Modeling Preparation Costs for Space Missions by Using Major Cost Drivers

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This article suggests a model for making long-range-planning cost estimates for DSN support of future space missions. The model is a function of major mission-cost drivers, such as maintenance and operations, downlink frequency upgrade, uplink frequency upgrade, telemetry upgrade, antenna gain/noise temperature, radiometric accuracy upgrade, radio science upgrade, and very long baseline interferometry.

The model is derived from actual cost data from three space missions: Voyager (Uranus), Voyager (Neptune), and Magellan. The model allows one to estimate the total cost and the cost over time of a similar future space mission.

The model was back-tested against the three projects—Voyager (U), Voyager (N), and Magellan—and gave cost estimates that range from 17 percent below to 19 percent above actual mission-preparation costs. The model was also compared with two other independent projects: Mariner Jupiter/Saturn (MJS later became Voyager) and Viking. The model gave total preparation-cost estimates that range from 15 percent above to 4 percent below actual total preparation costs for MJS and Viking, respectively.

I. Introduction

A. Project Objectives

The objective of this study is to develop a model that can be used in the early planning stages to estimate the cost to prepare the DSN for future space-mission support. The proposed model captures the major cost drivers of a mission, such as its use of an uplink, a downlink, a very long baseline interferometry system, etc. The proposed model gives cost estimates that are functions of the cost drivers and the duration of a project, which are demanded by the project's unique mission. The results of this study expand on previous cost modeling that was cost-driver and mission independent. The previous work can be used in the earliest stages of cost estimating, before the cost drivers and unique mission characteristics are defined [1].

The present study focuses on the major cost drivers that make up the total preparation cost of a particular project. Because of this focus, the total estimated project-preparation cost will reflect only those major cost drivers that pertain to that particular project, and thus a more project-sensitive cost estimate will be achieved.

B. Overview of Article

In Section II, the preparation cost drivers for space missions are defined, and the methodology for collecting the cost data and the cost history is summarized. The portion of the model concerning the total mission's cost-preparation drivers (Model A) is developed in this Section. Model A is back-tested against the three missions [Voyager (Uranus), Voyager (Neptune) and Magellan], and an example is given to show how to use it. In Section III, the aspect of the model concerning the cost drivers over a specific time period (Model B) is developed. Model B is back-tested against the three missions, and an example is given to show how to use it. In Section IV, as an "external" check, Model A is compared with two independent projects: Mariner Jupiter/Saturn (MJS, which later became Voyager) and Viking.

II. Development of a Model Based on Cost Drivers

A. Definition of "Cost Drivers"

The DSN-preparation costs for each project have been collected into the following major cost-driver categories:

(1) (M/O): maintenance and operations

(2) (D/L): downlink frequency upgrade

(3) (U/L): uplink frequency upgrade

(4) (TEL): telemetry upgrade

(5) (G/T): antenna gain/noise temperature

(6) (R/M): radiometric accuracy upgrade

(7) (R/S): radio science upgrade

(8) (VLBI): very long baseline interferometry

(9) (OTH): other

Here are the definitions of these cost drivers:

1. (M/O). These are initial entry and management costs for the project, e.g., funding for (M/O) network functions, network-operations project support, and the Tracking and Data System (TDS) manager for the project.

2. (D/L). These are the costs of adding new receiver, antenna, and microwave capabilities to the DSN: providing a new downlink frequency; giving additional performance capability to the existing receivers, antennas, and microwave instruments; increasing the number of channels provided by the existing antenna, receivers, and microwave instruments; etc.

3. (U/L). These are the costs of adding new transmitter, antenna, and microwave capabilities to the DSN: a new uplink frequency; additional performance capabilities to the existing transmitters, antennas, and microwave instruments, such as higher power, increased phase stability, etc.

4. (TEL). These are the costs of upgrading the telemetry and signal-processing equipment: adding new technical capability; adding to the monitor and control capability; providing new techniques, such as baseband combining for antenna arrays; etc.

5. (G/T). These are the costs of upgrading the ratio of the antenna gain to the receiving system noise temperature. (G/T) is a figure of merit for a telecommunications receiving system. Included are costs of providing new antennas, enlarging existing antennas, providing new/improved low-noise microwave amplifiers, providing antenna arrays, etc.

