'84	FY'85	FY'86	FY'87	FY'88	Total	Average	Standard deviation	Max.	Min.	Range
Costs (C)	2,652	7,769	9,211	9,076	5,358	6,833	8,012	8,275	1,278	1,677	60,141	6,014	3,081	9,211	1,278	7,933
Model (M)	3,502	6,381	8,193	8,787	8,302	7,076	5,510	3,949	2,619	1,611	55,933	5,593	2,558	8,787	1,611	7,176
Δ(M−C)	850	−1,388	−1,018	−289	2,944	243	−2,502	−4,326	1,341	−66	−4,208	−421				

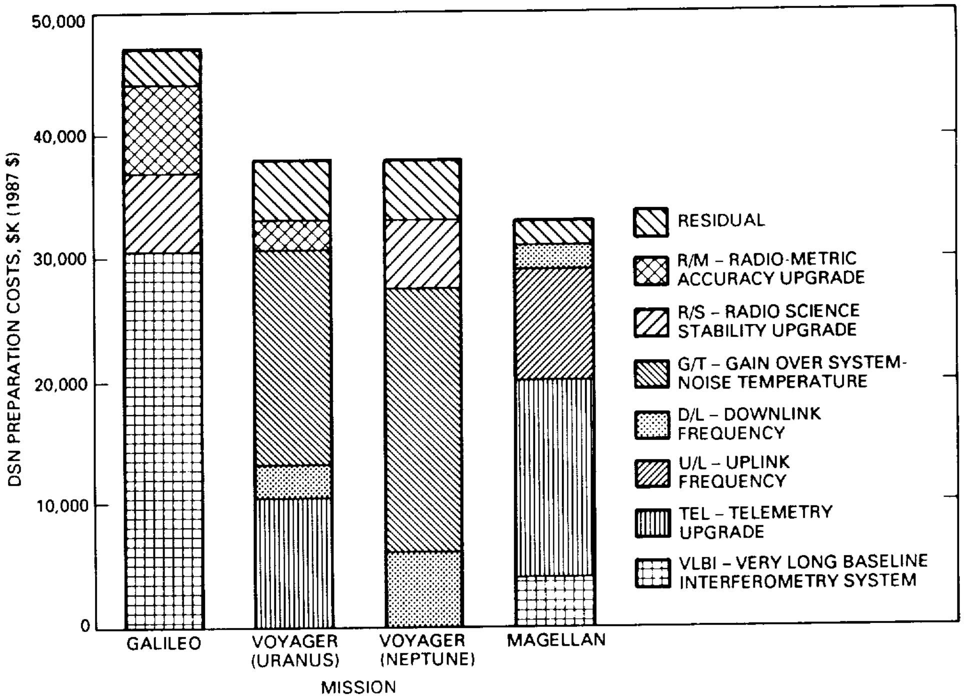

Fig. 1. DSN preparation costs by category.

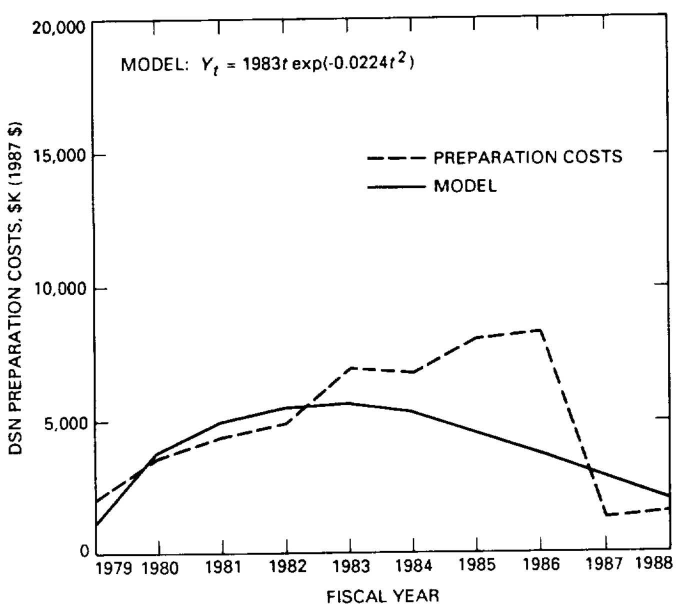

Fig. 2. Actual Galileo preparation costs versus costs predicted by Galileo model (fiscal years 1979–1988).

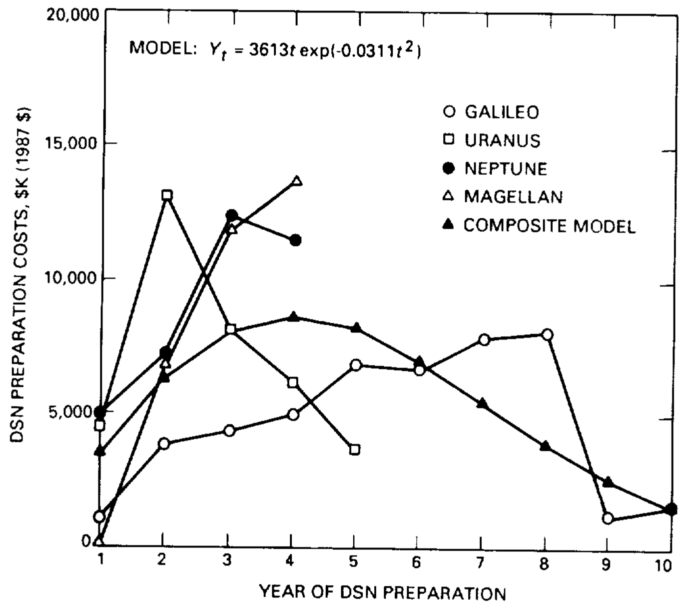

Fig. 3. Actual DSN preparation costs versus costs predicted by composite model.

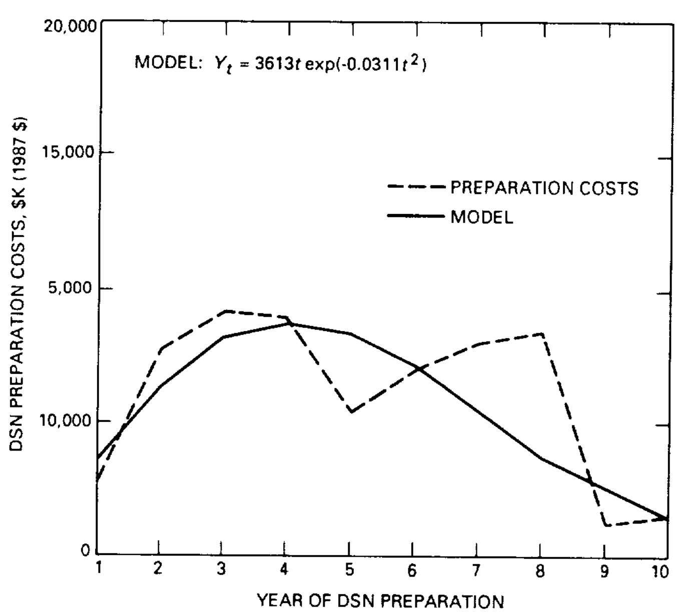

Fig. 4. Average DSN preparation costs for four projects versus costs predicted by composite model.