6. (R/M). These are the costs associated with upgrading the accuracy with which the spacecraft location can be measured. This includes upgrades to the data system equipment, improving DSN station location accuracy, improving time-synchronizing calibration throughout the network stations, etc.

7. (R/S). These are costs associated with upgrading the DSN radio science performance. These include adding new and/or improved receivers and data-processing and recording equipment; improved frequency and timing equipment/calibration, etc.

8. (VLBI). These are costs of implementing new, complete (VLBI) equipment for both 34-m Wide Channel Bandwidth (WCB) and 70-m Narrow Channel Bandwidth (NCB) systems. Included are receivers, low-noise amplifiers, and support for the Radio Source Catalog and Universal Time Engineering.

9. (OTH). These costs are for any miscellaneous tasks not fitting into one of the above cost-driver categories. In some cases, the costs allocated to a cost-driver category are so small as to be presumed to be of a miscellaneous nature. These costs have been placed in the (OTH) category in this article. See Section II.C for further details.

B. Data Collection and Summary

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 (CoF) costs, spacecraft costs, transportation costs, and/or other logistics costs.[1] All costs used in this article are adjusted for inflation to 1987 dollars by using the NASA Inflation Index. The preparation costs, grouped into cost drivers, for three projects—Voyager (U), Voyager (N), and Magellan—and the typical cost-driver values are shown in Table 1. The periods for tracking the preparation costs considered in this article are 1982 through 1986 for Voyager (U), 1985 through 1988 for Voyager (N), and 1985 through 1988 for Magellan [1].

C. Development of Model A: The Total-Mission Cost-Drivers Model

The assumption behind Model A is that the total preparation cost for a mission can be estimated by the summation of the typical cost-driver values given in Table 1 that are relevant to that particular mission. A typical cost-driver value in the model is an effective average value that is calculated after assigning any cost-driver values in a particular category that are less than 15 percent of the maximum value to the "Other" cost-driver category. It is assumed that a cost value that is that low reflects miscellaneous changes to the system rather than a significant cost-driver upgrade. For example, in Table 1, the 46 $K value for the (R/S) of Magellan is less than 15 percent of the 5,484 $K (R/S) value of Voyager (N); therefore, this cost driver for Magellan is considered "Other." Consequently, the typical (R/S) cost-driver value will be the average of those of Voyager (U) and Voyager (N), or 3,429 $K. The numbers in brackets in Table 1 were handled this way. Note that Magellan has 770 $K of miscellaneous costs in addition to the (R/M), 33 $K, and the (R/S), 46 $K, included in the "Other" cost-driver category.

D. Back-Testing the Total-Mission Cost-Drivers Model

The total-mission cost-drivers model (Table 1) was compared with the actuals for the three missions: Voyager (U), Voyager (N), and Magellan, as shown in Table 2.

A comparison of the actual preparation costs and those same costs, as predicted by Model A, for the three missions is shown in Table 3.

The average mission-preparation cost of 34.8 $M, as estimated by the model, is the same as the actual average cost. However, the difference in predicting individual mission-preparation costs ranges from 17 percent below to 18.9 percent above actual costs for Voyager (N) and Voyager (U), respectively. The preparation costs estimated from the model are about 1.9 percent below the actual preparation costs for Magellan.

E. How To Use Model A (the Total-Mission Cost-Drivers Model)

Model A is developed from the historical cost data of three space missions: Voyager (U), Voyager (N), and Magellan; the values of like preparation cost drivers are averaged. For example, to estimate the total preparation cost for a mission that has the cost drivers (R/M), (R/S), (VLBI), (U/L), (TEL), and (G/T), one determines the actual cost-driver value for each mission (in Table 1) and averages them to get cost-driver values for the model. A summary is given in Table 4.

Model A gives the total preparation cost of a mission, but it does not give a profile of costs over time. Model B does give the cost profile over time.

III. Model B: The Cost Drivers Modeled Over Time

A. Development of a Model of Cost Drivers Over Time

The average preparation cost over time for each major cost driver is calculated for each of the three missions:

[1] "Obligations Performance Reports, 1982–1988," TDA work authorization documents (WADs) (internal documents), Jet Propulsion Laboratory, Pasadena, California.

Voyager (U), Voyager (N), and Magellan. The individual cost-driver data are then regressed over time, and the best-fit equation is chosen. The best-fit equations are shown in Table 5, where Y_t is the cost in year t, $(t = 1, 2, ..., n)$; t is the number of the year in the DSN preparation-cost life of the mission; n is the total number of years of the DSN preparation; and the total cost of the DSN preparation is $Y(\text{total}) = \Sigma Y_t$.

B. Analysis of Model B: The Cost Drivers Modeled Over Time

The best-fit equations for the cost-driver data are linear for (U/L) and (VLBI); quadratic for (TEL), (G/T), and (R/M); and cubic for (M/O), (D/L), and (R/S). The equations have a goodness of fit (R^2) that ranges from 81 to 100 percent [2]. Figures 1 through 6 show the actual costs for each cost driver and those predicted by the equations. (U/L) and (VLBI) cost-driver figures are not shown since as of 1988, there were only two data points for each cost driver. This is the cutoff year of the data collected for the previous report on this research [1].

C. Back-Testing Model B: The Cost Drivers Modeled Over Time

Model B was checked against the three missions: Voyager (U), Voyager (N), and Magellan. Table 6 shows the actual average annual preparation costs of the three missions and those costs as predicted by the model. Table 7 shows that the 33.6 $M average preparation cost for the three missions, as predicted by the model, is 1.2 $M below the actual average preparation cost of 34.8 $M. The difference is about 3.4 percent. However, the difference in predicting individual mission preparation costs ranges from 22.5 percent below to 17.5 percent above actual preparation costs—for Voyager (N) and Voyager (U), respectively. The difference in predicting preparation costs for Magellan is 5 percent.

For planning purposes, a model that gives an accurate cumulative preparation cost for the life of the project is needed. For example, Fig. 7 shows the cumulative actual preparation cost over time and the cumulative preparation cost predicted by the cost-driver model for the Magellan mission, while Fig. 8 shows the cumulative actual preparation cost over time and the cumulative preparation cost predicted by the cost-driver model for cost driver (TEL) of Magellan.

In addition to comparing the actual preparation costs with those predicted by the model for a specific project or cost driver, the actual average preparation cost is also compared with the model's average for all three projects. For example, Fig. 9 shows the actual average preparation cost of a mission over time and the average preparation cost predicted by the model, while Fig. 10 shows the cumulative actual average preparation cost of a mission over time and the average cumulative preparation cost predicted by the model.

D. How To Use Model B: The Cost Drivers Modeled Over Time

Example 1. To estimate the annual preparation costs for a mission of five years that incurs all nine cost drivers, one looks up the model's results in Table 6 and sums the costs predicted by the model. A summary is given in Table 8.

Example 2. To estimate the total preparation costs over time for a mission of five years' duration that has the following six cost drivers: (R/M), (R/S), (VLBI), (U/L), (TEL), and (G/T), one looks up the model's results in Table 6 and sums the costs predicted by the model. The results are shown in Table 9.

This total value (50.5 $M) is close to the value (50.3 $M) predicted by Model A—the total-mission cost-drivers model, as described in Section II.E. The difference is about 0.2 $M, or 0.4 percent above that predicted by Model A.

Example 3. To estimate the preparation costs for any cost driver, such as (TEL), over a period of five years, one looks up the model's results in Table 6 and obtains the results shown in Table 10. This technique allows one to see the cost profile for this cost driver over time, and the same technique could be used for all the cost drivers for a proposed project.

IV. External Check and Comparison With Independent Missions

Model A was tested against two other independent missions: Mariner Jupiter/Saturn (MJS) and Viking.

The project MJS seems to have incurred all the major cost drivers that are covered in this article.[2] According to Table 1, the total cost for an average mission with a four- to five-year duration that incurs all the major cost drivers is 56.1 $M (1987 $M). Based on a previous study [1], it was concluded that the MJS mission (which continued for 10 years) might be viewed as having two distinct phases. It seems reasonable to consider the cost estimate for such

[2] J. R. Hall, private communication, Jet Propulsion Laboratory, Pasadena, California, April 1990.

a mission as twice that predicted for the "standard" five-year mission. That results in a predicted cost of 112.2 \$M (1987 \$M), as compared with the actual cost of 97.5 \$M.[3] The difference is about 15 percent.

The project Viking did not use (VLBI); however, it used the other cost drivers.[4] The estimated total preparation cost for Viking predicted by Model A is then 56,079 \$K − 4,436 \$K = 51,643 \$K (1987 \$K), or about 51.6 \$M, as compared with the actual cost of 49.7 \$M. The difference is 3.8 percent.

V. Summary

A cost model has been presented in this article to give estimates for future DSN-preparation costs. The model has two components: A and B.

Model A is called the total-mission cost-drivers model, and Model B models cost drivers over time.

Model A estimates total DSN-preparation costs based on the average values of DSN cost drivers from three space missions: Voyager (U), Voyager (N), and Magellan. The model is concerned with those cost drivers that are relevant to a mission, and thus, the model is sensitive to mission objectives and uniqueness. Model A does a reasonable job of representing the actual preparation costs for Voyager (U), Voyager (N), and Magellan. Based on back-testing of the actual three projects against the model, the results are in the range of 17 percent below to 19 percent above actual costs. Model A was also compared with two other independent projects, MJS and Viking. The model gave total-cost estimates that range from 15 percent above to 4 percent below actual total costs for MJS and Viking, respectively.

Model B estimates the annual preparation cost of each cost driver relevant to a mission and also estimates total mission-preparation cost. The model is time and cost-driver sensitive and thus will capture future missions' cost dependence on both time and relevant cost drivers. Model B also does a reasonable job of representing the actual preparation costs over time for Voyager (U), Voyager (N), and Magellan. Based on back-testing of the actual three projects against the model, the results are in the range of 22.5 percent below to 18 percent above actual costs.

Both Model A and Model B are applicable to missions that do not exceed five years' duration and that have the cost drivers discussed in this study.

[3] J. W. Layland, private communication, Jet Propulsion Laboratory, Pasadena, California, March 1990.

[4] D. J. Mudgway, private communication, Jet Propulsion Laboratory, Pasadena, California, April 1990.

References

[1] J. S. Sherif, D. S. Remer, and H. R. Buchanan, "Long-Range Planning Cost Model for Support of Future Space Missions by the Deep Space Network," *TDA Progress Report 42-101*, vol. January–March 1990, Jet Propulsion Laboratory, Pasadena, California, pp. 179–190, May 15, 1990.

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

Table 1. Preparation cost drivers for three missions, and typical cost-driver values, 1987 $K[a]

Cost Drivers	Missions			Typical Cost-Driver Value
	Voyager (U)	Voyager (N)	Magellan	
M/O	955	677	634	755
D/L	2,647	6,566	2,211	3,808
U/L	[700]	0	8,947	8,947
TEL	10,357	[1,134]	15,445	12,901
G/T	17,795	21,008	0	19,402
R/M	2,032	580	[33]	1,306
R/S	1,374	5,484	[46]	3,429
VLBI	0	[601]	4,436	4,436
Other	700	1,735	849	1,095
Total	35,860	36,050	32,522	56,079

[a] The bracketed numbers are discussed in Section II.C.

Table 2. Actual and Model A costs for three missions

Cost Drivers	Voyager (U)		Voyager (N)		Magellan	
	Actual	Model	Actual	Model	Actual	Model
M/O	955	755	677	755	634	755
R/M	2,032	1,306	580	1,306	0	0
R/S	1,374	3,429	5,484	3,429	0	0
D/L	2,647	3,808	6,566	3,808	2,211	3,808
VLBI	0	0	0	0	4,436	4,436
U/L	0	0	0	0	8,947	8,947
TEL	10,357	12,901	0	0	15,445	12,901
G/T	17,795	19,402	21,008	19,402	0	0
Other	700	1,095	1,735	1,095	849	1,095
Total	35,860	42,696	36,050	29,795	32,522	31,942

Table 3. Summary of actual and Model A total preparation costs in 1987 $M

Space Mission	Actual Preparation Cost, $M	Model A Preparation Cost, $M	Model A Minus Actual, Δ in $M	Error, %, Δ/Actual
Voyager (U)	35.9	42.7	6.8	18.9
Voyager (N)	36.0	29.8	−6.2	−17.0
Magellan	32.5	31.9	−0.6	−1.9
Average for all missions	34.8	34.8	0	0

Table 4. Preparation costs predicted by Model A in 1987 $M

Cost Driver	Cost Predicted by Model A
R/M	1.3
R/S	3.4
VLBI	4.4
U/L	8.9
TEL	12.9
G/T	19.4
Total	50.3

Table 5. The best-fit equation for each cost driver

Cost Drivers	Model	R^2
(M/O)	$Y_t = 352 - 318t + 144t^2 - 18.6t^3$	99
(D/L)	$Y_t = -3,053 + 4,558t - 1,474t^2 + 139t^3$	82
(U/L)	$Y_t = 4,561 - 25t$ (for $t = 3$ and 4)	100
(TEL)	$Y_t = -4,114 + 5,938t - 1,011t^2$	81
(G/T)	$Y_t = -2,175 + 5,880t - 1,053t^2$	99
(R/M)	$Y_t = 104 + 229t - 48.1t^2$	90
(R/S)	$Y_t = 1,339 - 2,207t + 1,218t^2 - 165t^3$	98
(VLBI)	$Y_t = -792 + 860t$ (for $t = 3$ and 4)	100

Table 6. Summary of actual average annual preparation costs for three missions and costs predicted by Model B, $K (1987 $). "A" = actual costs; "M" = Model B costs.

Year	M/O	D/L	U/L	TEL	G/T	R/M	R/S	VLBI	Other	Total
1 (A)	159	126	-	502	2,753	258	164	-	444	4,406
(M)	159	170	-	813	2,652	285	185	-	283	4,547
2 (A)	149	1,535	-	4,782	5,172	421	557	-	115	12,731
(M)	143	1,279	-	3,718	5,372	369	477	-	335	11,693
3 (A)	191	867	4,486	3,279	5,980	361	1,100	1,788	536	18,588
(M)	192	1,108	4,486	4,601	5,986	358	1,225	1,788	477	20,221
4 (A)	206	853	4,461	4,161	4,704	193	1,513	2,648	-	18,739
(M)	194	491	4,461	3,462	4,497	250	1,439	2,648	-	17,442
5 (A)	50	427	-	177	793	73	95	-	-	1,615
(M)	37	262	-	300	896	46	129	-	-	1,670
Total (A)	755	3,808	8,947	12,901	19,402	1,306	3,429	4,436	1,095	56,079
Total (M)	725	3,310	8,947	12,894	19,403	1,308	3,455	4,436	1,095	55,573
(M−A)	−30	−498	0	−7	1	2	26	0	0	−506

Table 7. Summary of the actual average annual preparation costs for three missions, and the costs predicted by Model B, $M (1987 $)

Space Mission	Actual Preparation Cost, $M	Model B Preparation Cost, $M	Model B Minus Actual, Δ in $M	Error, %, Δ/Actual
Voyager (U)	35.9	42.2	6.3	17.5
Voyager (N)	36.0	27.9	−8.1	−22.5
Magellan	32.5	30.8	−1.7	−5.0
Average for all missions	34.8	33.6	−1.2	−3.4

Table 8. Estimate of annual preparation costs for a five-year, nine-cost-driver mission by Model B, $K (1987 $)

Year	Actual Cost-Driver Total Cost, $K	Model B Cost-Driver Total Cost, $K	Model Minus Actual, Δ in $K	Error, %, Δ/Actual
1	4,406	4,547	141	3
2	12,731	11,693	−1,038	−8
3	18,588	20,221	1,633	9
4	18,739	17,442	−1,297	−7
5	1,615	1,670	55	3
Total	56,079	55,573	−506	0

Table 9. Estimate of annual preparation costs for a five-year, six-cost-driver mission by Model B, $M (1987 $)

Cost Driver	Cost Predicted by Model B
R/M	1.3
R/S	3.5
VLBI	4.4
U/L	8.9
TEL	13.0
G/T	19.4
Total	50.5

Table 10. Model B estimate of preparation cost of (TEL), $K (1987 $)

Year	Predicted (TEL) Cost, $K
1	813
2	3,718
3	4,601
4	3,462
5	300
Total	12,894

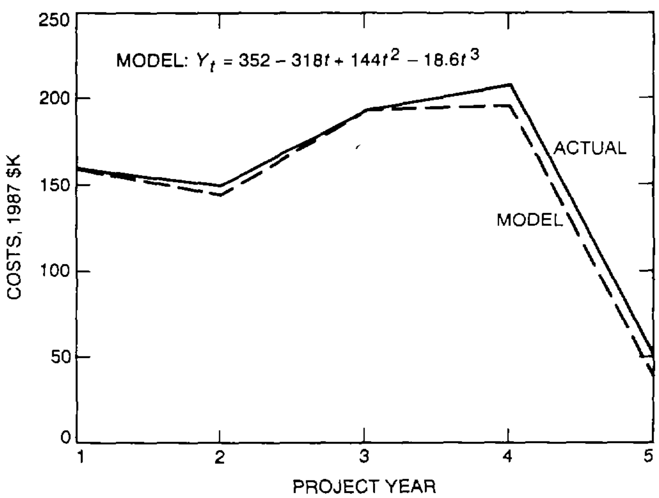

Fig. 1. Actual average maintenance and operations (M/O) costs versus costs predicted by Model B.

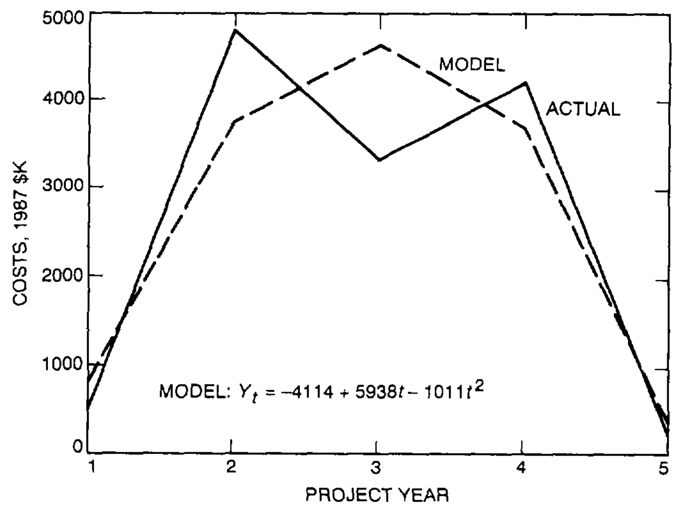

Fig. 3. Actual average telemetry upgrade (TEL) costs versus costs predicted by Model B.

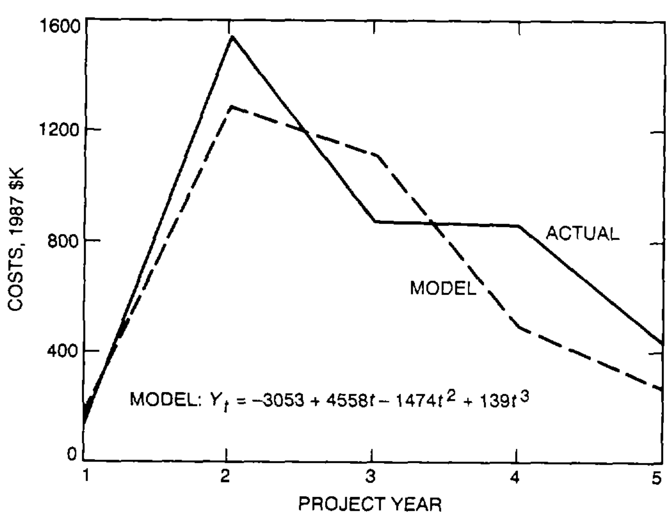

Fig. 2. Actual average downlink frequency upgrade (D/L) costs versus costs predicted by Model B.

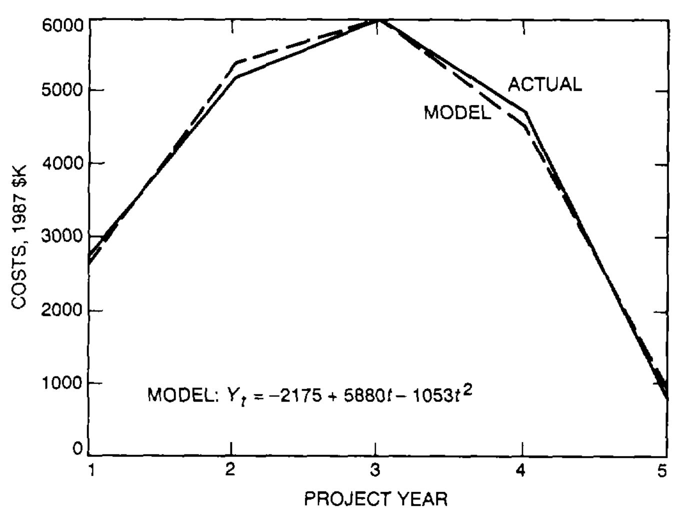

Fig. 4. Actual average antenna gain over system noise temperature (G/T) costs versus costs predicted by Model B.

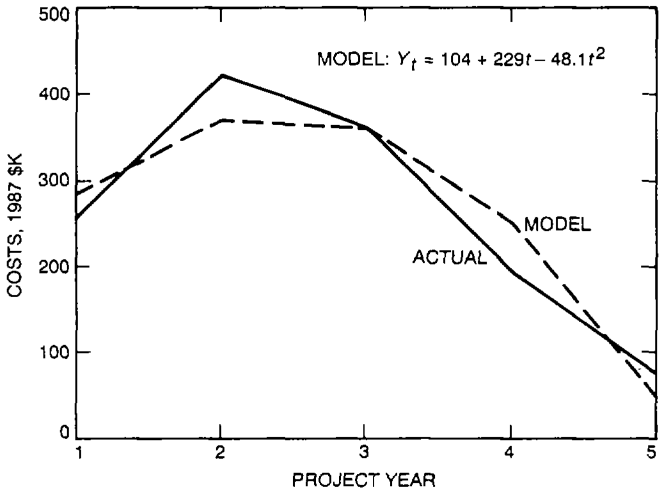

Fig. 5. Actual average radiometric accuracy upgrade (R/M) costs versus costs predicted by Model B.

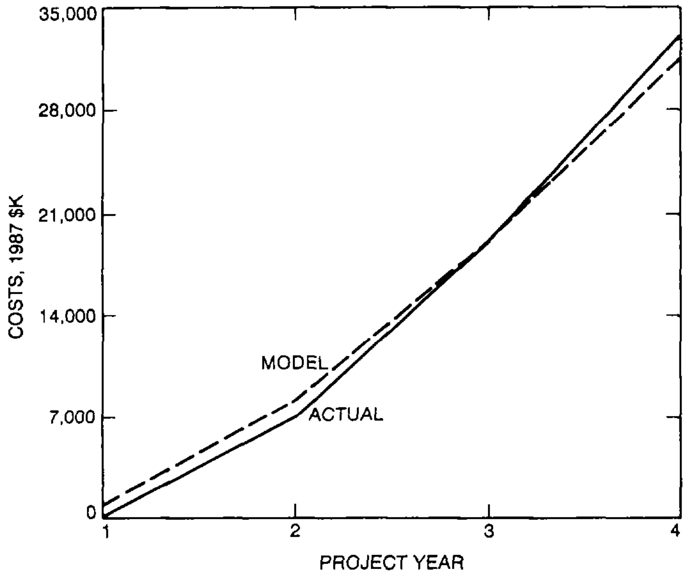

Fig. 7. Actual cumulative preparation costs and costs predicted by Model B for Magellan mission.

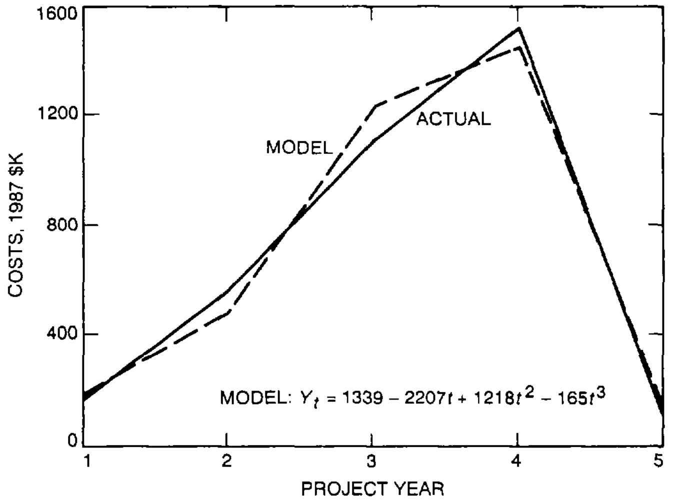

Fig. 6. Actual average radio science stability upgrade (R/S) costs versus costs predicted by Model B.

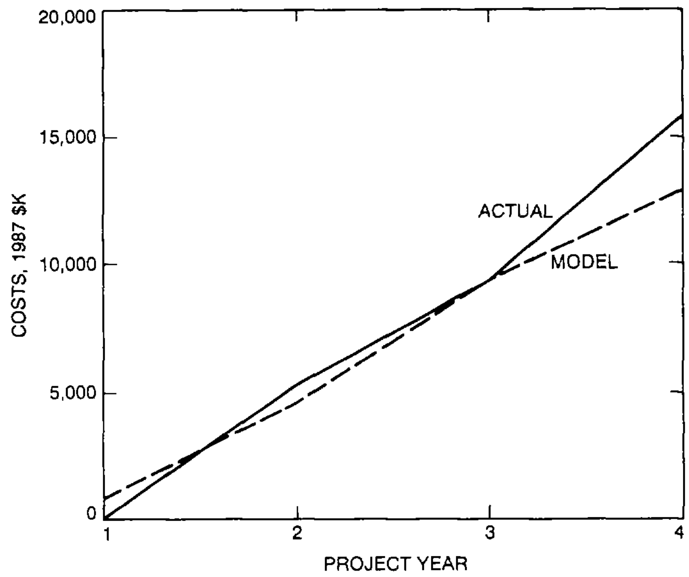

Fig. 8. Actual cumulative preparation costs and costs predicted by Model B for (TEL) cost driver of Magellan mission.

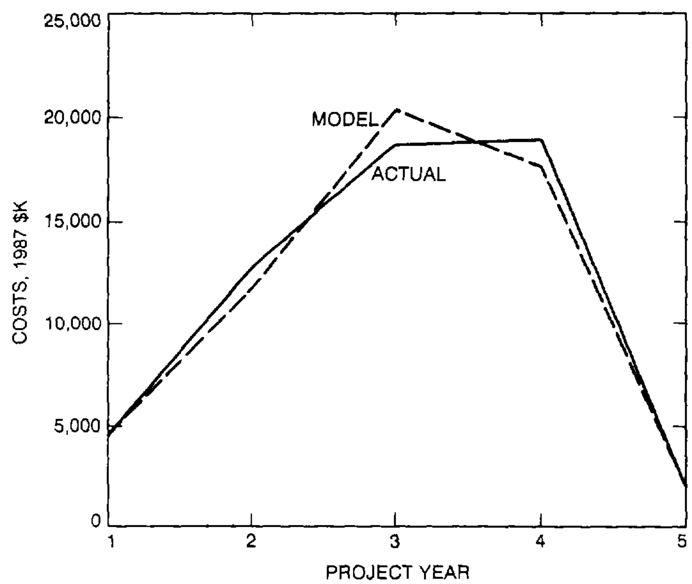

Fig. 9. Actual average preparation costs of a mission versus costs predicted by Model B.

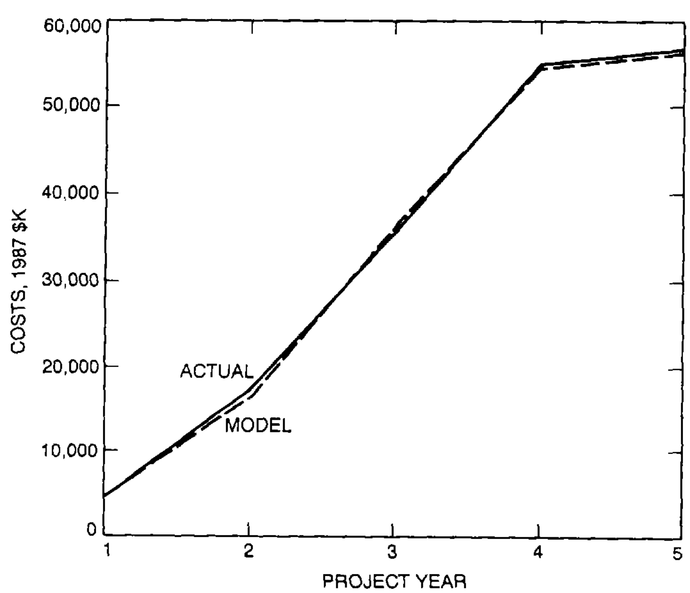

Fig. 10. Cumulative actual average annual preparation costs of a mission versus costs predicted by Model B.